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ORIGINAL PAPER

# How tidal regime and treatment timing influence the clipping frequency for controlling invasive *Spartina alterniflora*: implications for reducing management costs

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**Abstract** Treatment frequency is one of the key regulators determining the efficiency of and investment in controlling invasive plants. However, it is highly unlikely to find the optimal solution to the control of invasive plants through studying treatment frequency alone. In addition, the efficiency of controlling invasive plants is habitat-dependent. In this paper, clipping treatment was employed as the method to control invasive species *Spartina alterniflora*. We made an attempt to illustrate that clipping frequency can be reduced by considering the habitat properties and other relevant controlling regulators. Our full factorial test of combining clipping timing with considerations of clipping frequency and tidal regime showed that four-time clipping treatment started at florescence in high marsh or three-time clipping treatment started at florescence in low marsh was effective for controlling *S. alterniflora*. This implies that the control efficiency could be enhanced if treatment timing is optimized in relation to treatment frequency and habitat properties, which will lead to reduced management costs of controlling invasive species.

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**Keywords** Clipping · Habitat-dependence · *Spartina alterniflora* · Tidal regime · Treatment frequency · Treatment timing

## Introduction

Controlling invasive plants is expensive, because no single method requires only one application but repeated ones (Genovesi 2005; Hansen and Wilson 2006; Hulme 2006; Wilson and Clark 2001). Therefore, the treatment frequency determines the efficiency and costs of a control practice. How to reduce the treatment frequency and find the best scenario, i.e., minimum frequency demand (MFD), is one of the major tasks for invasive plant managers.

Many classical methods such as clipping for controlling invasive *Spartina alterniflora* Loisel (hereafter as *Spartina*) need a high treatment frequency to ensure and enhance the treatment efficiency (An et al. 2007; Wang et al. 2006a), which leads to limited implementation because of high costs. The study of how to effectively reduce the necessary clipping frequency would not only reduce the management costs but also provide a model way of consolidating the control effect, especially for physical methods including hand pulling, digging, covering, burning, and milling.

In order to study how to minimize treatment frequency, other relevant regulators affecting control efficiency should be considered simultaneously. Previous studies have indicated that treatment timing is the important regulator for enhancing control efficiency (Emery and Gross 2005; Gao et al. 2009; Pysek et al. 2007; Ruesink and Collado-Vides 2006). This can infer that treatment timing might determine the final MFD. In other words, when the same treatment frequency with different starting time is applied in a control practice, the total cost spent on the repeated treatment is equivalent but the resultant efficiencies are different because plants' susceptibility to control treatments is variable at different growth periods. In order to find the MFD, the effects of treatment timing logically need to be considered. However, the previous studies have paid little attention to the MFD, perhaps because the effects of treatment frequency and timing have been studied separately (Hammond 2001; Li and Zhang 2008).

In addition, control efficiency of invasive plants in tidal saltmarshes may be habitat-dependent (Hacker et al. 2001; Hansen and Wilson 2006), and may be different from controlling weeds on the arable lands. Compared to heterogeneous habitats of invasive plants in tidal saltmarshes, the arable lands are uniform because of human management. Habitat heterogeneity has direct or indirect effects on control efficiency for an invasive plant. For example, dilution of herbicide caused by tide water may lead to differing control efficiency of chemical methods in different tidal zones (Hammond 2001). The influence of fire on *Spartina* in the high-tide zone is more significant than that in the low-tide zone, because the temperature in the low-tide zone is reduced by surface water, leaving the underground structures unaffected (Wang et al. 2006c). The indirect effects include the different resistance and recovery ability of target species caused by habitat properties, which might explain why control efficiency varies along a certain habitat gradient (Neira et al. 2007; Wang et al. 2006b). For example, waterlogging time and soil pore water salinity are important environmental gradients in many *Spartina*-invaded estuarine wetlands and coastal marshes (Wang et al. 2006a; Weber 2003). As the habitat properties of *Spartina* patches may affect treatment efficiency, finding the MFD in different habitats can also potentially reduce the management costs. It is likely that waterlogging time and salinity may affect the control efficiency through influencing the recovery of clipped *Spartina*. In other words, the MFD may differ in different tidal zones.

