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Invasive *Spartina* and reduced sediments: Shanghai's dangerous silver bullet

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Abstract

Aims
This synthesis paper is developed to provide a summary of ecological, socioeconomic challenges facing the estuarine wetlands within the Yangtze River delta.

Methods
We combined literature review of the estuarine wetlands and ground measurements of sedimentation, vegetation, and carbon fluxes to illustrate the foreseeable crises in managing these wetlands that play a critical role in Shanghai's urban development. Where the Yangtze River meets the Pacific Ocean, 4.15×10^8 mg/year of suspended sediments are deposited along mainland and island shorelines of the 40 000 km^2 delta—resulting in an average growth rate of land outwards 64 m/year since 1951. However, completion of the Three Gorges Dam in 2003, and earlier dam projects, reduced the rates of sedimentation and growth of the islands. To meet the increasing demands for lands and agriculture, policymakers have attempted to enlarge the islands by diking coastal areas and introducing *Spartina alterniflora*—a grass native to tidal salt marshes of the southeastern USA but exotic to China. *Spartina* is one of the 16 greatest invasive species listed by the State Environmental Protection Administration of China. Successful plantations and rapid spread of this species have increased the production and fertility of the coast, but at the cost of native ecosystems. We outline the social, economic, and ecological controversies related to this land management strategy in the context of global warming.

Important findings
Combinations of these changes, including sea level rise, and alterations to storm patterns and long-shore currents, with the continued spread of *Spartina*, human population growth, and river flow and sediment reduction will make current management untenable.

Keywords:
invasive • Yangtze • *Spartina* • estuarine • wetlands

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Introduction

Behind the iconic neon-lit skyscrapers of Shanghai, major environmental crises are emerging. Decisions on water and land management, designed to cope with the demands of an increasing population and the need for a habitable, productive land base, have led to unforeseen ecological consequences. Shanghai City is sinking because it is too heavy for the coastal soils on which it sits, the water table is receding, and the population is still growing rapidly. Attempts to increase the city's land base by accumulating sediment at its margins are now contributing to a new crisis—the loss of native ecological diversity—that may further threaten the region's social and economic stability.

Where the Yangtze River meets the Pacific Ocean (Figure 1), massive sediment loads are deposited along the shorelines and around the islands of the 40 000 km^2 delta. The delta is home to 82 million people, including the 17 million residents of Shanghai, and plays a vital role in China's economic development (Liu and Diamond 2005; Zhao *et al.* 2006). With the

