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# On the potential of plant species invasion influencing bio- geomorphologic landscape formation in salt marshes

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## Abstract

Species invasions are known to change biotic and abiotic ecosystem characteristics such as community structure, cycling of materials and dynamics of rivers. However, their ability to alter interactions between biotic and abiotic ecosystem components, in particular biogeomorphic feedbacks and the resulting landscape configuration in tidal wetlands, such as tidal channels have not yet been demonstrated. We studied the impact of altered biogeomorphic feedbacks on geomorphologic features (i.e. tidal wetland channels), by comparing proxies for channel network geometry (unchanneled flow lengths, fractal dimension) over time between non-invaded and invaded salt marsh habitats. The non-invaded habitats (the south of eastern Chongming Island, Yangtze estuary, China) show little change in network geometry over time with a tendency for an increased drainage density. The invaded site (salt marshes in the north of eastern Chongming Island invaded by the exotic plant species *Spartina alterniflora*) showed a decreasing tendency in channel drainage density throughout and after the species invasion. This suggests that species invasions might not only affect biotic ecosystem characteristics, but also their ability to change biogeomorphic feedback loops, potentially leading to changes in existing geomorphologic features and therefore landscape configuration. Our results further suggest that the species invasion also altered sediment composition. Based on observations we propose a mechanism explaining the change in channel drainage density by an alteration in plant properties. The physical and physiological characteristics of the invading species *Spartina alterniflora* clearly differ from the native species *Scirpus mariqueter*, inducing different biogeomorphic feedback loops leading to the observed change in salt marsh channel configuration.

Accepted Article

## Introduction

In recent decades significant progress in recognizing vegetation as an important geomorphological agent influencing landscape formation has been made. Interactions between vegetation and its abiotic environment (e.g. influencing flow patterns) can establish so-called bio-geomorphic feedbacks, which are able to sculpt landscape features such as channels or bars (Gurnell et al., 2012). Recent studies have shown that the effect of bio-geomorphic feedbacks on landscape development is scale dependent, epitomized by the increased sedimentation within vegetation patches (due to flow reduction - small scale positive feedback) and enhanced erosion around vegetation patches (due to flow acceleration - larger scale negative feedback) in salt marsh pioneer zones (van de Koppel et al., 2012; van Wesenbeeck et al., 2008). This scale-dependency and therefore the ecosystem shaping potential of biota is dependent on a variety of abiotic and biotic factors (e.g. flow velocity or vegetation height) which determine the characteristics of these so called bio-geomorphologic landscapes (e.g. (Bertoldi et al., 2014; Lanzoni et al., 2014; Murray et al., 2008)). Studies on a variety of ecosystems, such as alluvial flood plains (e.g. (Corenblit et al., 2007; Gurnell et al., 2012; Tal and Paola, 2007)), intertidal floodplains (Bolla Pittaluga et al., 2015; Temmerman et al., 2007), dune landscapes (e.g. (van de Koppel et al., 2015)) and hill slope ecosystems (e.g. (Istanbulluoglu and Bras, 2005)) underlined the importance of bio-geomorphic feedbacks on landscape formation across ecosystems (Bertoldi et al., 2014; Lanzoni et al., 2014; Murray et al., 2008).

Although the above-mentioned studies significantly increased our knowledge on how bio-geomorphic feedbacks influence landscape formation. Our understanding in how changes in bio-geomorphic feedbacks, precipitated through altered vegetation properties (e.g. species invasions), are able to influence geomorphologic features is still lacking. We investigate the influence of species invasion on bio-geomorphic feedbacks utilizing salt marshes as model ecosystem. Although salt marshes have been widely recognized as landscapes being strongly influenced of bio-geomorphic feedbacks little is known on how species invasions might influence their main morphologic features, namely tidal channels.

The Smooth Cordgrass *Spartina alterniflora* is one of the most examined species in intertidal coastal wetlands. It is a perennial rhizomatous cord grass native to the coasts of North America (Simenstad and Thom, 1995; Teal, 1985). *Spartina alterniflora* has strong ecosystem engineer capabilities (Crooks, 2002), similar to other *Spartina* species (Bouma et al., 2009; van Hulzen et al., 2007). The ability of *Spartina* to modify its habitat is mainly due to its dense and stiff above-ground shoots, which create hydrodynamic friction, reduce flow velocities and hence increase mineral sediment accretion within its patches (Bouma et al., 2005; Bouma et al., 2009; Bouma et al., 2007; Vandenbruwaene et al., 2011), in combination with its below-ground roots, which reduce erosion and contribute to organic matter accretion (Neubauer, 2008; Nyman et al., 2006)). Introductions of these species worldwide

have resulted from a variety of causes, ranging from accidental introductions via agriculture and ship ballasts, to deliberate introduction for erosion control and accelerated rates of accretion for land reclamation (Callaway and Josselyn, 1992; Li et al., 2009). *Spartina* species are among the few salt marsh species that have been introduced outside their native range; such as plantings of *Spartina anglica* in New Zealand (Hubbard and Partridge, 1981), China (Chung, 2006) and Europe (Ranwell, 1964). *Spartina alterniflora* has mostly been introduced along the Pacific coast of North America (Frenkel and Boss, 1988), in New Zealand (Partridge, 1987) and the East Coast of China (An et al., 2007). Its high stress tolerance and reproduction rate, entailing its wide distribution across the intertidal zone and its ability to rapidly colonize open areas and stabilize eroding shorelines made it the perfect candidate (Callaway and Josselyn, 1992).

Many studies have discussed the general impact of species invasions on ecosystem processes, such as shifts in species composition, accumulation of materials and interactions with abiotic factors (Fei et al., 2014; Li et al., 2009; Strayer et al., 2006; Theoharides and Dukes, 2007). Specifically with respect to *Spartina alterniflora* introductions, literature reports many positive and negative effects. This includes effects on the invaded biota such as competition with the native flora (Frenkel and Boss, 1988; Huang and Zhang, 2007), altered habitat for the native fauna including benthos (Chen et al., 2004; Li et al., 2009; Wang et al., 2010), altered gross primary production (Coleman et al., 2008) and loss of shorebird, and wading bird foraging grounds (Goss-Custard and Moser, 1988; Ma et al., 2007). For the abiotic environment, *Spartina* invasions were reported to influence estuarine sediment dynamics (e.g. promoted accretion) (Yang, 1999a). This not only altered sediment quantity and quality in existing marsh ecosystems (Yang et al., 2008), but also led to accelerated marsh expansion rates altering pioneer zone composition as observed on salt marshes in the Yangtze estuary (China) and North America (Ge et al., 2013; Huang and Zhang, 2007; Li et al., 2009; Rosso et al., 2006).