In this study, the efficiency of 15 clipping treatments for controlling *Spartina* in high and low marshes was investigated. We aimed to illustrate how the MFD was different in various habitats for controlling an invasive plant. In so doing, the main effects of frequency and effects of related factors need to be studied together. The following three questions are particularly concerned in the paper: (a) whether does the MFD change in different habitat or not; (b) how does the MFD change with other factors; and (c) why should the treatment timing, habitat properties and treatment frequency be considered together?

## Materials and methods

### Study site

The study site is located in the core area of Shanghai Chongming Dongtan National Nature Reserve on Chongming Island in the Yangtze River estuary (31°250′–31°380′N; 121°500′–122°050′E), China. It is one of the most important migratory stop-over sites in the North Temperate Zone. *Spartina* was introduced to this wetland for the purpose of reclamation and amelioration of saline soil several years ago. Because of the rapid expansion of *Spartina*, the endemic species *Scirpus mariqueter* (hereafter as *Scirpus*), which forms favourable habitats and foraging site for the birds, was locally excluded, and restricted to a small area close to the region of 0 m (Ma et al. 2003). At present, *Spartina* is still rapidly expanding in *Scirpus* areas, which narrows the habitats for birds (Jing et al. 2007). Higher coverage and biomass of *Spartina* have reduced the habitat quality for birds as they could not forage and build nests effectively in it (Li et al. 2009). *Spartina* also creates dense below-ground systems affecting the growth of meiofauna, which is also the fine food of carnivorous birds (Chen 2004). Because our study area is an important natural reserve for East Asian-Australian migratory shorebirds, the spread of *Spartina* has a significant negative impact on the management of the reserve.

Tidal fluctuation in this area is regular and semidiurnal with maximum and average tidal height range from 4.62 to 5.95 m and 1.96 to 3.08 m, respectively. Annual mean air temperature is 15.2°C with 229 non-frost days. Annual precipitation varies around 1,100 mm (Huang et al. 1993). Based on our measurements, soil pore water salinity in the marshes ranged from 8 to 13‰ during our study period.

## Experiment design

Because the effect of treatment timing and frequency can not be separated completely by using a single factor experiment, a factorial design (Table 1) was used to cover the two factors. Meanwhile, to illustrate if tidal regime had any effect on control efficiency, the experiment was conducted simultaneously both in high-marsh and low-marsh areas. We clipped the *Spartina* ramets by sickle as close as possible to the ground. All the clipping treatments were performed in the morning (from 6:30 a.m. to 11:30 a.m.) when tide flooding did not happen. Furthermore, all the clippings were performed as planned regardless of tidal height as the clipping intervals used in this study did not reflect the tidal cycle.

In early May 2006, two transects perpendicular to the dike were established, which were 2 km apart. Each transect was divided into two parts, representing high and low tidal marshes, respectively. The high tidal zone was about 300 m away from the seawall, and was affected only by spring tides, while the low tidal zone was 1,100–1,400 m away from the seawall, and frequently submerged by neap tides. Therefore, the flooding time in the high tidal zone was about 4 h during maximum tide level and about 4 h per day during neap tide period and 7 h during spring tide period (Xu and Zhao 2005). In each part, three replicate plots of 20 × 20 $m^2$ were randomly chosen, and they were at least 20 m away from each other. In each plot, 15 treatments and a control were set up in randomly selected 3 × 3 $m^2$ quadrat (Fig. 1).

In order to assess the control efficiency, an area of 1 × 1 $m^2$ from each quadrat was randomly sampled to make the spot checks in early November 2006 (Fig. 1). We first measured canopy height in the field and harvested the above ground tillers and carried to the lab for estimating ramet density and heading ratio (percentage of flowering ramets). All of the tillers including inflorescence were oven-dried to constant weight at 80°C, and weighed. Further, to evaluate the persistent effects of clipping, additional measurements in randomly selected area of 1 × 1 $m^2$ in each quadrat of the remainder were performed in early May 2007 (Fig. 1), including canopy height, plant density, and dry biomass.

## Data analysis

In order to investigate the control efficiency of clipping treatments, a parameter named performance ratio (PR) was proposed, which is a relative measure of plant performance. It can indicate the regrowth and recovery status of clipped *Spartina* by filtering the effect of spatial heterogeneity. The formula takes the form:

$$\mathrm{PR} = \frac{P_{\mathrm{T}}}{P_{\mathrm{C}}} \times 100\%, \quad (1)$$

where PR represents the performance ratio, $P_{\mathrm{T}}$ and $P_{\mathrm{C}}$ the measure of a given plant trait such as dry biomass, density, or canopy height for clipping treatment and control. In the formula, a greater value of PR reflects lower control efficiency.