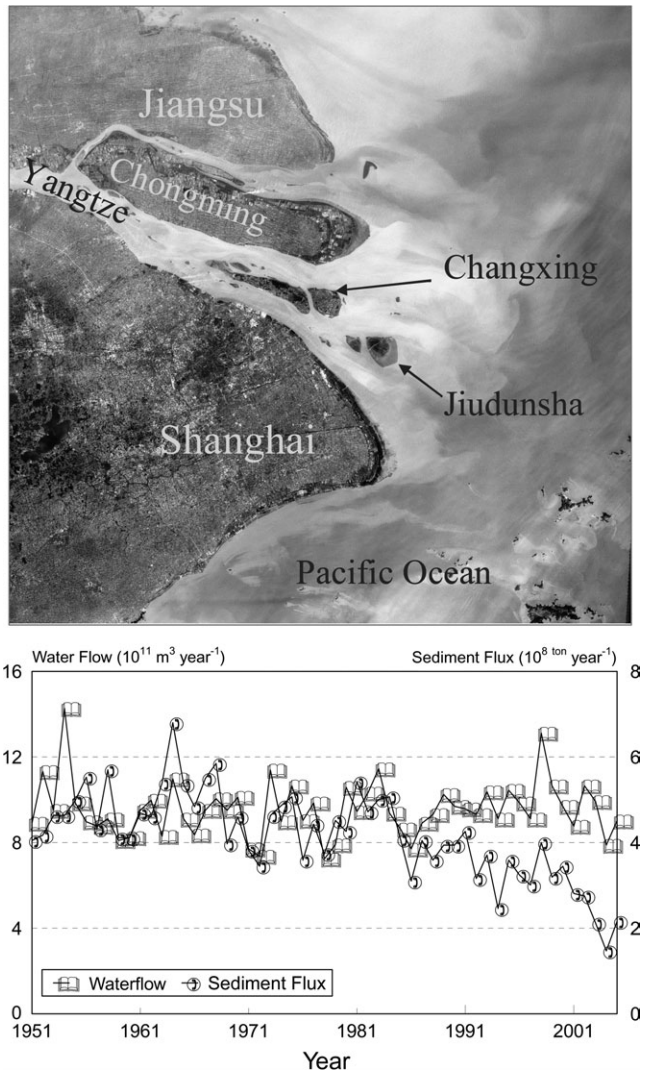

Figure 1 The growing islands (e.g. Chongming, Jiuduansha) are maintained by the massive sediments (light grey color on a Landtsat Image in 2003) transported from the Yangtze River (top). High sedimentation rates have been maintained since 1951 by intensive land management and serious soil erosion in the upper Yangtze River watersheds (bottom); alterations to the flood dynamics of the Yangtze from a series dams are projected to reduce the sedimentation.

completion of the Three Gorges Dam (TGD) in 2003, the amount of sediment carried by the Yangtze River was suddenly reduced (Yang *et al.* 2006). This followed an earlier, major reduction with the construction of another water conservancy project—the Gezhouba Dam—in 1981. The reduced sedimentation has a direct consequence to the growth of estuarine islands (Fig. 1). With escalating demands for space and agricultural and recreational land as the economy grows, policymakers have vigorously sought to enlarge the islands.

Two major approaches to land expansion and enhancement have been utilized: diking and the introduction of a salt marsh plant—*Spartina alterniflora* (*Spartina* hereafter). *Spartina* is fast becoming a silver bullet for reclaiming coastal lands. The government introduced this grass—native to the tidal salt marshes of the southern and eastern USA—to China in 1979 (Chen *et al.* 2004a). Successful plantations of this exotic species and its rapid spread have increased production and fertility of the coast, but at the cost of native habitats and loss of biological diversity.

Spartina was widely introduced to the east coast of China (Chung 2006) and is widely distributed along the east coast of China, from Tianjin to Baihai in Guangxi (Wang *et al.* 2006). The coverage of *Spartina* was ~260 ha in six counties by 1985 (Chung 1989) and increased to >112 000 ha by 2000 (An *et al.* 2007). *Spartina* was first found in 1995 in Dongtan wetlands on Chongming Island in the Yangtze River estuary and is believed to have arrived there though natural dispersal by water flow from Qidong, Jiangsu Province. For rapid sediment accretion in mudflats in the estuary, *Spartina* was intentionally introduced to Jiuduansha Islands in 1997 and Dongtan on Chongming Island in 2001, which has led to a rapid range expansion in the estuary. It has become a dominant plant species of wetland ecosystems on these islands just over 10 years since its first occurrence in the estuary, and its impact on the native ecosystems has become more and more profound (Chen 2004).

The Growing Islands

The islands in the Yangtze delta have been expanding for ~1300 years (Fig. 2). Between 1951 and 2005, the 6300 km Yangtze River carried 9.56×10^{11} m^3/year of water and deposited 4.15×10^8 tons/year of suspended sediments within the delta and near the shore of the Pacific Ocean (Chen *et al.* 2004; Yang *et al.* 2006). The massive deposition associated with flooding is the primary source for the emergence and growth of 19 islands within the delta, constituting the largest alluvial islands on Earth. Chongming Island, the largest with a population of over 650 000 (up from 420 000 in 1950), originated as a small sandbar in 614 AD; it has been growing outward toward the Pacific Ocean at an average rate of 64 m/year since 1951 (Fig. 2; Zhao *et al.* 2008). Jiuduansha Island became visible in 1954 following catastrophic flooding of the Yangtze River; and had grown to 423 km^2 by 2002, was designated as Shanghai's natural reserve in 2003, and was upgraded to a national natural reserve in 2005. With the projected decrease in sedimentation rate, the island's expansion will be slowed and the island area may be eroded by any future elevation of the longshore current (Ma *et al.* 2007).

Rapid expansion of island land area within the delta has been enhanced by policies of intensive management (Zhao *et al.* 2004). In the early 1950s, the Chinese government instituted a coastal 'diking' plan (i.e. refilling the back portion of the dikes) to accelerate the conversion of the coastal wetlands to agricultural lands and residential areas. Since 1950, a total of 480-km^2 land area has been reclaimed on the Chongming Island alone. To accelerate the process, the government also

