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Coastal vegetation invasion increases greenhouse gas emission from wetland soils but also increases soil carbon accumulation

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HIGHLIGHTS

- Soils of exotic wetlands have higher greenhouse gas fluxes than native wetlands.
- Exotic coastal wetlands have higher soil organic carbon stock than native ones.
- Exotic *Sonneratia* mangrove forest has the highest total greenhouse gas fluxes.
- Exotic *Spartina* marsh has the highest fluxes of trace greenhouse gas, CH_4 and N_2O.

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ABSTRACT

Soil properties and soil–atmosphere fluxes of CO_2, CH_4 and N_2O from four coastal wetlands were studied throughout the year, namely, native *Kandelia obovata* mangrove forest vs. exotic *Sonneratia apetala* mangrove forest, and native *Cyperus malaccensis* salt marsh vs. exotic *Spartina alterniflora* salt marsh. Soils of the four wetlands were all net sources of greenhouse gases while *Sonneratia* forest contributed the most with a total soil–atmosphere CO_2-equivalent flux of 137.27 mg CO_2 m^{-2} h^{-1}, which is 69.23%, 99.75% and 44.56% higher than that of *Kandelia*, *Cyperus* and *Spartina*, respectively. The high underground biomass and distinctive root structure of *Sonneratia* might be responsible for its high greenhouse gas emission from the soil. Soils in *Spartina* marsh emitted the second largest amount of total greenhouse gases but it ranked first in emitting trace greenhouse gases. Annual average CH_4 and N_2O fluxes from *Spartina* soil were 13.77 and 1.14 μmol m^{-2} h^{-1}, respectively, which are 2.08 and 1.46 times that of *Kandelia*, 1.03 and 1.15 times of *Sonneratia*, and 1.74 and 1.02 times of *Cyperus*, respectively. *Spartina* has longer growing season and higher productivity than native marshes which might increase greenhouse gas emission in cold seasons. Exotic wetland soils had higher carbon stock as compared to their respective native counterparts but their carbon stocks were offset by a larger proportion because of their higher greenhouse gas emissions. Annual total soil–atmosphere fluxes of greenhouse gases reduced soil carbon burial benefits by 8.1%, 9.5%, 6.4% and 7.2% for *Kandelia*, *Sonneratia*, *Cyperus* and *Spartina*, respectively, which narrowed down the gaps in net soil carbon stock between native and exotic wetlands. The results indicated that the invasion of exotic wetland plants might convert local coastal soils into a considerable atmospheric source of greenhouse gases although they at the same time increase soil carbon accumulation.

1. Introduction

Spartina alterniflora (smooth cordgrass, hereafter referred as *Spartina*), a perennial grass native to North America, was introduced to China in 1979 to stabilize sediments in coastal areas (Qin and Zhong, 1992). In the past few decades, this species is widely reported to have invaded into mangrove forests (e.g., Zhang et al., 2012; Li et al., 2014) and suppressed native salt marshes (e.g., Tong et al., 2012, 2014) and it is now becoming a dominant vegetation type over most of the Chinese coast covering a latitude range of more than 19°. A further transition of coastal wetlands from mangrove forests to salt marshes is forecasted in Southeast China under the combined effects of global climatic changes and anthropogenic disturbances which increasingly fragment mangrove habitats and create hospitable environment for salt marshes (Zhang et al., 2012; Li et al., 2014). In spite of extensive studies documenting the spatial and temporal dynamics of coastal landscape between native mangrove forests and *Spartina* marshes (e.g., McKee et al., 2007; McKee and Rooth, 2008; Perry and Mendelssohn, 2009), only a few have ever discussed the invasive mechanisms of *Spartina* into local wetlands (e.g., Zhang et al., 2012; Li et al., 2014), and even less is known about its ecological implications, especially on carbon cycling in these regions.