Although the influence of *S. alterniflora* invasion on geomorphological processes in the vertical dimension (e.g. vertical accretion rate within the vegetation) has been investigated (Sheehan and Ellison, 2014; Xiao et al., 2010; Zhu et al., 2011), its impact on spatial landscape organization in the horizontal dimension remains unclear (e.g. including development of tidal creek networks that typically dissect marsh landscapes). The spatial landscape organization in the horizontal dimension can be regarded as the integrated outcome of scale dependent bio-geomorphic feedback processes, which may be modified by the invader and potentially lead to spatially altered hydrodynamics and sedimentation/erosion patterns.

An important mechanism of intertidal landscape organisation is the development of tidal channel networks as a result of physical, chemical and biological interactions. The development of these tidal channel networks plays an important role in the functioning of tidal marsh ecosystems, as they further control hydrodynamics and fluxes of sediments, nutrients, pollutants and biota between salt marsh, tidal flat and

the adjacent open water body (Marani et al., 2002). Previous research has shown that changes in vegetation cover have the potential to change spatial flow and sedimentation-erosion patterns in tidal marshes, and consequently are also able to alter tidal channel morphology, either through vegetation colonization on initially bare tidal flats (Schwarz et al., 2014) or vegetation removal in mature tidal marshes (Temmerman et al., 2007; Temmerman et al., 2012). It was shown that channel drainage density increases from mudflat to salt marsh systems. The underlying mechanism for the observed increase in channel density was identified as increased flow routing adjacent to vegetation patches leading to erosion and subsequently channel incision. This phenomenon is moreover amplified through increased sedimentation within patches leading to spatial dependent sedimentation/erosion patterns resulting in a higher drainage density. On the mudflat, where increased flow routing is absent, the probability of a critical bottom shear stress to be exceeded is lower leading to less channel incisions and therefore lower drainage densities (D'Alpaos et al., 2006; Temmerman et al., 2005; Temmerman et al., 2007; Vandenbruwaene et al., 2012a; Vandenbruwaene et al., 2014).

We hypothesize that also species replacement, through the process of species invasion, has the potential to change spatial flow- and sedimentation/erosion patterns, hence adjusting existing tidal channel network geomorphology. Knowledge about changes in the spatial landscape organization is essential to judge impacts of species invasions on ecosystem services provided by tidal wetlands, such as storm surge protection, sustainability with rising sea level and nursery function for fish and crustaceans. This is due to the fact the channel network properties such as density, channel convergence are major determinants for the percolation of storm surges and sediment transport through tidal wetlands (van Rijn, 1993; van Rijn, 2011).

In this study we investigate the potential of species replacement (via invasion) to influence existing geomorphologic features (tidal channel networks). Because the replacing species, *Spartina alterniflora*, has different physical (e.g. plant height, stiffness) and physiologic (e.g. stress tolerance) properties compared to its native predecessor (*Scirpus mariqueter*), we hypothesize it will establish different biogeomorphic feedback loops and therefore reshape existing channel networks (Li et al., 2009; Xiao et al., 2010; Zhu et al., 2011; Schwarz et al., 2015). First, we investigate the development of tidal channel network properties over time (i.e. the unchanneled flow lengths and fractal dimension as a proxy for channel drainage density) in the absence of invading species, further referred to as the reference cases. Subsequently, we compare these reference cases to the spatiotemporal tidal channel network development of an invaded salt marsh system. Since abiotic system properties are subjected to change over time (e.g. tidal prism), we are only able to assess the potential of the plant species shift to shape geomorphologic features.

We utilize one reference case for the non-invaded scenario, in the Yangtze estuary, China. The channel networks in the Yangtze estuary are regarded as expanding drainage systems. Because the amount of incoming suspended sediments lies

above the system's equilibrium concentration, salt marshes and therefore the channel systems are expanding seawards and also grow in the vertical direction (Yang, 1999b). We compare these network developments with a recent species invasion on salt marshes in the Yangtze estuary, China (Huang et al., 2008; Li et al., 2010). In addition to a comparison of network characteristics we assess changes in sediment composition between multiple Chinese invaded and non-invaded sites, potentially caused by species invasion. Finally, based on literature and field evidence, we propose a possible mechanism enabling the invasive species (*Spartina alterniflora*) to change established channel network features.

## Methods

### The Study areas

In order to evaluate the development of tidal channel network drainage densities pre and post species invasion, we first studied channel evolution in two systems without recent invasions and used these insights as reference cases. These reference cases are located in different estuarine systems to underline the generality of the observed signature.

The reference case, the Yangtze estuary, is located at the east coast of Mainland China and covers large areas of the provinces Shanghai and Jiangsu, and is about 90 km wide at its mouth. This meso-tidal estuary is characterized by a semidiurnal tidal regime with a mean tidal range of 2.95 m (Wusong datum). Due to the large sediment input coming from upstream, the Yangtze estuary has been expanding seaward in the south-eastern direction, creating a systems of islands of which Chongming Island is the largest (Fig.1) (De Vriend et al., 2011; Li et al., 2009). The intertidal areas on eastern Chongming Island (31.6619 °N, 121.4780 °E) nowadays comprise an area of 24155 ha ([www.dongtan.cn](http://www.dongtan.cn)). Due to the large sediment inputs (sedimentation rates comprise up to 1 mm d<sup>-1</sup>, at marsh sites, (Yang and Chen, 1994)) and species introductions, marsh expansion is significantly sped up (recent lateral expansion rates reach up to: 25 m y<sup>-1</sup> (Xiao et al., 2010)). Salt marshes on Chongming Island are characterized by *Spartina alterniflora* and *Scirpus mariqueter* pioneer vegetation, moving on to predominant *Spartina* meadows at mid elevations and finally ending with *Phragmites australis* vegetation at the highest elevations. *Spartina alterniflora* and *Scirpus mariqueter*, the dominating species in low and mid elevations, show major differences in physical (e.g. plant height, density, stiffness) and physiological (e.g. stress tolerance) plant properties potentially influencing the proliferation (Chen et al., 2004; Li et al., 2009; Schwarz et al., 2011).

In the Yangtze estuary *Spartina alterniflora*, can reach plant heights of up to 240cm, with stem densities of 334-600 stems m<sup>-2</sup> and an average diameter of 5.2 mm ± 1.7. *Scirpus mariqueter* was reported to reach plant heights of up to 55 cm, with stem

densities of 741-2352 stems m<sup>-2</sup> and an average diameter 2.2 mm ± 0.14 (Sun et al., 2002; Yang et al., 2008; Ysebaert et al. 2011; Schwarz et al., 2015). An indirect stiffness comparison can be found in a flume experiment conducted by Schwarz et al. (2015), where increased bending of the more flexible *Scirpus mariqueter* has been found in comparison to *Spartina alterniflora* when subjected to the same flow velocity. It was shown that these parameters result in different sediment trapping efficiencies, range expansion patterns and tussock scale bio-geomorphic feedbacks, potentially influencing large-scale scale-dependent feedbacks altering landscape configuration (e.g. drainage density) (Xiao et al., 2010; Zhu et al., 2011; Ge et al., 2013; Schwarz et al., 2015).