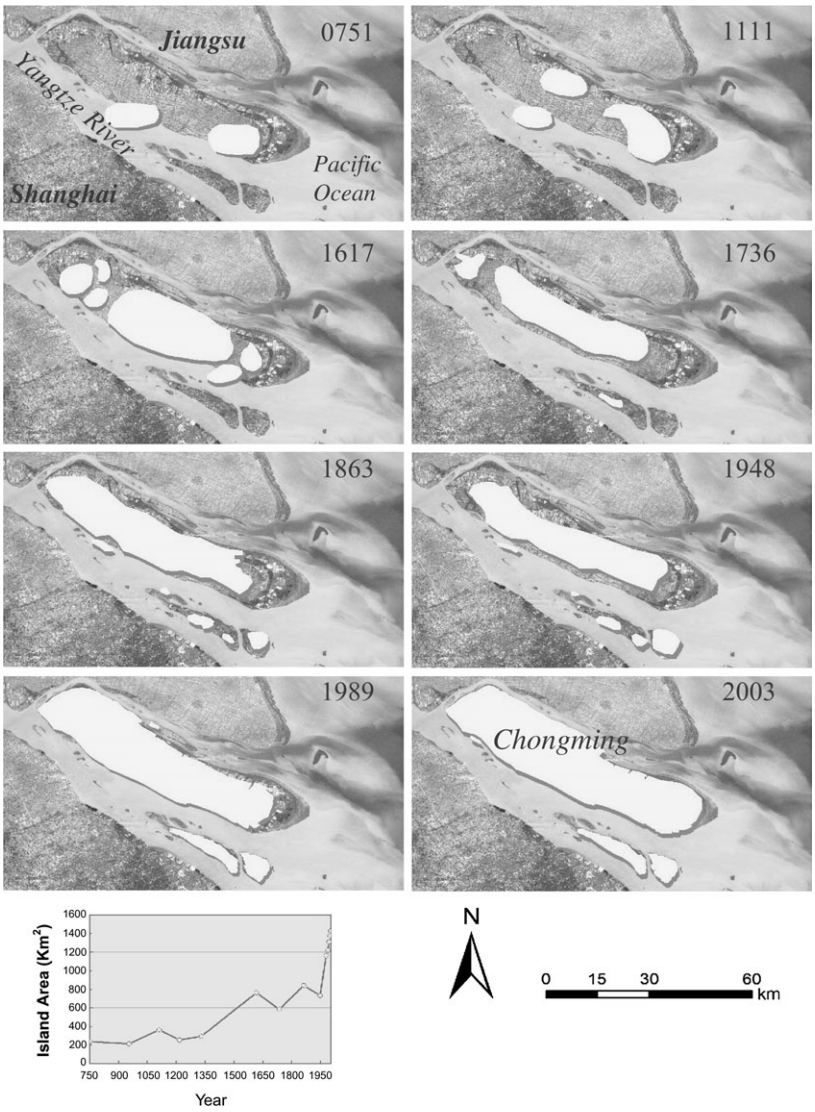

Figure 2 Formation and change of islands (light polygons) in the Yangtze River Estuary from 751 AD through 2003 AD. An accelerated rate started after the formation of the P.R. China in 1949. The background image is the same as for Fig. 1.

intensified management of the emerging tidal flats, where new land surface was formed from sediment deposition (Fig. 3a). In the absence of intervention, these mudflats are slowly occupied by *Scirpus mariqueter*, creating a critical habitat for waterfowl and migratory neotropical birds (Ma *et al.* 2007). Wetland systems dominated by *S. mariqueter* are designated as Wetlands of International Importance by the Ramsar Convention (http://www.ramsar.org/profile/profiles_china.htm). To speed up the vegetation process, *Spartina* was introduced and promoted through plantations (Fig. 3a) beginning in 2001. At Dongtan, Chongming Island, *Spartina* covered 43% of the vegetated area by 2004. On Jiuduansha Islands, although diking was not instituted, intentionally introduced *Spartina* already covered 37% of the islands in 2005 and constituted more than half of the islands' biomass by 2003 (Wang *et al.* 2006). Presently, the Pacific Eurasia southeastern coastal area has the second largest population and land area of *Spartina*, after its native Gulf of Mexico (Wang 2007).