To determine if there was any significant difference caused by location variation of the two transects, an independent *t*-test was used. The comparisons were made for PRs of dry biomass, plant density, and

**Table 1** Dates repeated clipping treatments were applied

| Clipping timing | Clipping frequency 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Sprouting period—initial flowering period | 26 May | 26 May, 7 Jun | 26 May, 17 Jun, 8 Jul | 26 May, 17 Jun, 8 Jul, 30 Jul | 26 May, 17 Jun, 8 Jul, 30 Jul, 21 Aug |
| Vegetative growth period—florescence period | 17 Jun | 17 Jun, 8 Jul | 17 Jun, 8 Jul, 30 Jul | 17 Jun, 8 Jul, 30 Jul, 21 Aug | 17 Jun, 8 Jul, 30 Jul, 21 Aug, 12 Sep |
| Initial flowering period—senescence period | 8 Jul | 8 Jul, 30 Jul | 8 Jul, 30 Jul, 21 Aug | 8 Jul, 30 Jul, 21 Aug, 12 Sep | 8 Jul, 30 Jul, 21 Aug, 12 Sep, 4 Oct |

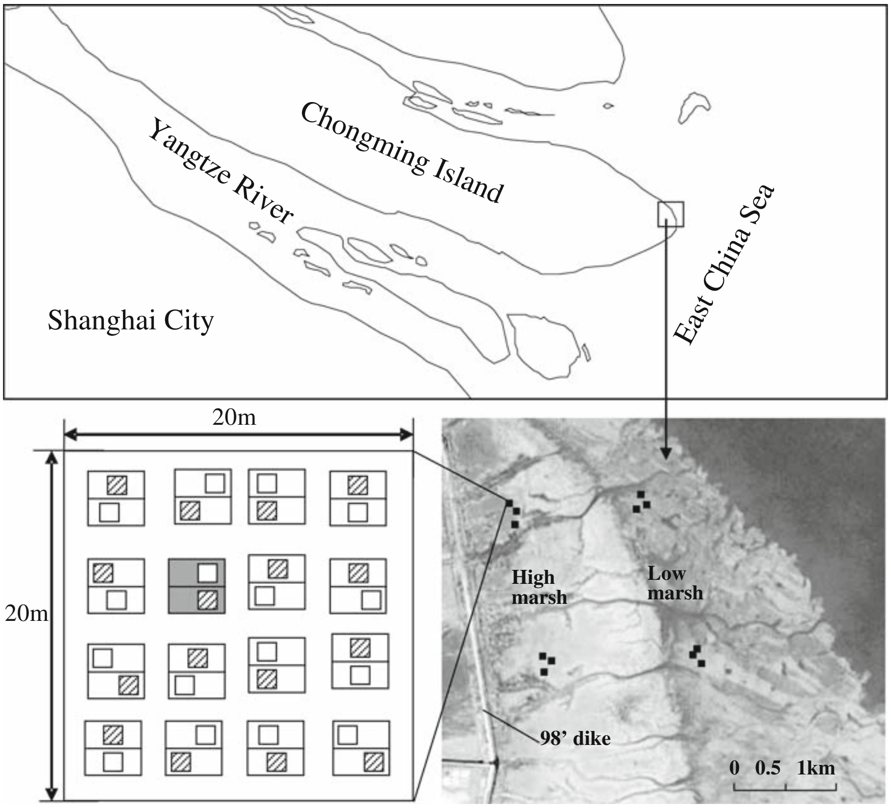


**Fig. 1** Schematic representation of experimental layout. **a** Map of Chongming Island in the Yangtze River estuary. **b** Location of preset plots. **c** Layout of treatment quadrats; (⊟) treatment quadrat (3 × 3 $m^2$); (▤) control quadrat (3 × 3 $m^2$); ▨ investigation area at the end of the first growing season (1 × 1 $m^2$); and (□) investigation area in the recovery period

canopy height of *Spartina* in 2006 and 2007, and heading ratio in 2006. No significant differences between the two transects were found by these tests ($p_{min} = 0.281$), thus, in the following analysis, we pooled the data from the two transects.