At the northern part of eastern Chongming Island, *Spartina alterniflora* was planted in 2001. From there it expanded along the northern and mid-parts of the Island (Li et al., 2009). Three channel networks in this area were selected and will be further referred to as the invaded sites (Fig.1, northern part). In the southern part of eastern Chongming Island three channel systems were selected as a reference case, since this area remained mainly unaltered since the last land reclamation in 2001 and is still inhabited by the native salt marsh (*Scirpus mariqueter*) (Fig.1, southern part).

### **Aerial image analysis**

Channel networks in false colour aerial photographs with a resolution of 2.5 m × 2.5 m (for used time-steps) were digitized utilizing a pixel threshold value of the image's red band (vegetation had a high red band value, channels had a low red band value). The threshold was empirically found by comparison with the extracted channel network. Different thresholds were tested at different time-steps to assess the influence of variation in channel detectability between subsequent steps of the analysis. These tests revealed that differences in channel detectability originated from small tidal channels, situated at the detection limited (width of about 2.5 m) of the aerial images, which however did not influence the interpretation of our results (comparison of slopes in drainage densities and fractal dimensions). Misclassified isolated pixels were reclassified using a neighbouring filter, however for clusters of misclassified pixels, situations were more complex, and errors had to be corrected manually. Extracted channels were then subsequently converted to line features, with the lines representing the boundaries of vegetated-unvegetated areas (red band classification) equal to channel edges of the networks.

### **Time-steps and locations**

For the reference case on eastern Chongming Island, we selected three channel networks in the southern part, which remained unaltered since the last event of land reclamation in 2001. To investigate the species invasion we selected three channel networks in the northern part of Chongming Island, not far from the location of the original species introduction. The selection of time steps was dependent on the availability of aerial photographs (2.5 m pixel resolution) (2003, 2005 and 2011) and

the spatial spreading of the invasive species (*S. alterniflora*). The assignment of drainage areas and channel networks were done according to the description below.

Since the terrestrial approach of delineating watersheds according to topographic divides proves more difficult in intertidal systems, we utilized the approach described in (Vandenbruwaene et al., 2012a) to determine the watershed areas of our study sites (Fig. 2 g,h,i; Fig. 3 g,h,i).

### **Unchanneled flow lengths:**

To evaluate the drainage densities of tidal channel networks, previous studies utilized the frequency distribution of unchanneled flow lengths on the marsh platform (D'Alpaos et al., 2007; Marani et al., 2003a; Marani et al., 2003b). Unchanneled flow lengths describe the distance a water drop has to travel until it reaches the closest channel. Following Vandenbruwaene et al. (2012), the unchanneled flow lengths were calculated in this study, per drainage area, as the shortest distance from any platform point to the nearest channel edge. The slope of the frequency distribution of unchanneled flow lengths is then a measure for drainage density. The shorter and steeper the unchanneled flow lengths curve is, the higher is the drainage density and the shorter the maximum unchanneled flow length (Vandenbruwaene et al., 2012a). The slopes of the probability density function of unchanneled flow lengths, shown in (Fig.2 a-c) and (Fig.3 a-c), were calculated by fitting a linear function to the linear part of the curve using the least squares method. The linear part of the slope was defined until a flow length probability ( $P(\text{Flowlength})$ ) of  $0.0003(10^{-3.5})$ , since the fitted function visibly levelled off beyond this threshold. We used the change in slope of the probability density function of unchanneled flow lengths over time to identify a trend in network development. Literature reports channel drainage density to generally increase over time during geomorphic development of tidal marshes (Allen, 2000; D'Alpaos et al., 2005). We therefore specifically aimed at distinguishing two trends; increase or decrease in drainage density over time. It should be noted, however, that this proxy is indicative without representing a rigorous statistical test. To ensure the independence of our results to the method of drainage basin delineation a test case was set up comparing unchanneled flow length development over time. We compared the development over time of the three separated basins to the development of the three basins merged into one, which resulted in the same behaviour.

### **Fractal dimension:**

Generally, the fractal dimension describes how the detail of a pattern changes across scales in the first, second or third dimension. It hence gives a statistical index of a pattern's space-filling capacity (Falconer, 2007). Literature already reported the fractal dimension to be linked with terrestrial channel network drainage properties (Baas, 2002; Rodriguez-Iturbe and Rinaldo, 2001). In our study we utilized it to track channel network changes over time. The main difference to the above described unchanneled flow lengths consists in its independence to the delineated drainage

area. Since it is a measure of how well a feature covers the two-dimensional plane it can also be used to compare relative changes in drainage density. The fractal dimension which was calculated using a box counting algorithm is in our case a measure of how well a channel network penetrates the two dimensional horizontal plane. The values can vary from 1, signifying the poorest plane cover (by a simple line), to a maximum of 2 denoting that the feature covers the plane completely.

### **Tracking species invasion**

The species invasion in the northern part of our research area on Chongming Island was only tracked qualitatively by comparing the high resolution quick bird images with the available results of previous studies discriminating plant species through differences in light reflectance in the same research area (Ge et al., 2013; Huang and Zhang, 2007). According to this comparison we could identify *Spartina alterniflora* as the species with high reflectance (white colour in Fig.3, a,b,c) invading the northern investigated research site. It should be noted that colour intensity does not give a direct relationship to plant coverage since reflectance also varies due to growth stage. Nevertheless the spreading of the light-coloured pixels in our aerial photographs follows the exact same trajectory as the spreading of *Spartina alterniflora* as suggested by previous studies (Ge et al., 2013; Li et al., 2009).

### **Sediment coring:**

Sediment cores were taken at 5 Chinese salt marsh locations (2 locations on eastern Chongming Island, 3 locations on the Jiuduansha shoals) with varying vegetation states (i.e. mudflat, *Scirpus mariqueter*, *Spartina alterniflora*, *Phragmites australis*), including invaded and non-invaded sites. The locations were selected according to the species development shown in (Huang and Zhang, 2007). The resulting 5 different sample sites were characterized by: scSP<sup>C</sup>, development from *Scirpus mariqueter* to *Spartina alterniflora* vegetation (Chongming, invaded); scSC<sup>C</sup>, constant *Scirpus mariqueter* vegetation (Chongming); mfSC<sup>J</sup> development from mudflat to *Scirpus mariqueter* vegetation (Jiuduansha Shoals); phrPHR<sup>J</sup> constant *Phragmites australis* vegetation (Jiuduansha Shoals), scSP<sup>J</sup> succession from *Scirpus mariqueter* to *Spartina alterniflora* vegetation (Jiuduansha Shoals, invaded)(Table.1). Due to logistic reasons sediment cores at the Chongming stations (scSP<sup>C</sup>, scSC<sup>C</sup>) were taken to a depth of 80 cm and sediment cores at the Jiuduansha stations were taken to a depth of 180 cm (mfSC<sup>J</sup>, phrPHR<sup>J</sup>, scSP<sup>J</sup>) (Fig.1). Sediment cores were subsequently analysed (in a 2 cm depth interval) for their grain size distribution using a Beckman-Coulter® LS 13320 particle size analyser, where specifically the median particle diameter (D50) of the particle distribution was compared. Sediment cores have not been dated, but the change over time was compared between invaded and non-invaded sites in time scales where the invasion took place (using sedimentation rates provided in literature, for instance 7.5 cm/year on mudflats of Chongming Island between 2006 and 2010 as proposed in Yang et al., (2011)) (Huang et al., 2008; Zhu et al., 2011).