Spartina Invasion

Spartina was listed as one of the 16 greatest invasive species by the State Environmental Protection Administration of China in 2003. Under natural conditions, there is a gradual transition from the dominance of *S. mariqueter* within the mudflats to *Phragmites australis* inland. Since *Spartina*'s introduction to Chongming and Jiuduansha Islands for erosion control, soil melioration, and sediment accretion to promote island expansion, *Spartina* has been rapidly out-competing both native species, *Scirpus* and *Phragmites* (Fig. 3)—a reversed situation where *Spartina* is replaced by *Phragmites* in the east coast of the USA (Kimball and Able 2007; Robertson and Weis 2005; Saltonstall

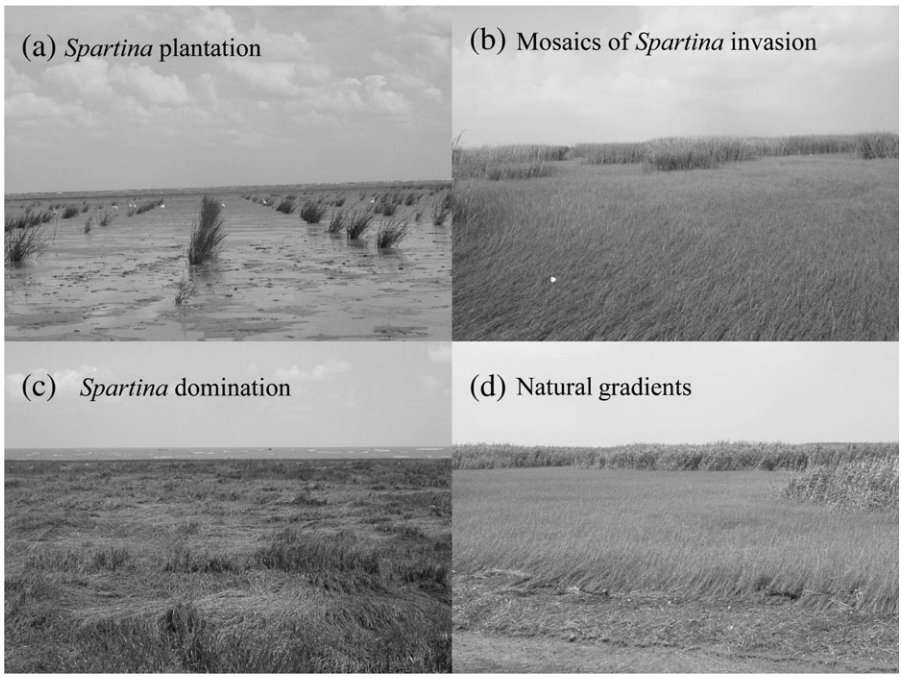

Figure 3 Introduction of *Spartina* into the estuary islands in the Yangtze River began with plantations on the mudflats (a). Rapid spread of *Spartina* (tall patches in the photo) quickly turned the coastal area into green lands (b); but at the expense of losing native ecosystems (c), including the native, endangered *Scirpus* community from marginal mudflat to *Phragmites* in the inland (d). Photos were taken in Jiuduansha and Chongming Islands from 2005, 2003, 2004, and 2003, respectively.

2002). On Chongming Island, a plantation of 4.5 km by 0.75 km was made in 2001 (Fig. 3a). The introduction of *Spartina* to Jiuduansha Island was intended to create green space to attract migratory birds and draw them away from nearby Pudong International Airport. Now, however, the unexpectedly rapid spread of the invasive species is threatening other native species that are dependent on *Phragmites* and the mudflat ecosystem. As a consequence of the reduction of Yangtze River flow to the delta flow after completion of the TGD and the South-North Water Transfer Scheme (Stone and Jia 2006), the amount of saltwater from the Pacific Ocean has increased and will favor the spread of *Spartina* over the native species. The foreseeable sea-level rise associated with the global warming for this coastal region (Nicholls *et al.* 2007; IPCC at http://www.ipcc.ch/) will further facilitate the invasions.

Relative to the native *Scirpus* and *Phragmites*, *Spartina* exhibits a greater growth rate, a more complex belowground system (i.e. more efficient trapping of sediment), higher tolerance to salinity, greater reproductive capacity through both clonal and sexual reproduction, and year-round shoot emergence (Cheng *et al.* 2007; Wang *et al.* 2006). Following invasion of *Spartina* into the mudflats, the *Scirpus* community exhibits decreased density, seed production, and biomass (Chen *et al.* 2004b; Chen *et al.* 2005). Across the islands, plantation of *Spartina* and its rapid spread have also eliminated much of the aerial coverage of native *Phragmites* and *Scirpus* (Fig. 3b and c). *Spartina*'s biological traits have resulted in significant increases in ecosystem production and soil fertility within these communities. Using biometric method, we have estimated a carbon stock of 170.7, 195.1, and 209.4 tons/ha at *Scirpus*, *Phragmites*, and *Spartina* communities on Jiuduansha Island, respectively (Liao *et al.* 2007). *Spartina* sequestered 3.29 tons/ha and 9.18 tons/ha more carbon than *Scirpus* and *Phragmites* communities, respectively. The high carbon sequestration is further confirmed by measurements taken from the three eddy-covariance towers and stable isotope analysis (Cheng *et al.* 2006) indicated that the net carbon sequestered by the *Spartina*-dominated ecosystem was 837.28 g C/m^2/year in 2005, compared to 599.2 g C/m^2/year and 672.8 g C/m^2/year in the *Phragmites* and *Scirpus*–*Spartina* ecosystems, respectively. The elevated production, comparable to other coastal wetlands (Chmura *et al.* 2003), appeared to be the result of an extended growing season of *Spartina*, higher leaf area index, higher photosynthesis, significantly lower decay rate of *Spartina* litter (Liao *et al.* 2007), and greater amount of lateral flows carried by the tides (Yan *et al.* 2008). After considering the lateral flows, they still found that these coastal wetlands could sequester significantly more carbon than other wetlands and terrestrial ecosystems. These figures suggest that the expanding coastal area is becoming a major carbon sink with the invasion of *Spartina* and growth of the islands.