The PRs of dry biomass, canopy height, plant density in 2006 and 2007, and heading ratio in 2006 were subject to multivariate analysis of variance (MANOVA) as a timing (3) × frequency (5) × tidal zones (2) factorial arrangement of treatments. Three-way ANOVA was used to analyze the effects of clipping timing, frequency, and tidal zone on control efficiency at the end of the growing season of 2006 and at the beginning of 2007, and Tukey's test was employed as the post hoc test. Significance level was set at 5%. All the analyses were performed on software package Statistical Analysis System® 8.0 (SAS Institute Inc, USA).

## Results

Tables 2 and 3 show that clipping frequency, clipping timing and tidal regime as well as their interactions all had significant effects on the clipping efficiency ($P < 0.01$ in all MANOVAs). In 2006 and 2007, the main effects of frequency were the most significant (Wilk's $\lambda_{min} = 0.001$, 0.005). The interaction between timing and tidal regime was the least (Wilk's $\lambda_{min} = 0.674$, 0.812) although it was significant ($P < 0.01$ in 2 year). Tables 4 and 5 show that these main factors and their interactions strongly influenced all the parameters of the growth and sexual reproduction of clipped *Spartina*, including dry biomass, plant density, canopy height in 2006 and 2007, and heading ratio in 2006 ($P < 0.01$ in all three-way ANOVA).

Figures 2 and 3 indicate that frequency, timing, and tidal regime were all important to the control efficiency by clipping. PRs showed that there were significant effects of treatment frequency on control efficiency. Except for PR of density in 2007 (Fig. 3 III, IV), the PRs of dry biomass, density, canopy height, and heading ratio in 2006 (Fig. 2 I–VIII), and dry biomass and density in 2007 (Fig. 3 I, II, V, VI) all significantly decreased with an increase of clipping frequency ($P < 0.05$). In 2006, when the treatment frequency was three times or higher, PR

**Table 2** MANOVAs for testing the effects of clipping timing, frequency, and tidal zone on the control efficiency of *Spartina alterniflora* in 2006

| Source | No. of parameters | Wilk's $\lambda$ value | *F*-value | *P*-value |
|---|---|---|---|---|
| Timing | 4 | 0.052 | 123.65 | <0.0001 |
| Frequency | 4 | 0.001 | 225.35 | <0.0001 |
| Tidal zone | 4 | 0.151 | 206.78 | <0.0001 |
| Timing × frequency | 4 | 0.018 | 33.68 | <0.0001 |
| Timing × tidal zone | 4 | 0.674 | 8.01 | <0.0001 |
| Frequency × tidal zone | 4 | 0.114 | 29.03 | <0.0001 |
| Timing × frequency × tidal zone | 4 | 0.222 | 8.58 | <0.0001 |

**Table 3** MANOVAs for testing the effects of clipping timing, frequency and tidal zone on the control efficiency of *Spartina alterniflora* in 2007

| Source | No. of parameters | Wilk's $\lambda$ value | *F*-value | *P*-value |
|---|---|---|---|---|
| Timing | 3 | 0.070 | 51.12 | <0.001 |
| Frequency | 3 | 0.005 | 216.72 | <0.001 |
| Tidal zone | 3 | 0.187 | 215.09 | <0.001 |
| Timing × frequency | 3 | 0.475 | 5.25 | <0.001 |
| Timing × tidal zone | 3 | 0.812 | 5.42 | <0.001 |
| Frequency × tidal zone | 3 | 0.311 | 18.12 | <0.001 |
| Timing × frequency × tidal zone | 3 | 0.731 | 2.05 | 0.003 |

**Table 4** Three-way ANOVA testing the effects of initial clipping timing, clipping frequency, and tidal zone on the PRs of *Spartina alterniflora* in 2006

