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Vegetation restoration of secondary bare saline-alkali patches in the Songnen plain, China

S.-C. Jiang, N.-P. He, L. Wu & D.-W. Zhou

Abstract

Questions: What factors limit vegetation restoration of secondary bare saline-alkaline patches (BSAP) in the Songnen grassland of northeast China? Is there any adaptive approach to promote revegetation in the shortest time possible and at a low cost?
Location: Northeast China.
Methods: Considering the climate, soil saline-alkalization and available seed sources, a new approach was adopted to restore vegetation in BSAP, which were formed by the degradation of typical *Leymus chinensis* grasslands owing to long-term overgrazing. The experimental treatments included no treatment (CK), fencing (F), fencing+inserting cornstalks (FS), fencing+inserting cornstalks+sowing *L. chinensis* (FSL) and fencing+inserting cornstalks+sowing *Puccinellia chinampoensis* (FSP). The assumptions behind inserting cornstalks were not only that they would create safe sites for initial revegetation but also that they would enhance seed input by trapping and containing the seeds from seed movement on the BSAP surface.
Results: Seed bank shortage was an important factor limiting initial revegetation in BSAP; seed movement on the BSAP surface could provide the necessary seed source if it were contained by effective measures. Vegetation at the sites FS, FSL and FSP was restored well in terms of the above-ground biomass and coverage. Inserted cornstalks acted as safe sites that enhanced the plant survival rate in BSAP; they also enhanced the ability to contain seed movement, thus providing a seed source for initial revegetation. Along with initial revegetation, tussocks around cornstalks can provide better safe sites, which in turn can accelerate subsequent vegetation restoration in BSAP.
Conclusions: The approach entails the strategic use of diverse seed sources and the construction of safe sites with agricultural byproducts (cornstalks); therefore, it is a low-cost method and can be used on a widespread scale. The results provide vigorous support in favor of vegetation restoration in BSAP and severely degraded grasslands in the region. In practice, this approach can be used in degraded ecosystems with compacted soil surfaces (including arid and salt-affected soils) to promote revegetation in various regions.

Keywords: Grassland; Restoration; Safe site; Saline-alkaline patches; Seed bank; Seed movement.

Abbreviations: BSAP = bare saline–alkaline patches; CK = control; F = fencing; FS = fencing+inserting cornstalks; FSL = fencing+inserting cornstalks+sowing *L. chinensis*; FSP = fencing+inserting cornstalks+sowing *P. chinampoensis*.

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Introduction

The Songnen plain, which is dominated by perennial *Leymus chinensis* Tzvel. Grasslands, is one of the most important grazing and mowing pastures in China. However, the *L. chinensis* grasslands have degraded as a result of overgrazing and reclamation owing to population pressures, which have increased since the late 1970s (Zheng & Li 1999). Currently, secondary bare saline-alkaline patches (BSAP), which have been formed as a result of degradation of typical *L. chinensis* grasslands owing to long-term overgrazing or reclamation, are common in the Songnen plain (Zheng & Li 1999). The alkalization of surface soil worsens plant growing conditions in BSAP (Zheng & Li 1990; Gao et al. 1996; Wu & Li 2003). The real challenge for ecologists and managers is determining ways to restore the above-ground vegetation of BSAP in the shortest time possible, and at a low cost.

Understanding the important factors that limit ecological restoration is essential; in particular, the way in which these factors change during the restoration process must be known (Ruiz & Aide 2005;

Hobbs 2007). To some extent, ecological restoration depends on the availability of seeds that are naturally dispersed at a site (Standish et al. 2007; Wolters et al. 2008). One of the key components is the seed bank, which plays a very important role in linking the past, present and future of the community structure and dynamics (Martin & Wilsey 2006; Ghorbani et al. 2007). In some extremely deteriorated habitats, such as secondary bare patches and deserts, soil seed banks are important factors for initial revegetation, because they usually exist in small numbers or are lost owing to surface soil destruction in these habitats (Snyman 2003; Cummings et al. 2005). Moreover, seeds moving laterally across the soil surface (i.e. seed movement) can help provide a seed source for initial revegetation (Aguiar & Sala 1997; Chambers 2000). Thus, how seed banks can be added and how seed movement can be contained are important issues in promoting vegetation restoration.

