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A model of vegetation dynamics of *Spartina alterniflora* and *Phragmites australis* in an expanding estuarine wetland: Biological interactions and sedimentary effects

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ABSTRACT

Spartina alterniflora (Smooth Cordgrass) and *Phragmites australis* (Common Reed) are dominant types of vegetation in Jiuduansha Shoals in the Yangtze Estuary of China. Each species has advantages in terms of growth and competition in different tidal zones. The vegetation types are dynamic due to the variation in the extension and position of different elevation zones due to the deposition of the sediments carried by river runoff. A model was constructed to simulate the vegetation changes over time due to the changes in sediment loads and zonation. A structurally dynamic model was built using Stella software which based on: (i) *S. alterniflora* and *P. australis* biological interaction at different elevation; (ii) the morphometric changes of the island which are increasing based on sediment disposition and the sediment trapping effect of plants. The model simulations predict that the areas of *P. australis* will continue to increase; it will be reach to 1100 ha in 2028. *S. alterniflora* areas will decrease after the areas slightly increasing to maximum 712 ha in 2015.

1. Introduction

Tidal marshes in estuaries form important interfaces between marine, freshwater and terrestrial ecosystems (Eisma, 1998; Attrill and Rundle, 2002). Tidal marshes support biodiversity, filter contaminants, dissipate water energy, and offer intrinsic values such as aesthetics and education (Goodwin et al., 2001).

The spatial distribution of tidal marsh vegetation is spatially correlated by a striking vertical zonation that is particularly pronounced in regions with large tidal amplitude (Chapman, 1974). A number of authors (e.g. Chapman, 1976; Vince and Snow, 1984; Levine et al., 1998; Pennings and Callaway, 1992; Rogel et al., 2001; Silvestri et al., 2005; Bockelmann et al., 2002; Costa et al., 2003) have described plant zonation in salt-marsh environments and have evaluated the environmental factors affecting the distribution of salt marsh vegetation.

The salt marshes in Jiuduansha are an important part of the Yangtze River Estuary Wetlands in China; and they are rapidly growing through the deposition of sand, silt and mud carried by the river runoff (Yang, 1999). Also a simple pattern of plant zonation in the intertidal zone in the Jiuduansha Shoals has been observed. Native *Scirpus mariqueter* (Sea-bulrush) marshes occupy the low tidal zone, *Phragmites australis* (Common Reed) and the exotic species *Spartina alterniflora* (Smooth Cordgrass) occur as monocultures in the middle and high tidal zones, respectively (Wang, 2007; Li et al., 2009; Wang et al., 2010).

P. australis and *S. alterniflora* populations have different traits (biomass, density, stems heights etc.) in different elevation zones. *P. australis* has a higher growth rate in the high elevation tidal zone than in the middle, as opposed to *S. alterniflora* growth rates which are higher in middle elevation tidal zone than in high. Studies on the competition ability have shown that *P. australis* has an advantage over *S. alterniflora* in high marshes, and *S. alterniflora* has a advantage over *P. australis* in low elevation zones (Marks et al., 1994; Windham and Lathrop, 1999; Wang et al., 2006, 2010). Because the Jiuduansha Shoals are growing through the deposition of sediments carried by river runoff, the area and position of different elevation zones are changing. The vegetation pattern on Jiuduansha is also changing due to the interspecies interaction and geomorphic progress.

There are very few mathematical models that consider this type of interspecies interaction such as a Lotka–Volterra type of model modified for competition for space (Armstrong, 1976; Sebens, 1987; Liddel, 2001). Recently some cellular automaton models were constructed to simulate spatial variation as a consequence of competitive interactions (Silvertown et al.,

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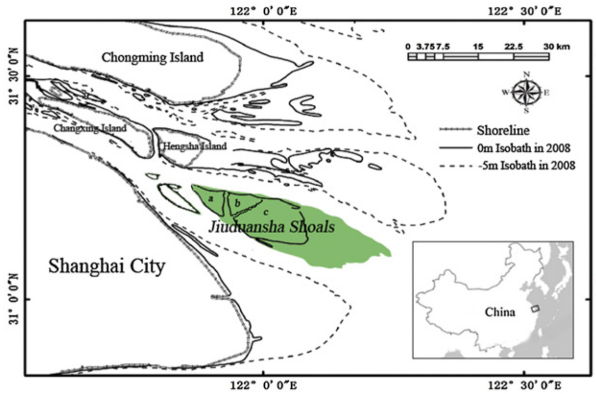

Fig. 1. The location of Jiuduansha Shoals in Shanghai. (a) Shangsha; (b) Zhongsha; (c) Xiasha.

1992; Huang et al., 2008). Huang et al. (2008) developed a cellular automaton model to simulate the expansion process of *S. alterniflora* on Jiuduansha Shoals. Meanwhile, neither the Lotka–Volterra model approach nor the cellular automaton model is able to describe the variation in the biological processes in such a dynamic habitat.