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Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are three primary greenhouse gases exchanged between wetland soil and the atmosphere. The soil–atmosphere fluxes of greenhouse gases CO_2 and CH_4 are integral components of carbon cycling. Coastal wetlands are among the most productive and carbon rich ecosystems (Kirwan and Megonigal, 2013), but the anoxic and reduced environments in wetlands favor denitrification and methanogenesis in which large quantity of trace greenhouse gases (CH_4 and N_2O) as well as CO_2 is generated, which renders coastal wetland soils a major source to atmospheric greenhouse gases (e.g., Allen et al., 2007; Chen et al., 2012). The fluxes of greenhouse gases can offset part or all of any carbon burial benefit of coastal environments (Andrews et al., 2006; Luisetti et al., 2011), given the strong Global Warming Potential (GWP) of trace greenhouse gases CH_4 and N_2O, which is 23 and 296 times that of CO_2 on a molecular basis over 100 year time scale, respectively (IPCC, 2007; Shindell et al., 2009). In Blackwater estuary of the UK, the fluxes of CH_4 and N_2O reduce the carbon burial benefit of intertidal wetlands by up to 49% (Adams et al., 2012). With global warming continuing, it is forecasted that more carbon will be released from tropical ecosystems including mangrove forests and salt marshes to the atmosphere in the form of greenhouse gases (IPCC, 2013).

Cyperus malaccensis (shichito matgrass, hereafter referred as *Cyperus*) is a dominant native species of salt marshes in Southeast China. The aggressive invasion of *Spartina* into *Cyperus* communities in Min River Estuary has greatly increased the emission of CH_4 and CO_2 from this region by facilitating both the production and the transport of these gases through *Spartina* plants (Tong et al., 2012, 2014). However, to the best of our knowledge, no research has ever compared the emission of all three primary greenhouse gases simultaneously from invasive salt marshes with native marshes or with mangrove forests. With the ever-growing expansion of *Spartina* marshes and the continuous decline of mangrove forests in China, it is therefore urgent to evaluate the impacts of such large-scale vegetation shifts on greenhouse gas emission from coastal regions.

On the other hand, in order to compensate mangrove loss and restore degraded mangrove forests, several exotic mangrove species have been introduced to China over the past three decades, the most widely used of which is *Sonneratia apetala* (hereafter referred as *Sonneratia*), a fast-growing mangrove species native to Bangladesh. It is reported that the total area of *Sonneratia* forests in China has reached 3800 ha accounting for more than 50% of replanted mangroves in China (Chen et al., 2009). Mature *Sonneratia* trees could be as tall as 15 m, much taller than most native mangrove species, and the dense canopy poses great shading effects on adjacent native forests (Lu et al., 2014). Moreover, it is reported that this exotic mangrove species is now spreading out steadily from their original sites into native mangrove forests (Ren et al., 2009; Lu et al., 2014). Due to its fast-growing nature, *Sonneratia* trees demonstrate greater carbon accumulation potential than many native mangrove species by sequestering larger amounts of carbon in biomass and sediments (Liao et al., 1990; Ren et al., 2008, 2010), and for this reason, *Sonneratia* is favored for projects aiming at promoting coastal carbon accumulation (Chen et al., 2009). On the other hand, the litterfall from *Sonneratia* was reported to have lower carbon to nitrogen ratio than native mangroves which speeds up carbon cycling in these regions (Lu et al., 2014). However, there is no published research which has ever attempted to quantify the emission of three greenhouse gases from these replanted *Sonneratia* forests. Without counting to what extent the carbon accumulation capacity is offset by greenhouse gas fluxes, it could not be decided whether the introduction of this species would bring significant carbon burial benefits to coastal environments.