A safe site is a useful concept not only for examining the regeneration potential of many plant species (Harper et al. 1961; Dalling & Hubbell 2002) but also for promoting the vegetation restoration of degraded ecosystems (Elmarsdottir et al. 2003). The characteristics of safe sites that enable some species to grow and survive in extremely deteriorated habitats are often most critical in the early stages of germination and seedling establishment (Visser et al. 2004). Therefore, while planning initial revegetation and ecological restoration, it is important to determine how safe sites can be successfully constructed in BSAP. Vegetation restoration in BSAP by natural succession is a very slow process because of high pH and saline-alkali stress, both of which restrict plant growth and survival; therefore, effective restoration technologies need to be applied to promote and accelerate restoration of vegetation (Li & Zheng 1997; Zheng & Li 1999). Some important and well-accepted hypotheses have been put forward: (1) the availability of a seed bank is an important factor limiting revegetation in BSAP, but seed movement would help provide an important seed source if contained; (2) safe sites facilitate initial revegetation and subsequent vegetation restoration in BSAP; and (3) initial revegetation helps improve soil conditions and further enhance available seed sources, which in turn accelerate subsequent restoration.

In this study, experimental evidence is provided for the nature of restoration constraints in BSAP and a strategy is suggested for restoration of vegetation on the basis of improved understanding of these constraints. The main aims of the present study are (1) to determine the main constraints for revegetation of BSAP and (2) to propose an approach based on constructing safe sites, retaining seed movement, and sowing formerly dominant species to restore vegetation in BSAP quickly and at low cost.

Materials and Methods

Site description

Our study was carried out in the Songnen plain in Jilin Province, China (44°40′N, 123°44′E). The plain has an average altitude of 160 m (Fig. 1). The climate in this region is warm and humid in summer but cold and dry in winter, with a mean temperature of 23°C in July and -20°C in January. The mean annual precipitation (1980-2007) is 410 mm, with $>80\%$ of the precipitation occurring between July and September, inclusive. The monthly temperature and precipitation from 2002 to 2007 are shown in Fig. 2. The soil type is meadow solonchaks (comparable to Solonhaks in the FAO/UNESCO taxonomy). The soil in the 0-10 cm soil layer is dominated by sand (particle size, 53-2000 μm, 77.37%), then silt (2-53 μm, 18.08%), and finally clay (<2 μm, 4.5%). The main vegetation type is meadow steppe dominated by *L. chinensis* Tzvel., *Puccinellia chinampoensis* Ohwi, and *Phragmites communis* Trin.; the subdominant species are *Chloris virgata* Swartz. and *Suaeda corniculata* Bunge (Zheng & Li 1999).

The Songnen plain is largely a basin surrounded by mountains, and it thus has very poor drainage. The accumulation of solutes induces a primary soil alkalization process, with Na_2CO_3 and $NaHCO_3$ being the major sources for soil alkalization. Soil alkali is the major ecological gradient and the main limiting factor for vegetation development in the area (Gao et al. 1996). A well-accepted hypothesis is that the provision of better surface vegetation would improve the soil physical characteristics by increasing the number of non-capillary pores in the surface soil, where plant roots reside (Li & Zheng 1997; Zheng & Li 1999). The greater the downward flux created by non-capillary pores, the greater is the downward flux of alkaline elements, namely sodium (Na^+). This process would lead to surface soil dealkalization and further improve plant growth conditions. However, overgrazing or reclamations, both of which have previously deteriorated surface soil and vegetation, results in fewer non-capillary pores in the surface soil. Consequently, the upward water flux induced by evapotranspiration may exceed the downward water flux; this may transport alkaline solutes to the surface soil from the deep soil layer. The primary surface soil in BSAP has been