## Results

At the expanding salt marsh on southern Chongming Island (non-invaded) unchanneled flow lengths were calculated and compared for three drainage networks (Fig.2, a, b, c). All of them show a similar trends with little change between 2003 to 2005 (latest land reclamation in 2001) (Chen et al., 2004). In 2011 the unchanneled flow lengths in all basins show a visible decrease, implying an increase in drainage density, which can be seen through the increase in slope in the probability density function of the unchanneled flow lengths (Fig.2, a,b,c). It is important to note that in all our reference cases (expanding or stable), drainage density either shows an increasing trend or stays constant.

In the northern part of Chongming Island (Fig.3 d,e,f) the species invasion is visible through the white coloured pixels (high reflectance of *Spartina alterniflora*), invading the research area and occupying the entire area by the end of 2011. In (Fig.3 a,b,c) it is visible that from 2003 to 2005 unchanneled flow lengths of all three basins exhibit little change with an increasing trend. In 2011 the unchanneled flow lengths of all the northern basins show a visible decrease in slope and an increase in maximum unchanneled flow length, signifying a decrease in drainage density. This is in agreement with field observations where channels from previous years disappeared in the field.

The analysis of fractal dimensions revealed a less pronounced relationship than observed with unchanneled flow lengths. The comparison of the fractal dimension of the merged northern networks was compared to the fractal dimension of the merged southern networks (Fig.4). The southern networks seem to exhibit almost no change in fractal dimension over time, whereas the northern networks show an apparent decrease in 2011. This means that a geometrical comparison of the channel networks (i.e. how well they cover the horizontal dimension) shows no change in the southern part, whereas in the northern part the network coverage over the horizontal dimension decreases over time.

A comparison in Sand:Silt:Clay composition and the d50 along the depth of sediment cores taken at the 5 sampling locations (Fig.1) reveals different trends which can be linked to transition in plant species cover (Fig.5). It is visible that at the two non-invaded salt marsh sites only little change in Sand:Silt:Clay composition and d50 can be observed over depth (scSC<sup>C</sup>, phrPHR<sup>J</sup>), with at scSC<sup>C</sup> a d50 of 31.57 microns at the top layer and a d50 of 28.45 microns at the bottom layer, and at phrPHR<sup>J</sup> a d50 of 20.46 microns at the top layer and a d50 of 21.23 at the bottom layer (Table.1). In the other non-invaded site, that developed from a mudflat into a *Scirpus mariqueter* marsh (mfSC<sup>J</sup>), we observed a decrease in d50, starting from 100 microns and evolving towards 33.85 microns, similar to the observed value in the *Scirpus mariqueter* marsh (scSC<sup>C</sup>). This site (mfSC<sup>J</sup>) further shows, that the reduction in d50 was accompanied by a decrease in the Sand fraction and an increase in the Silt and Clay fraction. At the two invaded sites (scSP<sup>C</sup>, scSP<sup>J</sup>) the d50 decreased to a value

of 10.51 and 9.91 microns. This observed decrease in d50 was also accompanied by a decrease in the Sand fraction and an increase in the Silt and Clay fractions (refinement).

## Discussion

We suggest that, the observed channel network branching patterns (Fig.1,2) in the studied salt marshes are the result of biogeomorphic feedbacks between present hydrodynamic conditions (e.g. tidal currents, waves, tidal prism), geomorphologic properties (e.g. slope, coastal alignment, sediment properties) and vegetation characteristics (e.g. cover, density, stress tolerance, stiffness). These factors are governing the balance between erosion and deposition and vary across the studied channel network systems. This is the reason for choosing an approach investigating the relative change in network development over time utilizing proxies such as the probability density function of the unchanneled flow lengths and the fractal dimension. We use the change in these proxies over time to indicate trends in channel network development. Specifically, two trends are distinguished, increase or decrease in channel drainage density at a given site.

Previous literature on terrestrial and intertidal channel networks suggested the fractal dimension and the probability density function of unchanneled flow lengths are good proxies assessing changes in drainage density and general channel network characteristics (Cleveringa and Oost, 1999; D'Alpaos et al., 2005; Marani et al., 2004; Rodriguez-Iturbe and Rinaldo, 2001). These proxies proved useful comparing network properties between tidal and terrestrial networks, showing differences between channel networks on salt marshes and tidal flats (Fagherazzi et al., 1999; Vandenbruwaene et al., 2012a), and in assessing the importance of vegetation presence on channel network shape and structure (Pestrong, 1972).

The increase in drainage density is mainly through tidal meandering (Allen, 2000; Marani et al., 2002; Perillo et al., 2009; Steel and Pye, 1997). In contrast, the invaded channel networks in the northern part of Chongming Island show a decreasing trend in channel drainage density over time. This is due to the loss of small, low-order channels (Fig.3 a, b, c). We propose that the observed reduction in drainage density is potentially linked to the invasion by *Spartina alterniflora*. As previously suggested by Peralta et al. (2008) current reduction by vegetation (and consequently sedimentation) is dependent on vegetation stiffness (i.e. the stiffer the plant, the higher the reduction). Since the flexible indigenous species (*Scirpus mariqueter*) was replaced by an invasive stiff species, with different density and plant height (*Spartina alterniflora*), we expect potentially higher platform sedimentation rates, faster tidal prism reduction leading to the observed effect of reduced drainage density at the invaded site. However we cannot exclude that changes in other abiotic variables (such as, changes in the sedimentation-tidal prism relationship, i.e.

marsh platform sedimentation will instigate a reduction in tidal prism and subsequently drainage density) will also affect channel drainage densities. We nevertheless suggest, that due to our comparison of the temporal development between two uninvaded and one invaded site and under the assumption that hydrodynamic and geomorphologic parameters remain constant the link between channel drainage density reduction and species invasion can be proposed. This proposed mechanism is to the authors knowledge a new phenomenon in tidal wetlands that has not been investigated so far. Previously, retreat or expansion of tidal networks has been linked to decrease or increase of the tidal prism, watershed area or to the development from mudflat to salt marsh channels, showing the relation between channel drainage density and the tidal prism (Stefanon et al., 2012; Vandenbruwaene et al., 2012a). Since our Chinese research areas were under the same tidal forcing, network retreat through a reduced tidal prism should have been visible in both marshes, which was not observed. A comparison between the northern and southern areas further shows a difference in salt marsh expansion rate between 2003 to 2005 (large increase in salt marsh area) and 2005 to 2011 (moderate increase) (Fig.2, Fig.3). We propose that differences in marsh expansion between 2003 to 2005 and 2005 to 2011 could originate from altered sediment budgets due to dam constructions upstream (completion of the Three Gorges Dam in 2009), specifically the reduction in sediment load recorded at the most downstream gauging station from 400 Mt/y in 2000 to 154Mt/y in 2008 as proposed in literature (Yang et al., 2011).

