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Spatial distribution of phosphorus speciation in marsh sediments along a hydrologic gradient in a subtropical estuarine wetland, China

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In May and August 2013, a 360-m long transect (from a high to a middle tidal flat) was laid out in the Min River estuarine marsh to study the distribution of total phosphorus (TP) and its fractions (i.e., organic P (Org P), inorganic P (IP), aluminum-bound P (Al–P), iron-bound P (Fe–P), occluded P (O–P), and calcium-bound P (Ca–P)). The results showed that TP concentrations of the sediments ranged from 338 to 846 mg kg^{-1} (average 664 mg kg^{-1}) in May and from 353 to 932 mg kg^{-1} (average 657 mg kg^{-1}) in August. IP dominated the P fractions (accounting for 57–81% of TP) and was mainly composed of Fe–P (38%), O–P (30%), and Ca–P (25%). The TP, IP and Fe–P concentrations fluctuated along the hydrologic gradient during both measurement periods (except for the upper 10-cm sediments in August). Meanwhile, their concentrations decreased with depth (0–50 cm), but vertical variation declined in the middle tidal flat. A higher concentration of Org P was observed in the upper 20-cm sediments of the high tidal flat. The concentrations of Ca–P and Al–P increased from the high tidal flat to the middle tidal flat, but there was no significant difference between sediment layers ($P > 0.05$). The O–P concentration was significantly higher in *Phragmites australis* sediments compared with *Cyperus malaccensis* sediments ($P < 0.05$). Based on the space-for-time substitution rule, we predict that sea-level change will likely alter the composition and vertical distribution of TP in the Min River estuarine sediments.

1. Introduction

Phosphorus (P), an essential but limiting nutrient for wetland ecosystems, is often strongly influenced by hydrologic conditions (Xu et al., 2001; Łukawska-Matuszewska and Bolałek, 2008; Xiao et al., 2012; Wang et al., 2013b). Estuarine wetlands are the buffer zones between terrestrial and aquatic ecosystems, acting as either P sink or source due to plant uptake, sedimentation, and transformation (Jordan and Correll, 1991; Coelho et al., 2004; Hou et al., 2008). In contrast to fresh wetlands, water level fluctuations in estuarine wetlands play a significant role in P biogeochemical cycles (Hou et al., 2007, 2011; Liu et al., 2012; Steinman et al., 2014). Therefore, studying the spatial distribution of P speciation of sediments along a hydrologic gradient can help us to understand how the P speciation is regulated by the hydrology in estuarine wetlands. In addition, the hydrologic gradient can be used to predict the possible effect of sea-level change on P speciation in sediments.

The hydrologic gradient from upland areas to the beach is one of the most typical features of estuarine tidal marshes (Hou et al., 2007). The inundation frequency and duration change considerably along this gradient, e.g., a high tidal flat is only flooded during spring tide periods, whereas a middle tidal flat is consistently flooded by the rising tide. In addition, lots of studies found that a series of inter-related biotic and abiotic factors vary along this gradient, such as the sediment properties (pH, redox potential, organic matter, Fe oxides/hydroxides and grain size), microbial biomass, and vegetation net primary productivity (Poret-Peterson et al., 2007; Zhou et al., 2007; Łukawska-Matuszewska and Bolałek, 2008; Quan et al., 2010; Luo et al., 2014). All these changes will likely affect the source and physicochemical processes of P in tidal marsh sediments (Coelho et al., 2004; Reddy and DeLaune, 2004; Hou et al., 2011; Xiao et al., 2012; Wang et al., 2013b; Steinman et al., 2014). The effects of environmental

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factors on the P in estuarine sediments are dependent on the original existing chemical forms (Wang et al., 2013b). Total P (TP) in wetland sediments exists in both organic (Org P) and inorganic (IP) forms. Most studies have shown that Org P is strongly influenced by factors that include vegetation, moisture, temperature, and grain-size (Campbell and Racz, 1975; Ivanoff et al., 1998; Hou et al., 2008; Xiao et al., 2012). IP is found in combination with amorphous and crystalline forms of iron, magnesium, aluminum, and calcium (Malecki-Brown et al., 2007). Hence, IP can be further divided into iron-bound P (Fe–P), aluminum-bound P (Al–P), calcium-bound P (Ca–P), and occluded P (O–P) according to the IP fractionation described by Chang and Jackson (1957). Fe–P, which is an important indicator of the mobility of P, is significantly affected by oxygen, pH, and vegetation (Amirbahman et al., 2003; Hou et al., 2008; Ren et al., 2012). For example, prolonged inundation with reduced dissolved oxygen generally promotes the release of Fe–P (Prairie et al., 2002; Amirbahman et al., 2003). Ca–P and Al–P are more stable than Fe–P and insensitive to inundation, but are significantly regulated by pH and carbonate (Hou et al., 2009; Ren et al., 2012; Gireeshkumar et al., 2013). Similarly, O–P is stable and may increase with a higher oxygen content and pH (Berner and Rao, 1994; Nguyen, 1999). Numerous studies on P speciation in estuarine wetland sediments focused mainly on abundance, seasonal dynamics, availability, and influence factors (Chen and Twilley, 1999; Coelho et al., 2004; Hou et al., 2008, 2009; Gireeshkumar et al., 2013; Wang et al., 2013b). A few studies indicated that TP in surface sediments of estuarine wetlands varied irregularly from upland areas to the beach (Zhou et al., 2007; Quan et al., 2010). However, P speciation in marsh sediments of estuarine wetlands along a hydrologic gradient is poorly understood.