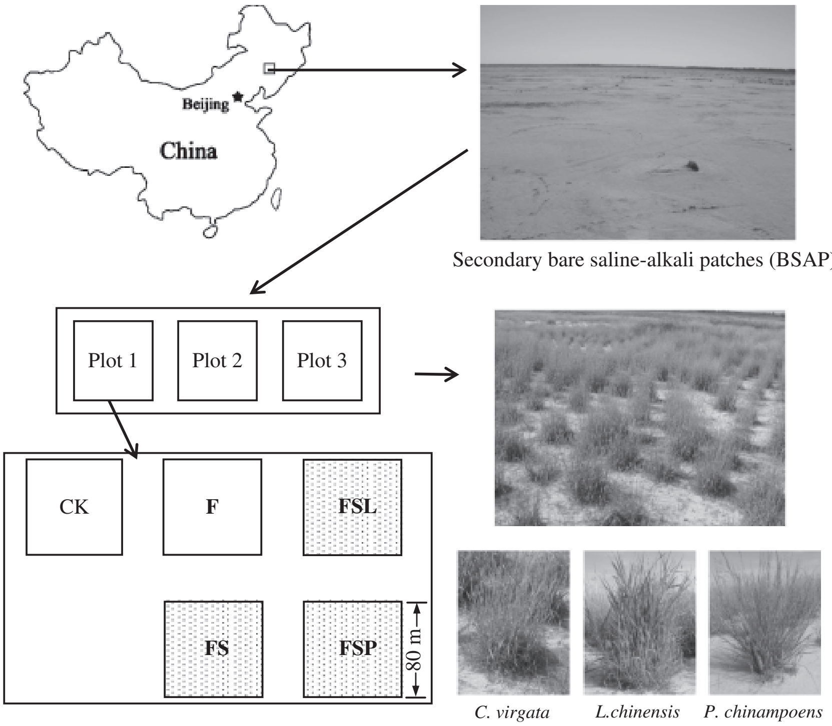

Fig. 1. Experimental site and design. CK, control; F, fencing; FS, fencing+inserting cornstalks; FSL, fencing+inserting cornstalks+sowing *L. chinensis*; FSP, fencing+inserting cornstalks+sowing *P. chinampoensis*.

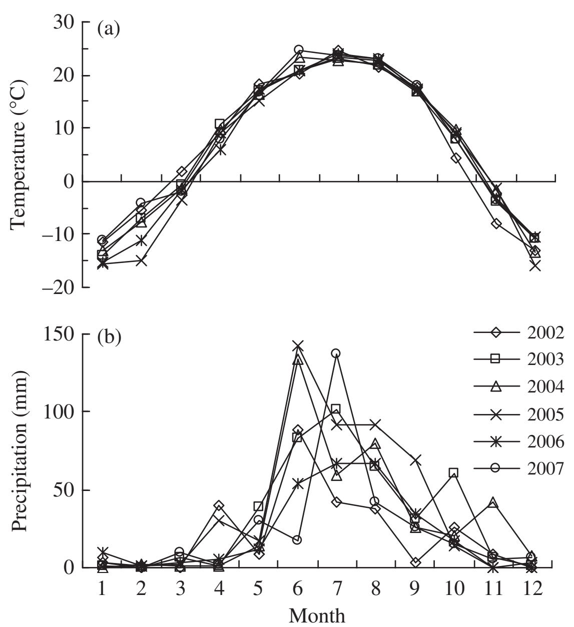

Fig. 2. Changes in monthly mean temperature (a) and precipitation (b) from 2002 to 2007.

destroyed owing to a loss of vegetation and the break-up of soil aggregates by wind erosion; more alkaline solutes have been brought to the surface soil from the deep soil layer, resulting in severe saline-alkalinization, and, as a result, the soil pH can be as high as 10 in spring. Most plant species, except for *C. virgata* and *S. corniculata*, cannot grow naturally and survive under BSAP conditions; moreover, the process of revegetation in BSAP is very slow under natural conditions (Li & Zheng 1997).