Kandelia obovata (hereafter referred as *Kandelia*) is one of the most dominant mangrove species in Southeast China and is vastly planted in coastal areas for mangrove restoration. In Jiulong River Estuary, replanted *Sonneratia* forests and native *Kandelia* forests locate next to each other. On the seaward side of the mangrove margin, naturally occurring *Cyperus* marshes and *Spartina* marshes mosaically colonize the intertidal areas and extend their cover toward nearest the sea. Vegetation composition and thermal and hydrological conditions are two key factors regulating the exchanges of greenhouse gases between wetland soil and the atmosphere (e.g., Berglund and Berglund, 2011; Chen et al., 2012). In Jiulong River Estuary, the four different vegetation types, native *Kandelia* forest vs. alien *Sonneratia* forest and native *Cyperus* marsh vs. invasive *Spartina* marsh, experience similar tidal influence and weather conditions which gives us natural advantages to study the influences of vegetation types on soil–atmosphere fluxes of greenhouse gases. In this research, we simultaneously studied the fluxes of three greenhouse gases (CO_2, CH_4 and N_2O) and soil properties throughout the year from the four adjacent wetlands dominated by *Kandelia* forest, *Sonneratia* forest, *Cyperus* marsh and *Spartina* marsh, respectively. This study is aimed to test the following two hypotheses, (1) the invasion and introduction of exotic species into local ecosystems will greatly promote the soil–atmosphere fluxes of greenhouse gases in coastal regions and (2) soil carbon stock will increase with the invasion of more productive exotic vegetations.

2. Materials and methods

2.1. Site description

The study area is located in the Jiulong River Estuary Mangrove Reserve (117°54′E, 24°23′N) in the monsoonal subtropics of Southeast China (Fig. 1). The climate of this region is warm and wet, with an average annual temperature of 21 °C and average annual precipitation of 1371 mm, most of which falls between April and September. Tide pattern in this region is typically semi-diurnal tides with an average tide range of 2.98 m and seawater salinity of 17.12 ppt. The four vegetation types, namely, native *Kandelia* forest, exotic *Sonneratia* forest, native *Cyperus* marsh and exotic *Spartina* marsh are adjacent under the same intertidal elevation and thus experience similar tidal influence (Fig. 1). Native *Kandelia* forest and *Cyperus* marsh have long existed in this region while exotic *Sonneratia* forest was introduced in 1997. The *Sonneratia* forest is now mature with closed canopy and many seedlings were found established near and under the canopy of adjacent *Kandelia* forest. *Spartina* invaded into this intertidal area after 2000 and has replaced part of native *Cyperus* marsh since then and is now expanding its distribution aggressively toward the mangrove margin. Soils in this region were rather muddy consisting of more than 80% silt particles and soil water content varied within a narrow range between 42% and 52%. Soil porosity ranged from 45% to 59% with many benthic borrows distributed on soil surface resulting from the activities of benthic fauna. Because of seawater inundation, soils in these wetlands were anoxic (redox potential E_h ranging from −158.5 to 11.2 mv) and slightly acidic (pH ranging from 6.13 to 6.85) with an average porewater salinity fluctuating between 16.78 ppt in summer and 17.47 ppt in winter. The four study sites, each representing one of the four vegetation types, were set at least 10 m apart from each other so as to avoid edge effects, and vegetation in each site was monoculture. Each site was then divided into three transects perpendicular to the coast with a distance about 10 m away from each other. Pilot experiments were taken on December 2nd, 2012 in each transect for every vegetation type to test the homogeneity of soil properties from seawards to landwards. Eight soil cores with the depth and diameter of 10 cm were collected at intervals of 1.5 to 2.0 m from seawards to landwards within each transect, and the results indicated that soil properties including soil texture, salinity, porosity, pH, E_h, nutrient contents (total carbon content, total nitrogen content and total phosphorus content), temperature and water content were homogenous with no significant differences detected across intertidal area or along coastal line within each site.

Stand structure of *Kandelia* forest and *Sonneratia* forest were studied by randomly setting three 5 m × 5 m quadrats within each site. Density (individuals m^{-2}), diameter at breast height (DBH, cm) and tree height