The objectives of this paper are to obtain answers to the following questions:

(1) Is it possible to develop a structurally dynamic model to simulate the vegetation changes as a function of time due to the changes in sediment loads and zonation on Zhongsha of Jiuduansha Shoals in Yangtze River Estuary?
(2) What is the accuracy of the model? Is it satisfactory for the use of the model for predictions?
(3) If the model is found satisfactory, how will the vegetation develop in the future, including the spatial distribution?
(4) Which factors are decisive for the changes that can be expected from the predictions by the use of the model? And are the predictions different from other types of models? Why?
(5) Could the model determine the results of ecological engineering to be applied as tool in environmental management and thereby be used to develop an environmental management plan for the wetland? How?

2. Description of the modelled ecosystem

The Jiuduansha Shoals are located between the southern and northern channels of the Yangtze Estuary, 12 km east of Pudong International Airport and between 31°03′–31°17′N, 121°46′–122°15′E (Fig. 1). It is composed of Shangsha, Zhongsha and Xiasha. This study focused on the wetland of the Zhongsha. The Jiuduansha Shoals initially emerged above the water surface in the 1920s and have been growing rapidly ever since. Today the highest elevation is above 4.9 m (Gao et al., 2010).

A typical zonation of the salt marsh vegetation has developed on the Jiuduansha Shoals over time. Since 1987, the native/endemic pioneer species *Scirpus mariqueter* community can be discerned from satellite images, which showed the community first colonizing the tidal flats at approximately 2 m of elevation. As sedimentation and succession progressed, the *P. australis* community replaced the *S. mariqueter* community above 2.9 m elevation (Zhang and Yong, 1992; Huang and Zhang, 2007). In 1997, *S. alterniflora* was introduced to Zhongsha in connection to an “Ecological Engineering Project for Pudong International Airport”, in order to achieve a more rapid sediment accretion and growth of the marshlands so that shorebirds could more easily find attractive habitats outside the airport area (He et al., 2007).

S. alterniflora was chosen as it has a number of superior traits such as fast root growth, great productivity, high tolerance to salt and well-developed belowground rhizomes that make it a popular ecosystem engineering species in many coastal and estuarine regions of the world (Callaway and Josselyn, 1992; Chung et al., 2004; Chen et al., 2004; Crooks, 2002). In 1997, *S. alterniflora* and *P. australis* were planted at the two sides of Zhongsha, *S. alterniflora* interrupted the natural succession of plant communities by excluding *S. mariqueter* in the lower tide zone and facilitating *P. australis* colonization in the high tide zone (Li et al., 2009). So *S. alterniflora* and *P. australis* continued expanding in the middle and higher elevation zones of the island in the following years. Until 2010, there was only few *S. mariqueter* in the circle of Zhongsha (Fig. 2).

The spatial extent of the different tidal zones is changing due to the increase in elevation of Zhongsha as it grows through the deposition of the sediment loads carried by the river. Both physical and biological processes influence the marshes elevation in Zhongsha. The physical process of increasing marsh elevation is merely due to hydrodynamic forcing like wind and waves. The biological process leading to the increase in marsh elevation is primarily due to the trapping effect of the tidal marsh vegetation on the suspended sediments (Le Hir et al., 2007; Leonard and Reed, 2002; Li and Yang, 2009).

The amount of sediments trapped by the plants depends on the aboveground biomass, bed level, and the concentrations of suspended sediments in the water (Mudd et al., 2004; Li and Yang, 2009). Li and Yang (2009) found the multiple regressions of trapping effects in each tide in Yangtze River estuarine based on the plant biomass and bed level:

$$y = 0.0725a - 156.6b - 422.7 \quad (r = 0.863, p = 0.0003)$$

where y represents the weight of sediment “adhering” to a plant per soil surface area ($g\,m^{-2}$); a and b represent plant biomass per soil surface area ($g\,m^{-2}$) and bed level (m), respectively. According to the dry bulk density of sediment in the northern part of the marsh in Eastern Chongming (i.e., $1.3\,g\,cm^{-3}$), the amount of sediment ($1\,g\,m^{-2}$) would result in a deposit of 7.2×10^{-5} m thickness (Gao et al., 2010).

3. Model description

Published information and observations by field surveys about the growth of the plants species and sediment deposition in the Jiuduansha Zhongsha were used to develop a dynamic model. For model construction, Stella® software (Isee Systems Inc.) version 9.0 was used. Stella® is a userfriendly software package that uses an icon-based graphic user interface specifically designed for dynamic systems modelling (Costanza and Voinov, 2001).

The focus of the model on: (1) *P. australis* and *S. alterniflora* dynamics according to their growth rate and competition in different tidal zones. (2) The change in area of the different tidal zones due to sediment deposition; and (3) area occupied by *P. australis* and *S. alterniflora* as response to the area of different tidal zones.

P. australis and *S. alterniflora* have different properties of growth and competitive ability in different tidal zones. Three zones: zone 1, zone 2 and zone 3 were divided according to vegetation properties and elevation on Zhongsha in the model (Table 1).

The model was based on (a) *S. alterniflora* and *P. australis* growth and competition at different environment elevation gradients; (b) physical changes of the island which are increasing based on sediment disposition and sediment trapping effect of plants. Thus, the model is divided into three interactive sections: (1) area of *P. australis* and *S. alterniflora* dynamics in zone 1; (2) area of *P. australis* and *S. alterniflora* dynamics in zone 2; and (3) area variation of