Assessment of seed banks and seed movement

Three BSAP, each with an area of approximately 500 m^2 and surrounded by a severe saline-alkaline grassland, were selected to assess seed banks and seed movement in early April 2001. A total of 30 pitfall traps were set up in each BSAP to assess seed movement over the soil surface; these traps were 6 cm×6 cm and 15 cm deep with small holes at the bottom for water drainage. The sampling of seed movement was conducted monthly from May to October 2001, and these traps were then replaced. Simultaneously, six soil cores (10 cm diameter, 10 cm deep) were sampled at 5-m intervals to survey the seed bank in each BSAP. Moreover, we investigated the seed bank of typical grasslands around the BSAP by sampling six soil cores (10 cm in diameter and 10 cm deep) in late August 2001. In the laboratory, the samples of seed banks and seed movement were first washed through a nested sieve

(0.2 mm diameter) to remove sediments and soluble material. The seeds were then identified under a magnifying glass by comparison with seed specimens gathered by Yang & Zhu (1995). Finally, seed banks (seed m^{-2}) and seed movement (seed $\cdot$ m^{-2} $\cdot$ d^{-1}) were calculated on the basis of the assessment data by converting these values for standard area (m^2).

Experimental set-up for revegetation in BSAP

The selected BSAP had a total area of approximately 600 ha; they were formed by the degradation of typical grasslands by long-term overgrazing (Fig. 1). The experiment was conducted in late April 2002. First, three 8 ha BSAP with flat topography were selected and designated Plot 1, Plot 2 and Plot 3. Five experimental treatments were performed in each plot, including no treatment (CK), fencing (F), fencing+inserting cornstalks (FS), fencing+inserting cornstalks+sowing *L. chinensis* (FSL), and fencing+inserting cornstalks+sowing *P. chinampoensis* (FSP) (see the Supporting Information, Appendix S1). The area for each treatment was 80 m×80 m.

Site F was fenced to preclude disturbances by large animals. At site FS, cornstalks were inserted as follows. Shallow pits (10 cm deep and 15 cm diameter) were dug into the soil manually with a shovel, cornstalks (30 cm long) were inserted aslant into these pits and the soil was replaced. The density of the cornstalks was 6.25 individuals m^{-2} (40 cm rows and columns). We assumed that inserting cornstalks could trap some moving seeds and provide safe sites for them to survive in the BSAP. Because of the limited seed availability, we sowed *L. chinensis* (20 kg ha^{-1}) in FSL and *P. chinampoensis* (10 kg ha^{-1}) in FSP with cornstalks inserted (Appendix S1).

Assessment of revegetation

Vegetation was assessed in late August 2002, 2003, 2004 and 2007. Three 10 m×10 m sampling plots were established at each experimental site in order to measure above-ground biomass, species composition and coverage. Above-ground biomass (g m^{-2}) was clipped at ground level in four replicated 2 m×2 m quadrants in each sampling plot and oven-dried at 65°C to constant weight. Coverage (%) was visually estimated. Simultaneously, we randomly assessed 100 cornstalks that had been inserted in order to measure the frequency of successful revegetation (%) and species composition in each sampling plot. More specifically, above-ground biomass and species composition at sites CK and F were repeatedly measured in the four quadrants (2 m×2 m) of each sampling site.

Assessment of seed productivity

Seed productivity was assessed on the basis of tussocks that had revegetated around the inserted cornstalks. We randomly selected 30 tussocks and measured their seed productivity for each species in each sampling plot in 2002, 2003 and 2004. This was done in late June for *P. chinampoensis*, in late July for *L. chinensis* and in late August for *C. virgata*. However, seed productivity was not investigated at sites CK and F because plant species at these sites could not yield mature seeds (as determined by visual inspection).

Analysis and statistics

All data sets were explored statistically to test whether there were normal distributions and homogeneity of variance for each collective using the Kolmogoroff-Smirnoff test and the Levené test. The results showed that data of seed banks, seed movement, above-ground biomass and coverage had neither normal distribution nor homogeneity of variance. Therefore, the nonparametric Kruskal-Wallis test was selected to analyse them, while the χ^2 index in the nonparametric Kruskal-Wallis test was used to identify whether these tested data were similar. As a *post-hoc* test, a Mann-Whitney *U*-test with the Shaffer correction was conducted to compare all possible combinations. However, the seed productivity data from sites FS, FSL and FSP were tested through repeated-measure ANOVA. All statistical analyses were performed using the SPSS program, version 13 for Windows (SPSS Inc., Chicago, IL, USA).