The reduction in drainage density has also morphologic consequences. We would expect the loss of small order channels to result in increased deepening of the main channel (D'Alpaos et al., 2005), further influencing the fluxes of water and sediment transport between the marsh and adjacent tidal flats and open water (Temmerman et al., 2012). A detailed description of the geomorphologic and hydraulic changes is, however, beyond the scope of this paper.

A comparison between depth profiles in sediment grain size distributions and development history of the aboveground plant cover, normalized by average field sedimentation rates shows a potential relationship between plant species cover and sediment grain size as previously reported in (Yang et al., 2008). We compared non-invaded sites (as reference sites) with invaded sites. The non-invaded salt marsh areas (scSC<sup>C</sup>, phrPHR<sup>J</sup>) show only little variation in sediment characteristics over depth, whereas both sediment cores taken in invaded areas (scSP<sup>C</sup>, scSP<sup>J</sup>) exhibit a trend of increasing clay and silt content with decreasing sediment depth (i.e. decreasing age since sediment deposition) (upward fining) (Fig.5). This comparison is based on the relative change in grain size distribution over depth, since non-invaded reference sites do not only differ from invaded sites in aboveground plant cover but also in relative location in the estuary (Fig.1), therefore receiving different types of incoming sediments and hence an absolute comparison between invaded and non-invaded sites cannot be made. Specifically scSC<sup>C</sup>, scSP<sup>C</sup> are mainly silt

dominated, however with the site scSP<sup>C</sup> exhibiting more cohesive properties due to the high clay content. Further are phrPHR<sup>J</sup> and scSP<sup>J</sup> receiving similar incoming sediment types due to their location, which might be not comparable to the site mfSC<sup>J</sup>.being located at the opposite end of the island. The observed upward fining of grain size composition at the non-invaded mudflat-*Scirpus mariqueter* transition, is in agreement with the previously observed influence of salt marsh plants on grain size sorting along a mudflat-salt marsh gradient (Yang et al., 2008). A comparison with a further non-invaded site (phrPHR<sup>J</sup>) shows that in *Phragmites australis* marshes upward fining did not cause such low d50 values (phrPHR<sup>J</sup> 20.46 microns), which is in agreement with previous studies (Yang et al., 2008). This may suggest that the increased refinement originates from the invasion by *Spartina alterniflora*. However, also other mechanisms, such as differences in sediment supply over the observation period or the different position of our field sites along the estuarine gradient might be able to cause the differences observed in grain size distribution.

We propose, supported by field observations and aerial images (Fig.6 a,b), that the species invasion by *Spartina alterniflora* on Chongming Island followed the same main distribution pathways as previously observed at the Petulama marsh in the San Francisco Bay, namely the tidal channel network. Fig.6a shows that establishment of *Spartina alterniflora* first took place at the levees of existing channels. Subsequently, because of its high stress tolerance, *S. alterniflora* was not only able to colonize and establish at channel levees and the marsh platforms but also in the channels (Fig.6 b). This underlying mechanism might explain the observed reduction in channel drainage density by closing off small tributaries, as observed after species invasion. *S. alterniflora* has superior competitive traits such as fast growth, high productivity, high tolerance to salt, clay and loamy sediment and a well-developed belowground root system making it a specifically strong ecosystem engineer (Crooks, 2002; USDA, 2007). The superiority of *S. alterniflora* in respect to physiological (e.g. stress tolerance) and physical characteristics (e.g. plant height) was also confirmed through a direct comparison with the native species *Scirpus mariqueter* (He et al., 2012) supporting our hypothesis.

## Conclusions

Our field measurements and satellite image analysis suggest that species invasions have the potential to change established geomorphologic features. They indicate that an invasion by a species with different physiological and physical properties (*S.alterniflora*) can result in changing the existing spatial habitat configuration. This change in spatial arrangement of the intertidal landscape affects the distribution of water with all its particulate, solute, organic or inorganic compounds, thus creating different local sedimentation rates and an altered ecological niche structure. The

results of our study point at the importance of biota induced habitat configuration, however we also show the need for further research on the relationship between species invasion induced change in channel density compared to un-invaded change in channel drainage density due to reductions in tidal prisms.

Unfortunately, our study could not distinguish whether changed channel network properties are mainly due to the differences in physical (e.g. plant height, stiffness, density, hydraulic resistance) or physiological plant properties (stress tolerance, growth velocity) of the invading species (*S. alterniflora*). We nevertheless could suggest a link between species-specific plant properties and changes in geomorphology on the landscape scale. An important direction for future research would be to elucidate whether physical or physiological plant properties influence channel network configurations across different salt marsh ecosystems.

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## Tables

Table.1: Overview of sediment coring sample size; including Development, Invasion history and specific location in the Yangtze estuary, China

<b>Label</b>	<b>Development</b>	<b>Invasion history</b>	<b>Location</b>
<b>scSP<sup>c</sup></b>	<i>Scirpus mariqueter</i> → <i>Spartina alterniflora</i>	Invaded	Chongming
<b>scSC<sup>c</sup></b>	constant <i>Scirpus mariqueter</i> vegetation	None	Chongming
<b>phrPHR<sup>j</sup></b>	constant <i>Phragmites australis</i> vegetation	None	Jiuduansha Shoals
<b>mfSC<sup>j</sup></b>	mudflat → <i>Scirpus mariqueter</i>	None	Jiuduansha Shoals
<b>scSP<sup>j</sup></b>	<i>Scirpus mariqueter</i> → <i>Spartina alterniflora</i>	Invaded	Jiuduansha Shoals