| Source | *df* | Dry biomass | | Density | | Canopy height | | Heading ratio | |
|---|---|---|---|---|---|---|---|---|---|
| | | *F*-value | *P*-value | *F*-value | *P*-value | *F*-value | *P*-value | *F*-value | *P*-value |
| Timing | 2 | 480.46 | <0.001 | 333.23 | <0.001 | 189.45 | <0.001 | 447.13 | <0.001 |
| Frequency | 4 | 1258.59 | <0.001 | 2,471.94 | <0.001 | 727.07 | <0.001 | 1,447.32 | <0.001 |
| Tidal zone | 1 | 163.31 | <0.001 | 241.12 | <0.001 | 322.26 | <0.001 | 431.11 | <0.001 |
| Timing × frequency | 8 | 167.55 | <0.001 | 33.69 | <0.001 | 6.65 | <0.001 | 67.84 | <0.001 |
| Timing × tidal zone | 2 | 15.42 | <0.001 | 8.20 | 0.004 | 15.30 | <0.001 | 10.33 | <0.001 |
| Frequency × tidal zone | 4 | 28.42 | <0.001 | 21.68 | <0.001 | 5.20 | 0.006 | 77.27 | <0.001 |
| Timing × frequency × tidal zone | 8 | 5.22 | <0.001 | 3.08 | 0.003 | 7.84 | <0.001 | 13.90 | <0.001 |

of above ground biomass decreased to a very low level (Fig. 2), and the sexual reproduction failed in low tidal zone (Fig. 2 I, VII). In contrast, more than four times of clipping were needed to control *Spartina* in high tidal zone (Fig. 2 II, VIII). In 2007, PRs of biomass and canopy height decreased with the increasing clipping frequency (Fig. 3 I, II, V, VI), though PR of density for two-clipping treatment was greater than those for other treatments (Fig. 3 III, IV). The control efficiency varied with clipping timing, i.e., late clipping was the most effective and early clipping the least effective. The PRs of dry biomass, plant density, and canopy height in 2006 and 2007, and heading ratio of early clipped *Spartina* were significantly higher than those of later clipped *Spartina* in most cases ($P < 0.05$). More specifically, for the clipping treatments with the same frequency, the efficiency of the clipping treatment started at sprouting period and ended at initial flowering period was the lowest, and that of the clipping treatment started at initial flowering period and ended at senescence period was the highest (Fig. 2 I–VIII, Fig. 3 I–VI). This illustrates that the latter was the optimal clipping period in our experiment. The same

**Table 5** Three-way ANOVA testing the effects of initial clipping timing, clipping frequency and tidal zone on the PR*s* of *Spartina alterniflora* in 2007

| Source | *df* | Dry biomass | | Density | | Canopy height | |
|---|---|---|---|---|---|---|---|
| | | *F*-value | *P*-value | *F*-value | *F*-value | *P*-value | *F*-value |
| Timing | 2 | 393.76 | <0.001 | 356.18 | <0.001 | 191.04 | <0.001 |
| Frequency | 4 | 915.21 | <0.001 | 1,019.18 | <0.001 | 103.40 | <0.001 |
| Tidal zone | 1 | 142.56 | <0.001 | 483.05 | <0.001 | 50.12 | <0.001 |
| Timing × frequency | 8 | 9.53 | <0.001 | 5.35 | <0.001 | 1.21 | 0.299 |
| Timing × tidal zone | 2 | 7.82 | 0.006 | 10.13 | <0.001 | 0.73 | 0.481 |
| Frequency × tidal zone | 4 | 44.66 | <0.001 | 18.76 | <0.001 | 1.02 | 0.402 |
| Timing × frequency × tidal zone | 8 | 1.67 | 0.110 | 4.42 | <0.001 | 0.45 | 0.891 |

treatment in low marsh was more efficient than that in high marsh except for canopy height in 2007 (Fig. 3 V–VI), the PRs of dry biomass, plant density, canopy height and heading ratio in the 2006 (Fig. 2 I–XI), and dry biomass and plant density in 2007 (Fig. 2 I–IV) in low marsh were significantly lower than those in high marsh ($P < 0.05$). This implies that MFD was lower in low marsh than that in high marsh.

## Discussion and conclusions

### Influence of frequency and timing on the control efficiency

The results obtained in this study show that the clipping frequency determined the final efficiency (Tables 2, 3, 4, 5; Figs. 2, 3), which is unsurprising. On the one hand, the root growth was suppressed by repetitive defoliation during clipping treatment, which resulted in the inability of the plant to take up sufficient nutrients and water. On the other hand, repeated clipping led to large consumption of energy storage for regrowth and sprouting, which reduced the root's vigor and also affected sprouting and growth potential (Hansen and Wilson 2006; Hempy-Mayer and Pyke 2008; Roundy et al. 1985). These processes might have an accumulative effect, i.e., repeated clipping could strongly inhibit not only the vegetative growth and reproduction of *Spartina* in the first year but also its regrowth in the following growing season.