Results

Seed banks and seed movement

The seed banks of BSAP differed significantly among the months ($\chi^2 = 61.99$, $df = 5$, $P < 0.01$) (Fig. 3a). *C. virgata* was predominant, and most seed banks were distributed at the soil surface (as determined by visual inspection). A good *L. chinensis* grassland in the vicinity showed 2083.4 ± 874.4 seeds m^{-2}, which was significantly higher than the value for BSAP. Seed movement in BSAP was abundant (Fig. 3b) and significantly differed among months ($\chi^2 = 425.10$, $df = 5$, $P < 0.01$). Seed movement was 33.1 ± 9.6 and 18.1 ±

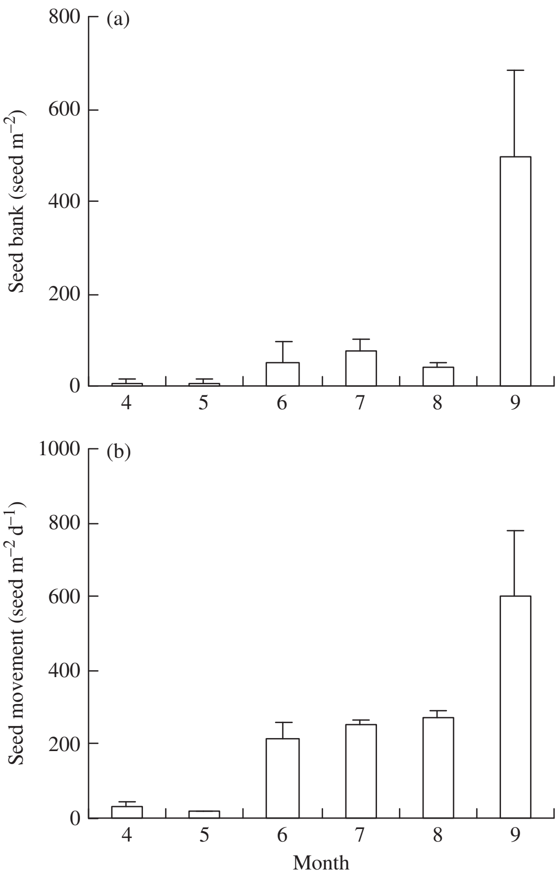

Fig. 3. Dynamics of soil seed bank (a) and seed movement (b) in bare saline-alkaline patches (BSAP). Data are mean $\pm$ 1 SD ($n = 3$). They were significantly different among various months ($\chi^2 = 61.99$, $df = 5$, $P < 0.01$ for seed bank; $\chi^2 = 425.10$, $df = 5$, $P < 0.01$ for seed movement).

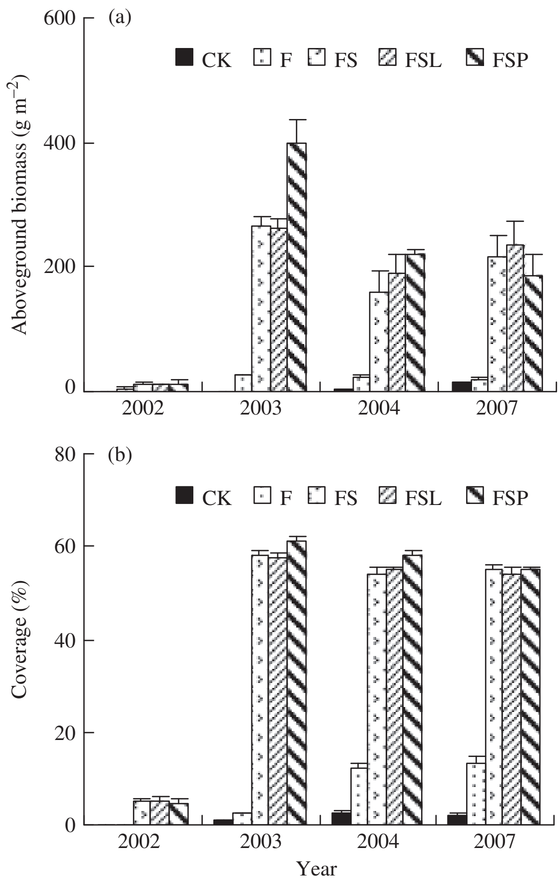

Fig. 4. Changes in aboveground biomass (a) and coverage (b) from 2002 to 2007. CK, control; F, fencing; FS, fencing+inserting cornstalks; FSL, fencing+inserting cornstalks+sowing *L. chinensis*; FSP, fencing+inserting cornstalks+sowing *P. chinampoensis*. Data are mean $\pm$ 1 SD ($n = 3$). Above-ground biomass and coverage increased significantly at early-stage restoration in sites FS, FSL and FSP (Kruskal-Wallis test, all $P < 0.01$).

