Eradicating invasive *Spartina alterniflora* with alien *Sonneratia apetala* and its implications for invasion controls

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**Abstract**

The smooth cordgrass (*Spartina alterniflora*) has invaded coastal areas throughout the world, including China, in the past decades. Scientists of China and other countries are trying all means to control its invasion, including physical removal, chemicals, and biological control by herbivores. The present research chose a small island (the Qi’ao Island) to study biocontrol of *S.alterniflora* with mangroves. In 1999, we began to introduce fast-growing mangroves (mainly an alien species, *Sonneratia apetala*) to control *S. alterniflora* invasion. In 2011, we successfully eradicated *S. alterniflora* (only 0.63 ha remained for experimental purpose) through expanding mangroves up to 300 ha. The dozen-year monitoring showed that *S. apetala* did not invade in native mangroves. The isolated island in the present study makes an experiment platform for scientists to find a strategy to check one invasive plant with another alien plant but not introducing new invasions.

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1. Introduction

Alien plants have been increasing in florals around the world, with invasive aliens considered as a global threat to biodiversity and ecosystem functioning (Bax et al., 2003; Bjørknes et al., 2007; Knapp and Kühn, 2012). Such invasive aliens usually cause negative economic impacts and costs in the recipient regions (Vilà et al., 2010). With intensified anthropogenic activities, new invasion of alien species continues all over the world, especially in regions with rapidly developing trade and economics, e.g., China (Kowarik, 2003; Lin et al., 2007; Liu et al., 2005). Moreover, global warming enables alien species to expand into regions where they previously could not survive and reproduce (Walther et al., 2009). Therefore, continuous strengthened efforts should be made in controls of invasive aliens, with early detection and rapid response (Huang et al., 2012).

Eradication of invasive alien species is acknowledged as a key management for mitigating invasion-caused impacts. However, regarding invasive alien plants, it appears that only some very localized removals have been completed (Capdevila-Argüelles et al., 2005). Biological control is an effective and valuable tool to control invasion through releasing natural enemies or competitors from the invader’s native range (Hoddle, 2004; Messing and Wright, 2006), though usually with risk of negative impacts of the introduced biological control agents on local ecosystems (Henneeman and Memmott, 2001; Messing and Wright, 2006).

The smooth cordgrass (*Spartina alterniflora*, Fig. 1) is a perennial C4 grass native to upper intertidal salt marshes across the Atlantic and Gulf coasts of North America. It was firstly introduced as ecological engineering species to prevent shoreline erosion, but quickly invaded the coastal ecosystems (Wan et al., 2009). Now it is found in coastal marshes almost all over the world. In 1979 *S. alterniflora* was introduced to China from the United States, also for ecological engineering purposes including reducing tidal wave energy, mitigating erosion, trapping sediments, reclamining tidal flats and protecting dike (An et al., 2007; Chung, 2006). With anthropogenic transplanting, natural dispersing and hybridizing with native species, *S. alterniflora* successfully invaded in nine of the fourteen coastal provinces of China (Wan et al., 2009), forming...
monocultures and expanding its coverage to more than 112,000 ha by 2000 (An et al., 2007). For its great negative effects on biodiversity and other ecosystem services, *S. alterniflora* is now regarded as one of the top 16 most harmful exotic plants in China (Wang et al., 2008). Several control methods have been used to prevent and mitigate the spread of *S. alterniflora*, including burning, harvesting, grazing by snails, herbicide application (not permitted now for health consideration), freshwater irrigation, and some combined methods, e.g. substituted by *Phragmites australis* after hydrology changing, but all with unclear effectiveness (An et al., 2007; Silliman and Zieman, 2001; Wan et al., 2009). Therefore, as an invasive plant, *S. alterniflora* is thought to be hard to eradicate (Qin and Chung, 1992). This paper reports a successful case of biocontrol (almost complete eradication) of *S. alterniflora* with an alien plant (*Sonneratia apetala*) in an island of China.