The Shanyutan tidal marsh in the Min River Estuary represents a typical estuarine habitat near the East China Sea. The concentrations of dissolved inorganic nitrogen (N) and dissolved IP in sea water vary from 0.511 to 0.698 mg L^{-1} and 0.019–0.086 mg L^{-1}, respectively, with a higher N: P (41.14) ratio than the Redfield values (Zheng, 2010). Total N (TN) and TP in the sediments in this area range from 0.24 to 1.91 g kg^{-1} and 0.21–1.34 g kg^{-1}, respectively (Tong et al., 2010a). We selected the Min River estuarine wetlands as a typical case. The primary objectives of this study were: (1) to investigate the spatial distribution of P speciation in marsh sediments along a hydrologic gradient (from a high to a middle tidal flat), and (2) to predict the possible effects of sea-level change on the P speciation in the sediments base on space-for-time substitution.

2. Materials and methods

2.1. Study area

This study was carried out in the Shanyutan Nature Reserve of the Min River Estuary (26°00′36″–26°03′42″ N, 119°34′12″–119°41′40″ E; Fig. 1). This area is dominated by a subtropical monsoon climate with an annual average temperature of 19.6 °C and an average annual precipitation of 1350 mm (Tong et al., 2010b). Highest temperatures are experienced in August, and the maximum rainfall is recorded in May. The tide is a typical semi-diurnal tide with an approximate 2.5–6 m high tide range. The average salinity of the tidal water is 4.2 ± 2.5 (Tong et al., 2010b). There are three vegetation zones (A, B and C) in the study area (Fig. 1). The vegetation in zones A and C is comprised of *Cyperus malaccensis*, while zone B is comprised of *Phragmites australis*. We examined nine sampling sites (sites A–I) in the intertidal zone, spanning an elevation of ~1.5 m from the dam (established in 1995) to the beach (Fig. 1). The interval between each sampling site was 40 m. Sites A, B, C, and D were located in the high tidal flat, while other sites were located in the middle tidal flat (Fig. 1). The flooding time in site D accounts for approximately 8% of a year, and its tidal water level ranges from 0 m to 1.4 m (Fig. 2). Site A is only flooded during spring tide periods (approximately 3% of a year), whereas site I is consistently flooded by the rising tide (approximately 40% of a year).

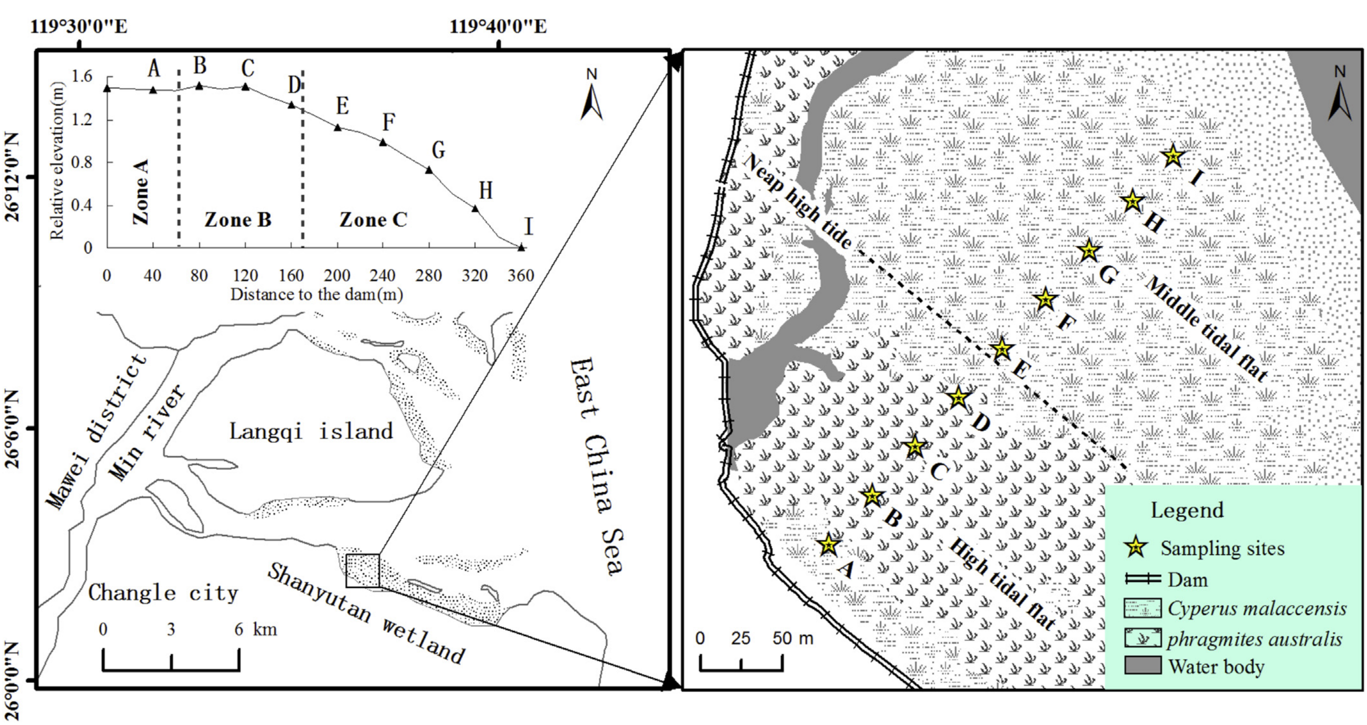

Fig. 1. Study area and sampling sites in the tidal marshes of the Min River Estuary.