3.3 seeds $m^{-2} d^{-1}$ in April and May, respectively, both of which are good periods for seed germination in the region. Furthermore, saline-tolerant pioneer plants (i.e., *C. virgata* and *S. corniculata*) accounted for 98.2% of the total seed movement.

Restoration of vegetation

The success rates of revegetation around the inserted cornstalks were 29.8%, 28.9% and 64.8% in 2002 for sites FS, FSL and FSP, respectively, and they exceeded 90% after 2003 (Appendix S2). The dominant species in revegetation were *C. virgata*, *L. chinensis* and *P. chinampoensis*; it should be noted that *L. chinensis* and *P. chinampoensis* were sown, and the seeds of *C. virgata* were made available by containing seed movement. Other pioneer species, such as *Kochia sieversiana* Pall, *S. corniculata*, and *Phragmites australis* Trin., were present at sites FS, FSL and FSP. The changes in the vegetation at sites CK and F from 2002 to 2007 were subtle and the only plant species in those sites was *C. virgata*.

Above-ground biomass increased significantly during early-stage restoration in sites FS, FSL and FSP (Kruskal-Wallis test, $P < 0.01$ for every site) (Fig. 4a), and the values for those sites were significantly higher than the values for sites CK and F (Mann-Whitney U-test, $P < 0.01$ for all comparisons). The above-ground biomass of *L. chinensis* at site FSL increased significantly as restoration progressed ($\chi^2 = 97.79$, $df = 3$, $P < 0.01$). However, the above-ground biomass of *P. chinampoensis* at site FSP increased considerably in 2003 and then significantly decreased with time ($\chi^2 = 95.97$, $df = 3$, $P < 0.01$; Fig. 5). Furthermore, vegetation cover at sites FS, FSL and FSP was significantly greater (Fig. 4b) than that at sites CK and F, and it

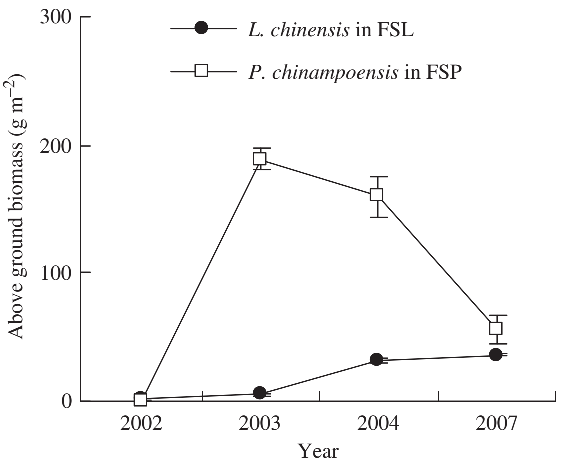

Fig. 5. Changes in aboveground biomass of *L. chinensis* in FSL (fencing+inserting cornstalks+sowing *L. chinensis*) and *P. chinampoensis* in FSP (fencing+inserting cornstalks+sowing *P. chinampoensis*) from 2002 to 2007. Data are mean ± 1 SD ($n = 3$). They were significantly different with the duration of restoration ($\chi^2 = 97.79$, $df = 3$, $P < 0.01$ for *L. chinensis*; $\chi^2 = 95.97$, $df = 3$, $P < 0.01$ for *P. chinampoensis*).