2. Methods and materials

2.1. Ethics Statement

Our field studies were approved by the Bureau of Qi’ao Mangrove Wetland Natural Reserve. The study was observational, involving no cruelty to animals, no damage to habitats and no harm to endangered plants, therefore no review from the ethnic committee was required in China. All the work was carried out under the Wildlife Protection Law of the People’s Republic of China.
2.2. Experiment site and S. apetala

The Q’iao Island in Zhuhai City, Guangdong Province has a total area of 24 km², with vast mudflat along the coast. The Q’iao Mangrove Wetland Natural Reserve is located in the northwest of the island (113°36’–113°39’E, 22°23’–22°27’N). The climate in the Q’iao Island is sub-tropical maritime climate, with an average annual temperature of 22.4 °C. The lowest average temperature (15.3 °C) appears in January, with the historically lowest temperature 2.5 °C. The mean annual precipitation is 1964.4 mm. Its tide is irregular semidiurnal tide; the mean high water level is 0.17 m, and the mean low water level –0.14 m. Southeast wind blows in summer while northeast wind blows in winter. The annual mean salinity of the sea water is 18.2%. Its soil is coastal saline marsh soil, with salinity about 20.8% in the surface (0–13 cm).

The 15 true mangrove species in this island belong to 10 families and 13 genera, with S. apetala plantation the main mangrove now. S. apetala (Fig. 1) is naturally distributed and serves as a very important restoration species in South Asia including India, Bangladesh and Myanmar (Mitra et al., 2012). It was originally introduced in 1985 to the Dong Zhaiqiang Mangrove Nature Reserve of China for mangrove restoration from Sundarban, southwestern Bangladesh (Liao et al., 2004). After 10-year restoration of mangroves, due to high adaptability and tolerance to salinity (Chen et al., 2000), S. apetala occupied about 95% of the restored mangroves (Liao et al., 2004). Currently covering 2300 ha, S. apetala is also listed as a leading restoration species in China (Ren et al., 2009). With some individuals of S. apetala occurring in native ecosystems of southern coastal China, Chinese scientists began to discuss its invasive potential (Ren et al., 2009; Tang, 2009). Some even listed S. apetala as an invasive species and tried to remove it (Tang, 2009; Wang et al., 2004). There existed no S. apetala on the Q’iao island before we introduced it in 1999.

2.3. Monitoring dynamics of S. alterniflora and S. apetala by remote sensing

We used Landsat TM/ETM+ image dating from 1990 to 2011 from the US Geological Survey (USGS) archive. Eight images were selected between November to January for little cloud cover and large contrast between mangrove and S. alterniflora. For each image we used 10 ground control points and controlled the root mean square error (RMSE) below ±0.5 pixel. We used the

![Mangrove and S. alterniflora](image)

Fig. 2. Area of Spartina alterniflora Loisel and mangroves in the Q’iao Island from 1990 to 2011. The three pictures from remote sensing data show the condition of 1995, 1999 and 2009.

### Table 1

<table>
<thead>
<tr>
<th>Shade treatment</th>
<th>Light transmittance</th>
<th>Height (cm)</th>
<th>Quantity of tillerings</th>
</tr>
</thead>
<tbody>
<tr>
<td>No shade</td>
<td>100%a</td>
<td>42 ± 0.5a</td>
<td>12 ± 1a</td>
</tr>
<tr>
<td>One-layer shade</td>
<td>65.8%b</td>
<td>36 ± 0.4a</td>
<td>7 ± 1a</td>
</tr>
<tr>
<td>Two-layer shade</td>
<td>32.5%c</td>
<td>24 ± 0.5b</td>
<td>4 ± 1b</td>
</tr>
<tr>
<td>Three-layer shade</td>
<td>15.2%d</td>
<td>0c</td>
<td>0c</td>
</tr>
</tbody>
</table>

Different letters mean significant differences (P < 0.05) among the shade treatments.

2.4. Shading experiments

To test the effect of mangrove shade on the growth of S. alterniflora, shading experiments were done in Research Institute of Tropical Forestry, Chinese Academy of Forestry, Guangzhou from April 15 to July 15, 2005. Shade nets were used to simulate shadiness of mangroves. Three treatments (one layer, two layers and three layers of shade nets) and one control (no shade) were set up. For each treatment, we set up triplicates for each of the eight pots of S. alterniflora incorporated. During the three-month experiment, we semimonthly measured the height and tiller number of S. alterniflora.

2.5. Monitoring controlling effects of different mangroves species on S. alterniflora

Since 1999, we cut S. alterniflora to form ridge belts and planted on them five kinds of mangrove with nutrition bags: Kandelia candel, Bruguiera gymnorrhiza, Rhizophora stylosa, Sonneratia caseolaris, and S. apetala. The plantation density was 0.3 m × 0.3 m for K. candel, B. gymnorrhiza, R. stylosa, and 1 m × 1 m for S. caseolaris and S. apetala. After 3 years, we set 3 quadrats (1 m × 1 m) in each plantation and in the S. alterniflora stand to measure the growth of S. alterniflora. We recorded the biomass, plant height, the quantity of tillers and growth diameter of S. alterniflora.