The previous studies (Hobbs and Humphries 1995; Pysek et al. 2007) have shown that the clipping timing is an important regulator of treatment efficiency. We also obtained similar results in this study (Tables 2, 3, 4, 5; Figs. 2, 3). The control efficiency with the same clipping frequency might be reduced by improper treatment timing, which could occur in all tidal zones and under various frequency levels. The evidence was that the double clipping treatment before the flowering phase stimulated the compensatory growth of *Spartina* (PR exceeded 100% in Fig. 3 III, IV). On the contrary, the clipping efficiency would be promoted if proper timing and frequency were both considered. More specifically, when only the treatment frequency was considered, four times of clipping were required in low marsh, and more than five times of clipping were required in high marsh to effectively control *Spartina*. If treatment timing was also considered, four-time clipping started at florescence was adequate in high marsh, and three-time clipping sufficed in low marsh (Figs. 2, 3). Obviously, clipping in July (florescence) was more efficient. The reason is that during the reproductive period, energy stored is allocated to flowering and seeding and lack of energy to maintain effective recovery such as regrowth and sprouting of below ground buds (Daehler and Strong 1994; Metcalfe et al. 1986).

### Effects of habitat properties on clipping efficiency

Based on our observations, the difference in control efficiency between two tidal zones was caused by the variation in waterlogging time. The low marsh sites were periodically submerged by tide water, i.e., 4 h per day during neap tide period and 7 h during spring tide period without above ground parts, the recovery of clipped *Spartina* was inhibited because of anoxia. Overall, the clipping treatment was more efficient in low marsh than in high marsh (Fig. 2 I–IX, Fig. 3 I–IV),

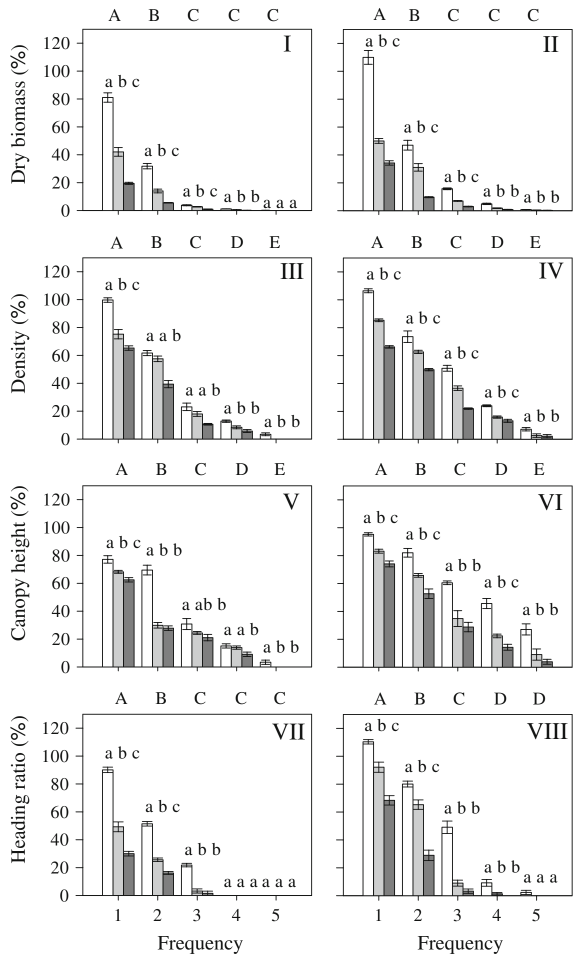


**Fig. 2** Effects of clipping frequency, clipping timing, and tidal zone on the control efficiency of *Spartina alterniflora* in 2006. **I**, **III**, **V** and **VII** represent PRs of dry plant biomass, plant density, canopy height, and heading ratio in low tidal zone, respectively; and **II**, **IV**, **VI** and **VIII** those in high tidal zone. (□) clipping from sprouting period to initial flowering period; (▒) clipping from vegetative growth period to florescence period; (■) clipping from initial flowering period to senescence period. (⌶) standard errors of six replicated plots. The different letters denote the significant differences at 5% significance level (the *capital letters* on the columns denote the difference among interval groups, while the *lowercase letters* denote the difference within interval groups)

but canopy height in the second year had the opposite trend (Fig. 3 V, VI). The possible reason is that the shading due to standing litter of *Spartina* in high marsh, stimulated *Spartina* juveniles to grow higher for acquiring more light, which was also observed in many other studies (Alber et al. 2008; Newell 1996; Xiong and Nilsson 1999). While in low marsh, the litter is frequently flushed by tide water and plant growth was