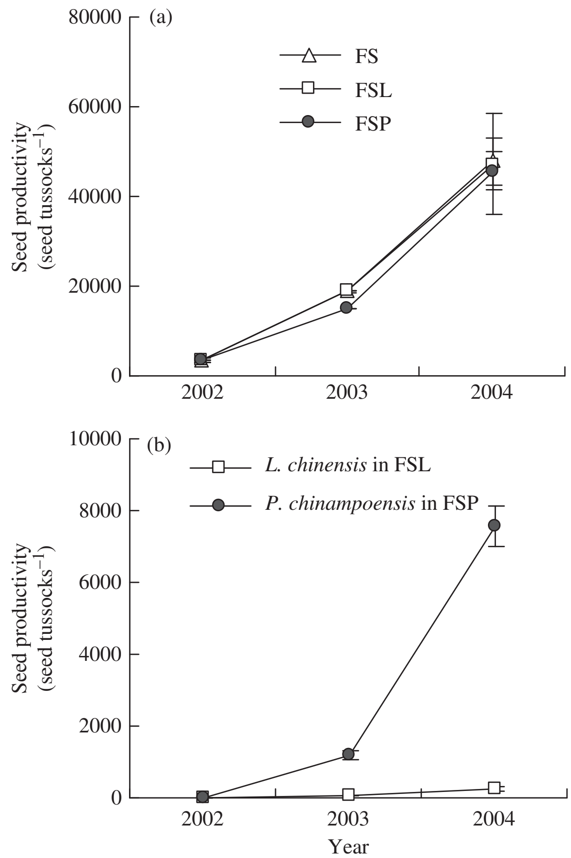

Fig. 6. Total seed productivity (a) and perennial seed productivity (b) from 2002 to 2004. Data are mean ± 1 SD ($n = 3$). Total seed productivity at sites FS (fencing+inserting cornstalks), FSL (fencing+inserting cornstalks+sowing *L. chinensis*) and FSP (fencing+inserting cornstalks+sowing *P. chinampoensis*) (a) and perennial seed productivity at sites FSL and FSP (b) increased significantly with time (repeated-measure ANOVA, all $P < 0.01$).

increased significantly as restoration progressed (Mann-Whitney *U*-test, $P < 0.01$ for all comparisons). Coverage was not significantly different among sites FS, FSL and FSP in any of the years.

Seed productivity

Along with high above-ground biomass, seed productivity was abundant and dominated by the seeds of *C. Virgata* at sites FS, FSL and FSP (Fig. 6a). Total seed productivity increased significantly with time at sites FS, FSL and FSP (repeated-measure ANOVA, $P < 0.01$), but there were no apparent differences among the treatments. The seed productivity of *L. chinensis* in FSL and *P. chinampoensis* in FSP increased significantly as restoration progressed ($P < 0.01$ for both), as they each provided necessary seed sources of perennial species for subsequent vegetation restoration and succession (Fig. 6b).

Discussion

The shortage of seed banks is an important limitation for the restoration of vegetation in BSAP, and seed movement could help provide an important seed source if it were contained by taking some effective measures. In BSAP, seed movement was abundant and dominated by seeds of pioneering species, although the seed banks were negligible. Several factors may explain why seed banks were so few in number and difficult to add naturally: (1) loss of intrinsic seed bank with soil loss; (2) rapid germination and high mortality of seedlings; (3) post-dispersal seed loss via wind and water; and (4) low addition of seed banks owing to the low retentive capacity related to seed movement. In the early stages of the restoration of vegetation, seed availability and environmental stress are the most critical constraints (Aguiar & Sala 1997; Hyatt & Casper 2000; Wolters et al. 2008). When *C. virgata* and *S. corniculata* were sown in BSAP, they grew successfully, survived and reproduced despite their relatively low survival rates (He et al. 2004). We therefore believe that a shortage of seed banks and high salt stress, rather than temperature and precipitation, are the main constraints for restoration of vegetation in the BSAP of the Songnen plain.

By inserting cornstalks, an adaptive approach was developed to undertake revegetation in BSAP, which considered the climate, soil saline-alkalization, and available seed sources, as well as the concept of creating safe sites (Appendix S3). Here, by inserting cornstalks in BSAP, seeds from seed movement can be trapped, and the inserted cornstalks can provide safe sites for initial revegetation. It was also found that sowing perennial seeds not only enhanced the seed source but also accelerated subsequent vegetation succession to native perennial grassland. Some researchers have pointed out that protective microsites or safe sites are very important for the germination and growth of seeds, especially in some severely degraded habitats (Harper et al. 1961; Dalling & Hubbell 2002; Elmarsdottir et al. 2003). The insertion of cornstalks could help provide safe sites for sown *C. virgata* and *S. corniculata* and could significantly enhance their survival rate in BSAP (He et al. 2004).