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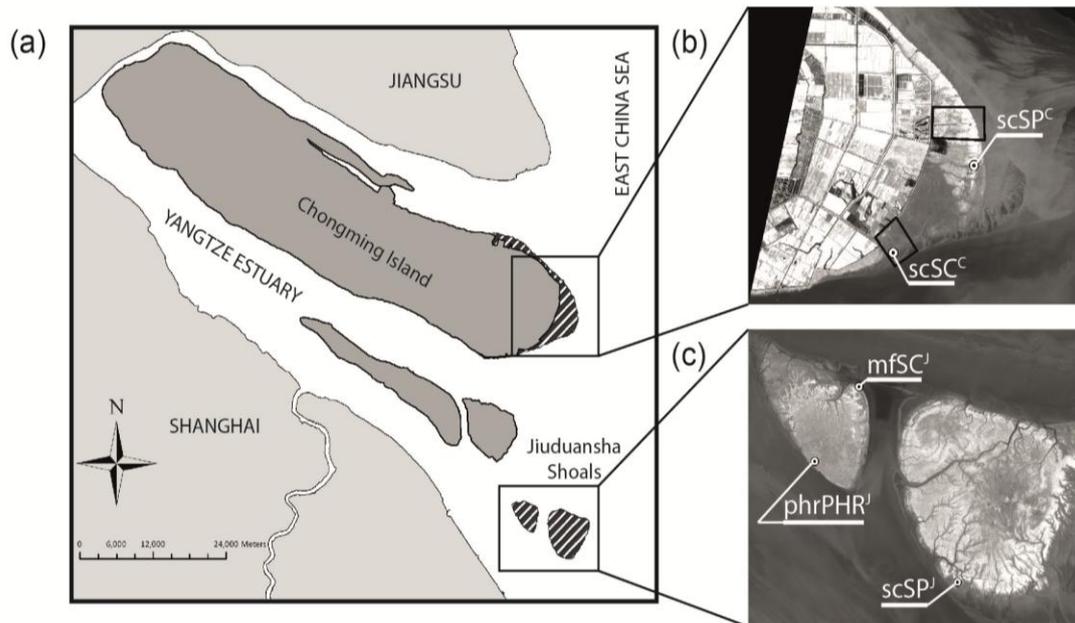


Fig.1: (a) Overview map Yangtze estuary, China; (b) Research Area on eastern Chongming Island, Black squares denote areas where channel networks were investigated (the northern (invaded) and southern (c) part); (right, bottom) Jiuduansha shoals, which also experienced a species invasion by *Spartina alterniflora*, Circles with centre points denote locations of sediment cores; for an overview of the used site codes please refer to Table.1

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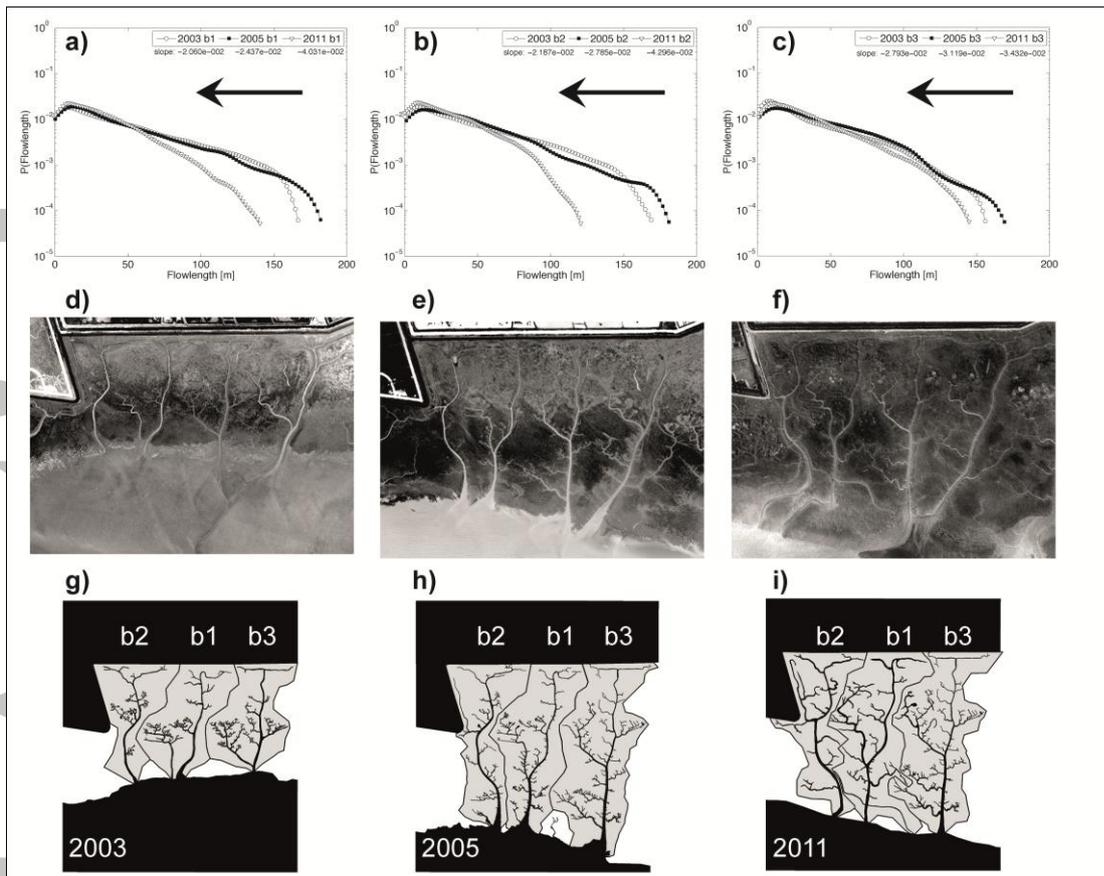


Fig.2 (a-c) Unchanneled flow length of three channel networks (b1, b2, b3) in the non-invaded southern part of Chongming Island (Yangtze estuary, China) at the selected time-steps, slopes are stated below legends, (d-f) grayscale aerial images showing expanding salt marsh development over time (2003, 2005 and 2011), (g-i) digitized channel networks and drainage basins (grey area) (2003, 2005 and 2011).