2.6. Monitoring S. alterniflora retreat and S. apetala growth

In 2005, we chose three S. apetala plantations with different ages (2-year, 3-year and 4-year) to monitor S. alterniflora retreat and S. apetala growth. For each plantation, we set up a typical plot (300 m²). In each plot, we set up three large quadrats (10 m × 10 m) to record the height, diameter at breast height (DBH), crown range

### Table 2

<table>
<thead>
<tr>
<th>Mangrove species</th>
<th>Quaadrature (m²)</th>
<th>Biomass (g m⁻²)</th>
<th>Growth index of S. alterniflora under mangroves</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Tillering number</td>
</tr>
<tr>
<td>S. apetala</td>
<td>1</td>
<td>20.5 ± 4.5a</td>
<td>2.6 ± 0.4a</td>
</tr>
<tr>
<td>S. caseolaris</td>
<td>1</td>
<td>4.1 ± 0.8a</td>
<td>5.0 ± 2.1a</td>
</tr>
<tr>
<td>K. candel</td>
<td>1</td>
<td>1788.8 ± 265.7b</td>
<td>220.6 ± 39b</td>
</tr>
<tr>
<td>B. gymnorrhiza</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>R. stylosa</td>
<td>1</td>
<td>1929.9 ± 350.0b</td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>1</td>
<td>1987.5 ± 179.0b</td>
<td></td>
</tr>
</tbody>
</table>

Different letters mean significant differences (P < 0.05) among the mangrove treatments.
and crown density of *S. apetala*, and three small quadrats (1 m × 1 m) to record the height, frequency, biomass and coverage of *S. alterniflora*.

### 2.7. Long-term monitoring of *S. alterniflora* plantations

In 2011, we set up 8 quadrats of 3-year, 5 quadrats of 6-year, 4 quadrats of 9-year, and 3 quadrats of 12-year *S. apetala*. At the opposite angles of the quadrat, 2 small quadrats of 4 m × 4 m were set up for the seedlings (shorter than 30 cm). Around each small quadrat, there were 12 sub-small quadrats of 1 m × 1 m. We recorded the height, DBH, basal diameter, crown size, clump number (arbor and herbaceous). We calculated the frequency, plant density, clump density and basal area.

### 2.8. Monitoring mangrove seedlings in different habitats

In 2004, we recorded the density, height and age of seedlings of different species with 2 m × 2 m quadrates inside a four-year plantation (*n* = 8), on its edge (*n* = 24), in a ditch around the plantation (*n* = 40), a *S. alterniflora* stand (*n* = 16) and a section of bare beach (*n* = 9). In the four-year *S. apetala* plantation, we randomly chose 6 individuals of *S. apetala* to harvest seeds from three big twigs (with diameter larger than 2.5 cm) and three small ones (with diameter smaller than 2.5 cm) for each tree to calculate seed harvest per tree.

### 2.9. Statistical analysis

Mean values of factors were calculated by averaging the replicates for each treatment. Analyses of variance (ANOVA) were performed using such means to test the difference of factors. The effect of a certain variable was considered statistically significant for *P* < 0.05. The above analyses were performed with SPSS 11.5 for Windows.

### 3. Results and discussion

#### 3.1. *S. alterniflora* vs *S. apetala* on the Qi’ao Island

In the early 1990s, *S. alterniflora* began to invade in the salty marshes, gaps of natural mangroves and barren flats of the Qi’ao Island (Fig. 1), with fast invasion pattern similar with other coastal regions in China (An and others 2007). After only five years, the invasive fast-growing *S. alterniflora* had formed monocultures and expanded its coverage up to 227 ha by 1995. Then during construction of fish or shrimp ponds, some of *S. alterniflora* was removed. However, *S. alterniflora* was still dominant in the coastal flat of this island, about 59 ha in 1999 (Fig. 2).