Along with the initial revegetation, the tussocks established around the inserted cornstalks enhanced seed sources by promoting seed productivity and by further trapping seeds during seed movement, provided better safe sites, all of which accelerated the subsequent restoration of vegetation. Above-ground biomass in sites FS, FSL and FSP increased to $180\,\mathrm{g\,m^{-2}}$ after a 3-year restoration period, accounting for 60-70% of the above-ground biomass in the good *L. chinensis* grassland in the vicinity. However, the species composition of the revegetation in BSAP differed significantly from that of the native *L. chinensis* grassland. In general, there are 10-15 plant species in a $1\,\mathrm{m} \times 1\,\mathrm{m}$ quadrant, and the biomass of a perennial species accounts for 60-80% of the total biomass in the native *L. chinensis* grassland (Li & Zheng 1997). The time required to restore BSAP to a good grassland could be longer than that required for native *L. chinensis* grasslands, if the integrity of species composition and biological interaction (rather than biomass and coverage) are considered.

It is important that perennial species (i.e. *L. chinensis* and *P. chinampoensis*) successfully regenerate by seed productivity at sites FSL and FSP, thus providing abundant seed sources for further restoration and succession, so that perennial grasslands can ultimately be rebuilt (Pywell et al. 2003; Ruiz & Aide 2005). *P. chinampoensis* was well established by sowing, but gradually decreased after 2004 because it self-degraded or aged with the increase in the duration of seedling establishment (Guo et al. 1998). *L. chinensis* was established very poorly (< 5%) because its seeds have a very low germination rate under natural conditions (Liu et al. 2002). However, once established, *L. chinensis* could rapidly increase in population via the asexual reproduction of rhizomes (Yang & Zhang 2006).

Certain methods, such as setting up a litter layer, making a gypsum amendment, adding sand bedding, sowing *L. chinensis* and transplanting *L. chinensis* have, to some extent, resulted in successful revegetation in severely degraded grasslands in the Songnen plain (Li & Zheng 1997; Guo et al. 1998). However, few of these approaches can be applied on a widespread scale because of their inherently high costs in restoring and maintaining vegetation. The cost of revegetating BSAP by inserting cornstalks and sowing adaptive plant species is very low because cornstalks are agricultural by-products that are very inexpensive and are found in great abundance in the region. However, our methods require a longer period in restoring the species composition of the plant community, because we assume that by providing better, safer sites the initial revegetation accelerates subsequent succession in vegetation. Sowing diverse plant species in subsequent revegetation would be necessary to accelerate succession, because it is essential to develop a species-rich perennial *L. chinensis* grassland to evaluate whether our restoration was successful (Li & Zheng 1997; Ruiz & Aide 2005; Hobbs 2007).

Above-ground vegetation in BSAP was well restored by using the adaptive approach, which considers climate, available seed sources (i.e. seed banks, seed movement and adaptive perennial species) and safe sites (i.e. inserted cornstalks). The results showed that (1) the shortage of seed banks is an important factor that limits revegetation in BSAP, but that seed movement could help provide an important seed source if contained; (2) suitable safe sites (i.e. inserted cornstalks) facilitate initial revegetation; and (3) initial revegetation would help provide better, safer sites that facilitate subsequent restoration of vegetation and succession. Compared with other restoration methods employed in the region, the merits of the proposed approach are: (1) using diverse seed sources and constructing safe sites by using agricultural by-products make this approach unique and optimal for widespread use and (2) the cost is low, which makes its widespread use possible. Our method is practical, and it should be especially useful in revegetating severely degraded ecosystems with a compacted soil surface, including arid, salt-affected soils in other regions.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Experimental treatment for the vegetation restoration of bare saline-alkaline patches (BSAP).
Appendix S2. Changes in species frequency (%) in 2002, 2003, and 2007.

Appendix S3. General framework and hypothesis to restore the vegetation of bare saline-alkaline patches (BSAP) in the Songnen plain of China.

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