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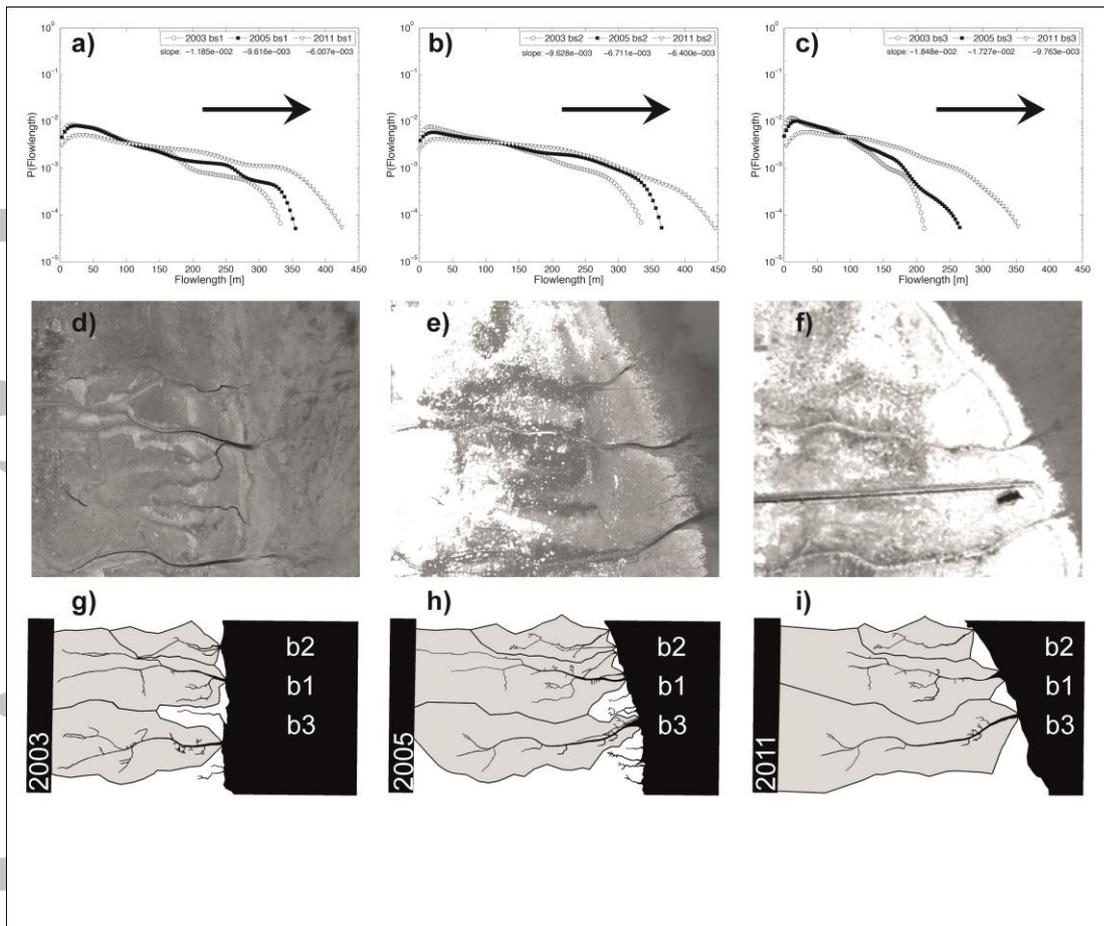


Fig.3 (a-c) Unchanneled flow length of three channel networks (b1, b2, b3) in the *Spartina alterniflora* invaded northern part of Chongming Island (Yangtze estuary) at the selected time-steps, slopes are stated below legend, (d-f) grayscale aerial images showing salt marsh development over time (2003, 2005 and 2011), *Spartina alterniflora* invasion is indicated by white pixels entering the research area in 2005 (e) and covering large parts of the research area in 2011 (f), (g-i) digitized channel networks and drainage basins (grey area) (2003, 2005 and 2011).

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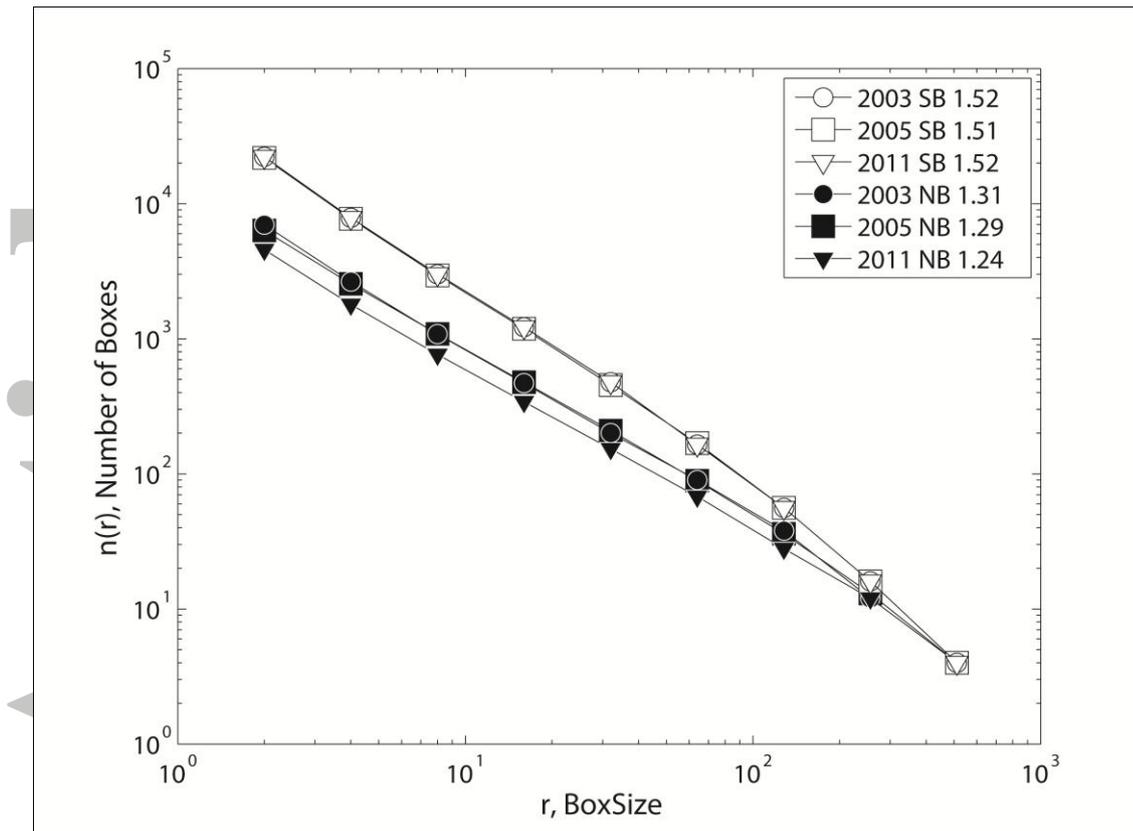


Fig.4 Box counting results of the merged drainage basins over time in northern (black, NB) and southern (white, SB) parts of Eastern Chongming Island; Fractal dimensions are stated in legend.