We realized the serious invasion of *S. alterniflora* and began to control it around this island in 1999. Through our three-month experiments, we found that increases in shadiness significantly reduced the height and number of tillers of *S. alterniflora* (Table 1). Therefore, we considered that the dense canopy of fast-growing mangroves might be an effective way to control the notorious weed. We began to introduce four native mangroves (*K. candele*, *B. gymnorrhiza*, *R. stylosa*, *S. caseolaris*) and *S. apetala* after clearing the aboveground part of *S. alterniflora* in 1999, hoping it could be substituted by the mangroves. Three years after the initial introduction, three of the four native species had no significant control on *S. alterniflora* regrowth, while only the native *S. caseolaris* and the alien *S. apetala* succeeded in forming dense canopy to control the regrowth of *S. alterniflora* (Table 2). Thereafter, we collaborated with the local government to afforest these two mangrove species to substitute *S. alterniflora*.

#### Table 3

<table>
<thead>
<tr>
<th><em>S. apetala</em> Plantation</th>
<th>Characteristics of plantation</th>
<th>Growth index of <em>S. alterniflora</em></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Height (m)</td>
<td>Crown density</td>
</tr>
<tr>
<td>2-year</td>
<td>2.5 ± 0.1a</td>
<td>0.60 ± 0.70</td>
</tr>
<tr>
<td>3-year</td>
<td>3.7 ± 0.1b</td>
<td>0.60 ± 0.75</td>
</tr>
<tr>
<td>4-year</td>
<td>6.1 ± 0.2c</td>
<td>0.65 ± 0.80</td>
</tr>
</tbody>
</table>

Different letters mean significant differences (*P* < 0.05) among the mangrove treatments.

**Fig. 3.** Height and crown density of *S. apetala* plantations of different ages in the Qi’ao Island. Different letters mean significant differences (*P* < 0.05) of the height among the plantations of different ages.

**Fig. 4.** Seeding density of the alien species (*S. apetala*) and native species (*A. ilicifolius* and *A. carriculatum*) in different habitats in a typical landscape of a 4-year *S. apetala* plantation, bare beach, ditch and *S. alterniflora* stand.
Since our annual afforestation of S. caseolaris and S. apetala, S. alterniflora coverage continually decreased and at the same time mangroves expanded their coverage up to 223 ha by 2007, mainly through S. apetala afforestation. In 2008, the large-scale ice storm in Southern China attacked this island, resulting in dying of most S. caseolaris individuals, which explained the decline of mangroves and a slight increase of S. alterniflora in 2009. Then we replaced the degraded S. caseolaris plantation with S. apetala, which was more tolerant of cold. To 2011, we eventually eradicated S. alterniflora (only 0.63 ha remained for experimental purposes) through expanding mangroves up to 300 ha.

3.2. Monitoring the eradication progress and aftermaths

In a dozen of years, the fast-growing S. apetala successfully controlled S. alterniflora, with its plantations of different age dominating the coastal line of the Qia’o Island. Since the very beginning of our biocontrol of S. alterniflora, we had monitored the dynamics of S. apetala, S. alterniflora and the native mangrove species. In 2005, we noted that a two-year S. apetala plantation had already formed a dense mangrove forest with a canopy about 60%–70% (Table 3). With time, S. apetala plantations greatly increased in height, crown range and DBH (Table 3). One exception was the crown density, which, after getting to its peak (100%) in the 6-year plantation, decreased to 90% and 80% in the 9-year and 12-year ones, respectively (Fig. 3), probably due to the self-thinning effect. Furthermore, the biomass accumulation and soil organic carbon (SOC) under S. apetala plantations were found to increase with time, e.g. in the 10-year plantation the total forest and SOC were up to 108.1 Mg ha$^{-1}$ and 35.0 Mg ha$^{-1}$, respectively (Ren et al., 2010). Simultaneous with the general increase of height, crown density, biomass accumulation and SOC of S. apetala on the Qia’o Island, significant reduction was found in the height, biomass and coverage of S. alterniflora (Table 3). In the 4-year plantation only three individuals of S. alterniflora were found in a 300 m² plot and no one was found in the 12-year plantation.