The influences of *Spartina* on faunal communities are similarly complex. While recent studies showed that the altered coastal land serves as major stepping stones for neotropical

birds in the East Asian-Australia Flyway (Chen *et al.* 2004; Ma *et al.* 2007), ecosystem composition, diversity, and structure of the coastal marshes have been significantly altered. Although Jiuduansha Islands provide habitats for 27 national priority-protected species (5 fish, 8 birds, and 14 aquatic plants), the avian species usually found in the native coastal wetlands appeared to avoid *Spartina* communities when possible (Ma *et al.* 2007).

Because of the positive influence on some fauna and increased level of carbon credits, the government perceives the introduction of *Spartina* as a success. However, the negative effects on native biological diversity and other ecosystem functions have not been adequately assessed. For example, *Spartina* marshes have significantly lower nematode trophic diversity than the native marshes, suggesting that the invasions will lead to a simplified benthic food web (Chen *et al.* 2007a; Wu *et al.* 2002). The relative abundance of bacteria-feeding nematodes tended to increase in *Spartina* marshes relative to native marshes whereas that of plant feeders decreased (Chen *et al.* 2007b). Similarly, fewer bird species and lower numbers of birds have been recorded in *Spartina* wetlands compared to native *Phragmites* and *Scirpus* communities (Ma *et al.* 2007).

Controversies

Shanghai provides 5.0% of China's GPD and the delta region accounts for 18.8% of China's GPD. With land values so high, at ~$11.2 million/ha in Shanghai's metropolitan area, policymakers will do everything possible to expand the territory. However, reduced water and sediment flow and sea level increase of up to 2 m due to global climate change (Alley *et al.* 2005; Shi *et al.* 2000) will work against these policies. The adoption of a New Orleans style solution—the development of protective dike systems—is an obvious choice. Critically, modern construction on refilled land, similar to that of west San Francisco, is more vulnerable to catastrophic disturbances from earthquakes and typhoons that are frequent in the Shanghai region. A natural catastrophe in Shanghai on the scale of Hurricane Katrina in 2005 should not come as a surprise.

The delta region is a battleground where multiple interests collide. The situation is further complicated by interactions of several key ecological and physical processes. Policymakers must reconcile social needs, economic development, and existing policies and regulations. Yet with changes such as those expected with global warming, including sea-level rises (IPCC 2007 at http://www.ipcc.ch/), alterations to storm patterns and longshore currents, continued spread of *Spartina*, human population growth, and river flow and sediment reduction, current practices will be less feasible in the future for the government (Lubechenco 1998). The diking and landfill in the past 50 years have greatly helped Shanghai to gain a significant amount of land. Presently, Shanghai plans to dike additional 600-km^2 coastal land area (i.e. an increase of 2.4 times that of the past five decades) between 2006 and 2020. Policymakers may welcome rapid spreading of *Spartina* to strengthen their Kyoto Protocol negotiations as the species rapidly sequester carbon and thus may slow global warming. Yet this practice of non-native introductions conflicts with the national policies on endangered and invasive species. The current 'no net loss of agricultural fields' set by the central government will continue to encourage local governments to expand the coastal wetlands outward to the Pacific Ocean, regardless of the pending threat of rising sea levels and faster currents. While attempts to solve these conflicts provide excellent experiments for the scientific community, we strongly recommend a new direction of stopping plantations of *Spartina*, seeking effective controls of its spread, and encouraging steady development of native *Phragmites* and *Scirpus* in reclaimed coastal wetlands.

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