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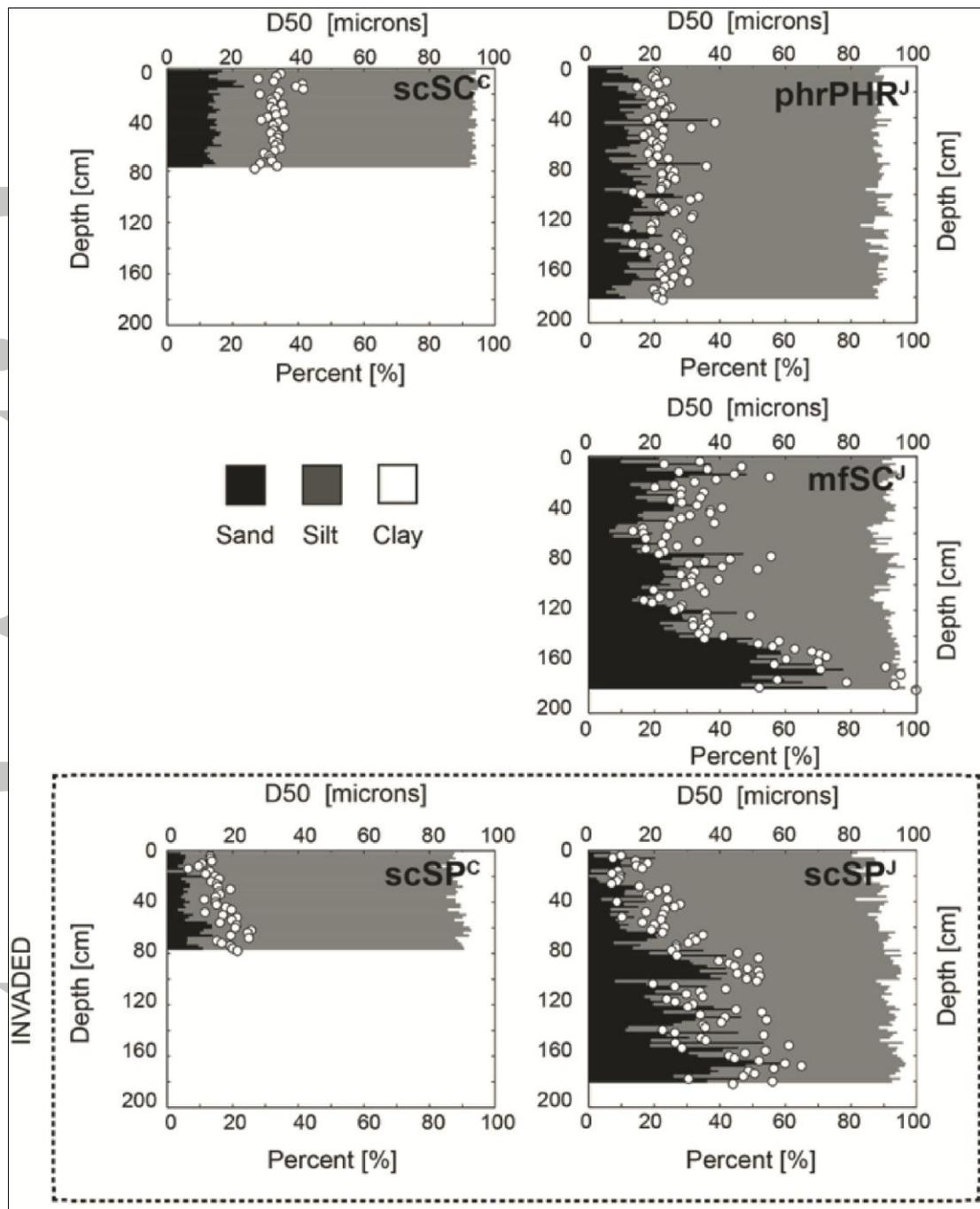


Fig.5 Sand: Silt: Clay composition (colored bars) and d50 (white circles) over depth of 80 cm sediment cores taken on Chongming Island (left), [scSC<sup>C</sup>, constant *Scirpus mariqueter* vegetation (Chongming), scSP<sup>C</sup>, succession from *Scirpus mariqueter* to *Spartina alterniflora* vegetation (Chongming, invaded)]; Sand: Silt: Clay composition and d50 over depth of 180 cm sediment cores taken on the Jiuduansha shoals (right), [mfSC<sup>J</sup> succession from mudflat to *Scirpus mariqueter* vegetation (Jiuduansha Shoals); phrPHR<sup>J</sup> constant *Phragmites australis* vegetation (Jiuduansha Shoals), scSP<sup>J</sup> succession from *Scirpus mariqueter* to *Spartina alterniflora* vegetation (Jiuduansha Shoals, invaded)].

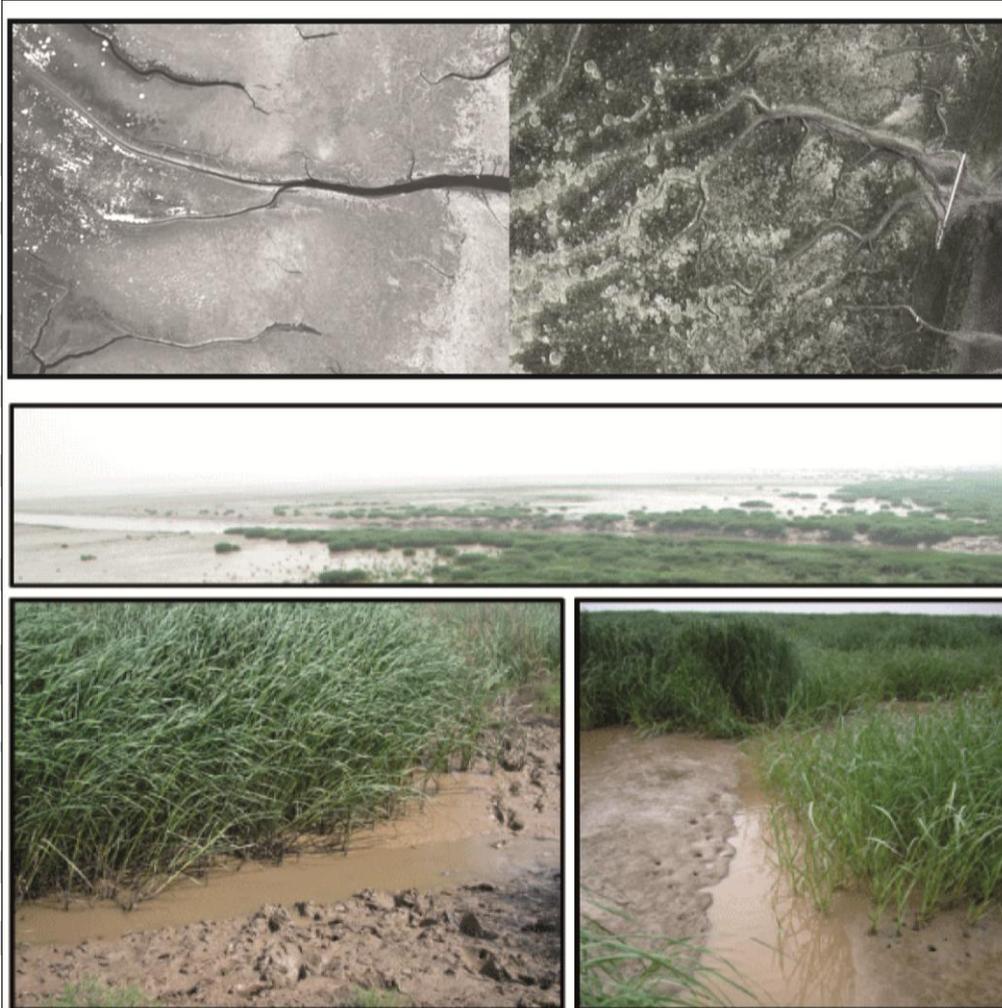


Fig.6 a) Aerial images of *Spartina alterniflora* (white pixels) invading existing salt marsh and mudflat channels and creek banks on Chongming Island (left) and on the Jiuduansha shoals (right)(*Spartina* introduction in 1997), Yangtze Estuary, China. b) Field observations showing *Spartina alterniflora* growing next and into small creeks