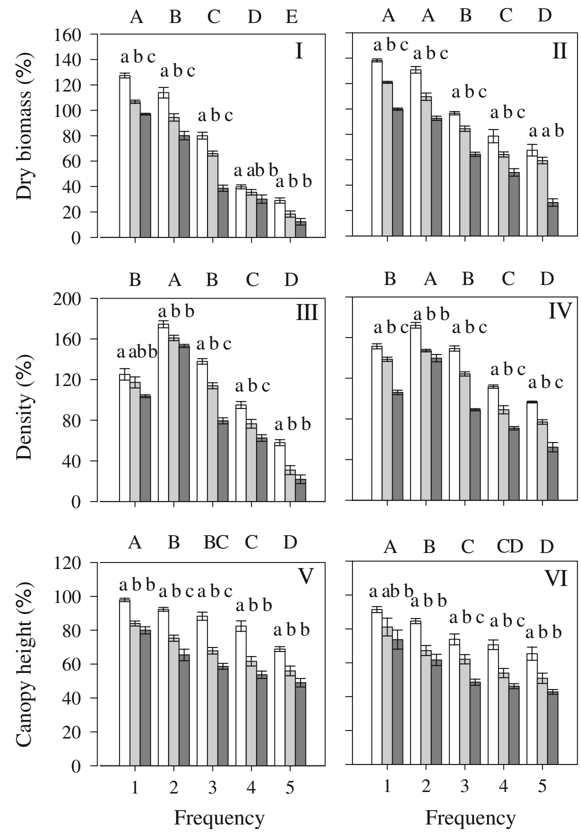


**Fig. 3** Effects of clipping frequency, clipping timing, and tidal zone on the control efficiency of *Spartina alterniflora* in 2007. The definitions of the *symbols* are the same as in Fig. 2

not significantly affected by canopy shading. Meanwhile, because the absolute canopy height of clipped *Spartina* was lower in low marsh (the height of control plants in low and high marshes were 40.3 ± 0.4 cm and 50.6 ± 3.9 cm, respectively; and that of clipped plants in low and high marshes were 29.0 ± 1.4 cm and 32.3 ± 1.9 cm, respectively), it presented higher $P_T/P_C$ ratio.

That the methods for controlling invasive plants are affected by habitat properties is worthy of notice (Hulme 2006). In general, invasive plants can be distributed in highly heterogeneous habitats because they have great stress tolerance and strong resistance to disturbance. Habitat heterogeneity, including the heterogeneity among the communities in the same ecosystem (Grevstad 2005), and among different natural ecosystem types (Pan et al. 2007), is an important factor affecting the control efficiency in the practice of ecological management (Hacker et al. 2001; Pan et al. 2007). Thus, in order to reduce the costs and enhance control efficiency, management strategies should be optimized according to habitat properties or types.

Optimal solution to control practice

According to our experiment, three-time clipping started at florescence in low marsh and four-time clipping started at florescence in high marsh were proper for *Spartina* control. With such clipping treatments, both in high and low marshes, above-ground parts were almost eliminated and sexual reproduction was completely inhibited (Fig. 2 I, II, VII, IX). Moreover, the density and canopy height were effectively reduced by the control treatment in the first year (Fig. 2 III–VI). The data on above-ground biomass and canopy height of clipped *Spartina* in the second year suggest that blindly increasing the clipping frequency might be unnecessary (Fig. 3 I–IV). It should be noted that these treatments need to be applied for at least two growing seasons to assure inhibition of population recruitment and plant vegetative growth. This is much more economical than the documented strategy elsewhere, which needs clipping 5–6 times a year and lasts for 3–4 years in the whole area (http://www.wapms.org/plants/spartina.html).

In conclusion, MFD of invasive plant control can not be found if only the treatment (e.g., clipping) frequency is considered. The clipping timing has significant effects on MFD; and the control efficiency is habitat-dependent. Our results suggest that an effective management strategy can be approached if clipping frequency and timing that determine the control efficiency are studied simultaneously with reference to habitat properties.

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