With the retreat of S. alterniflora, some kinds of native species (especially shrubs and herbs, such as Acanthus ilicifolius, Aegiceras cunninculatum, Acrostichum aureum, etc.) encroached in the understory of young S. apetala plantations. In 2005, we observed several native species and their seedlings under a 2-year plantation. Dense aerial roots of S. apetala provided more support for seedlings and further enhanced the settlement of shrubs, herbs and seedling of native mangroves. In 2011, we found that A. ilicifolius and their seedlings almost dominated the understory of the 9-year and 12-year plantations. In the 12-year plantation, we recorded a small amount of K. candel (about 67 individuals per ha), which is the dominant species of a native mangrove forest on the island. Though S. apetala was found in laboratory to release some chemicals to suppress other plants, the above-mentioned observations in plantations of different ages showed that S. apetala did not exclude native species but rather enhanced the settlement of shade-tolerant native species. Similar with our results, in a 14-year S. apetala plantation in Dongzhaiang of Hainan Island, two native mangrove species (A. cunninculatum and K. candel) were found to dominate the understory of the stand (Wang et al., 2011). However, in Leizhou Bay of southern China, native species were only observed in young plantations (less than 10 years) and disappeared in plantations older than 10 years (Ren et al., 2008). This was probably due to the limited seed source and low seedling quantity in the region. Therefore, given plentiful seeds and seedlings of native species, natural regeneration of native mangroves should gradually occur in S. apetala plantations after 10 years or so. Furthermore, we found that there was a higher density of A. cunninculatum in the edge of plantations than that inside the plantation, which indicated that increasing the range of edges through circled or striped plantation would accelerate natural regeneration of native mangroves (Ren et al., 2008).

As mentioned above, S. apetala has sometimes been regarded as an invasive species due to sporadic natural regeneration in native ecosystems in southern China (Ren et al., 2008). In our study, we found three-year-old individuals could blossom and bear fruit, producing more than 2700 berries per tree with 30 to 50 seeds per berry. Therefore, there were enough seed sources for S. apetala regeneration and “invasion”. However, after 17 years of S. apetala introduction to Dongzhaiang, there were only 64 mature individuals and 6 small ones along the edges of two rivers there (Liao et al., 2004), which indicated that S. apetala “invaded” very slowly, if they ever did. We investigated S. apetala seedlings in different habitats on the Qi’ao Island and observed a lowest density of S. apetala seedlings inside the 4-year S. apetala plantation (Fig. 4). These seedlings were youngest, only three or four months old among different habitats. There are several reasons for this. First, the natural germination rate of S. apetala was very low, which is limited by tides, salinity and sediments, etc. Second, S. apetala seedlings were shade-intolerant and hard to survive under the dense mangroves (Liao et al., 2004). Comparing with S. apetala, we found more native species seedlings in almost all kinds of habitats on this island except for the edge of its plantation and bare beaches (Fig. 4). Moreover, the ratio of native seedlings to S. apetala seedlings was much higher in older S. apetala plantations than in young ones. Based on these results, we do not think S. apetala can “invade” in native mangroves at the present status.

3.3. Replacing S. apetala plantation with native mangroves or not?

Some scholars regarded S. apetala as a nurse plant to facilitate settlement of native mangroves species at early stages, then compete with these seedlings, and later suppress the natural regeneration of native mangroves. Therefore, they suggested removing S. apetala in order to approach native mangroves (Ren et al., 2008). In Hong Kong, a few scientists already tried all means to eradicate such a fast-growing exotic species (Tang, 2009). However, although S.apetala plantations seem to be in the successive progress to native mangroves on the island and at some other sites (Wang et al., 2011), such progresses will take a long time with many uncertainties. Direct removals of S.apetala may not be a wise way to approach native mangroves. Our study was a good example, in which S.apetala did a good job in effectively controlling S. alterniflora. The ice storm of 2008 proved it a right decision not to remove S. apetala to approach native mangroves. If we had done so, it could have resulted in reinvasion of S.
**alterniflora.** The dieback of native *S. caseolaris* plantation created windows during the ice storm facilitating *S. alterniflora*’s reinvasion, which was suppressed by reforestation with *Sapetala* (Figs. 2 and 5). There are many challenges and questions concerning *S. apetala*. The greatest question is it if it is still necessary for us to help *S. apetala* plantations approaching native mangroves with expensive costs, especially when we have seen that the fast-growing *S. alterniflora* successfully controls *S. alterniflora* has very low invasive threat to local mangroves, and that native species can dominate the understory of *S. apetala* plantations to form a naturally successive stage approaching native mangroves. In the present study, the isolated Qi’ao Island makes an experiment platform for scientists to study the biocontrol of *S. alterniflora* with alien *Sapetala* and find a strategy to check one invasive plant with another alien plant but not introducing new invasions.

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