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Restoration of *Stipa kryloviisteppes* in Inner Mongolia of China: Assesment of seed banks and vegetation composition

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Abstract

The landscapes of Inner Mongolia are widely known for the vast *Stipa krylovii* steppes. However, overgrazing and other improper land uses have extensively degraded the *Stipa krylovii* steppe ecosystem in recent decades. Knowledge about the soil seed banks and the remaining vegetation in these damaged ecosystems is crucial for guiding the restoration efforts. Using a germination method, this study examined the size, composition, and species richness of the soil seed banks in three field types: overgrazed steppe, enclosed steppe and abandoned crop field. The abandoned crop field had the largest soil seed bank with mostly annual and weedy plant species. Seeds of desirable perennial grass species were impoverished by the intensive cultivation in the abandoned crop field. The lack of desirable perennial species in the abandoned field was a critical limiting factor for restoration. Grazing decreased the size of the seed bank in the overgrazed steppe. But seeds of desirable grassland species were present in both the overgrazed and the enclosed steppes. As indicated by the Sorenson's indices of community similarity (50–67%), plant species abundance and composition in the soil seed banks were closely related to the corresponding vegetation for each of the three sites.

Keywords: Agro-pastoral ecotone; Degraded steppe; Restoration; Similarity

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1. Introduction

Arid and semi-arid ecosystems occupy up to 30% of the global terrestrial area, and provide substantial support and ecosystem services to human societies (World Resources Institute, 1990). However, as a consequence of global environmental change and human utilization, a large portion of these ecosystems is either severely altered or on the verge of desertification (Schlesinger et al., 1990). Recovery or restoration of these impacted ecosystems is an important and challenging task for both concerned scientists and world society at large. This task is particularly daunting in north-western part of China where overgrazing, expansion of crop cultivation, and hasty development, combined with possible climate change, have resulted in a fast decline of the original ecosystems, severe soil erosion, and more frequent sandstorms.

The focal area of this study is in the eastern part of the Inner Mongolian grassland–cropland eco-tone which covers a total area of about 800,000 km^2 in the semi-arid region of northern China. The landscape consists mainly of steppe, woodlands and croplands. Typical steppe dominated by *Stipa krylovii*, a perennial bunch grass species, has been the major vegetation type in the region (Liu and Liu, 1994). Because of over-grazing and indiscriminate cultivation in past decades, about 60% of the land area in this region has become severely degraded (Yang et al., 2004). Hoping for natural recovery from the degradation, Chinese government has recently decided to ban grazing and cultivation on most of the degraded land. But it is largely unknown if the hoped natural recovery will occur at an acceptable speed. Active ecological restoration may be required to accelerate the recovery process. However, most past ecological restoration studies in China have focused on degraded forests (Li, 2004) or sandy woodlands (Zhang et al., 2004; Su et al., 2005). Little work has been done to restore the degraded steppe and abandoned field in northern China (Liu et al., 2002).

Identifying critical constraints is often the first step in ecological restoration of degraded ecosystems. High levels of atmospheric nutrient deposition, impoverished seed banks, and limited dispersal range have been identified as key constraints in the restoration of ecological diversity in European grasslands (Bakker and Berendse, 1999). Studies have often indicated that the lack of desirable seeds is the key limiting factor when cultivated land is restored back to its original grassland with diverse plant communities (Pywell et al., 2002; Walker et al., 2004). Soil seed banks are important components of vegetation dynamics affecting both ecosystem resistance and resilience (Pugnaire and Lázaro, 2000). Knowledge about seed banks is essential for achieving a thorough understanding of vegetation dynamics (Tracy and Sanderson, 2000). Persistence of seeds in the soil has very important implications for restoration and conservation of plant species and communities (Akinola et al., 1998; Coulson et al., 2001; Pywell et al., 2002; Alexander and Schrag, 2003; Riley et al., 2004). Soil seed banks act as an important seed source in a community undergoing restoration management (Kalamees and Zobel, 1998). If a land manager wishes to promote recruitment of desirable species from existing seed banks, the first crucial step is to determine the composition of the soil seed banks (Tracy and Sanderson, 2000).

Livestock grazing can reduce seed production either by reducing leaf area and the allocation of photosynthate to reproductive organs or by the direct removal of flowers and seeds (Sternberg et al., 2003). Grazed sites usually show a decrease in density and species number in the seed bank as compared to un-grazed sites (O'Connor and Pickett, 1992;

Jutila, 1998; Mayor et al., 2003). Under heavy grazing, impoverished seed banks may become a limiting factor for recovery or persistence of the palatable vegetation (O'Connor and Pickett, 1992; Sternberg et al., 2003). Agriculture has been shown to impoverish the seed banks of grassland species that are poorly adapted to frequent disturbance associated with intensive cultivation (Bekker et al., 1997). Annual and weedy plant species can replace grassland species in the seed bank of ex-arable land (Hutchings and Booth, 1996; Bekker et al., 1997).

In order to assess the restoration potential of degraded steppe either due to overgrazing or crop cultivation, this study examined the size, composition and species richness of the soil seed banks in three field types: (1) a continuously grazed *Stipa krylovii* steppe; (2) an enclosed *Stipa krylovii* steppe that has not been grazed for the past 3 years; and (3) a nearby old crop field that was abandoned 3 years ago. We also determined the species composition and abundance of the above-ground vegetation in these fields. Our working hypotheses were: (I) impoverished desirable seed banks in overgrazed and cultivated fields limit the restoration of the degraded *Stipa krylovii* steppe; (II) the stop of livestock grazing increases the density and species richness of the soil seed bank in the enclosed steppe as compared to the grazed steppe; and (III) the structure and species richness of the soil seed bank is closely related to the species composition of the current vegetation above-ground.

2. Materials and methods

2.1. Site description

The study site is located in the permanent experimental field of Duolun Restoration Ecology Research Station, Chinese Academy of Sciences, Duolun County of Xilingol League, Inner Mongolia (41°46′–42°36′N; 115°51′–116°54′E). The region is characterized with a temperate, semi-arid, and continental–monsoonal climate. The mean annual precipitation is 385.5 mm, approximately 67% of which falls during the period from June to August. The mean annual potential evaporation is 1748 mm. The mean annual temperature is 1.6 °C. The annual frost-free period is approximately 100 days (Bai et al., 2004).

The vegetation of *Stipa krylovii* steppe mainly consists of *Stipa krylovii*, *Artemisia sieversiana*, *Artemisia frigida*, *Agropyron cristatum*, *Allium bidentatum* and *Salsola collina*. Approximately two-thirds of the total land area in this region is covered by *Stipa krylovii* steppe, the rest one-third is cropland and abandoned field. The soil is a sandy, calcareous 'chestnut' soil, similar to a cambic Chernozem. Most of the steppe has been used for livestock grazing for centuries. The grazing intensity has increased substantially during the past decades. Livestock grazing has been stopped in the enclosed steppe since the year 2001. The old crop field was abandoned in 2001, wheat and oats were the main crops before 2001. Three sites, each representing a land use pattern (i.e. abandoned field, grazed steppe and enclosed steppe.), were chosen for sampling and field investigation.

2.2. Seed bank sampling

Soil seed bank sampling was performed at the end of March, 2004, just prior to natural germination of seeds. Four $20 \times 20\,m^2$-plots were chosen at each of the three field types.

Sixteen soil cores (6 cm in diameter) were sampled randomly to a depth of 5 cm from each plot.

Seed banks were determined using a germination method, which is a commonly used and convenient approach for the field survey of soil seed banks (Pugnaire and Lázaro 2000). After removing gravels, litter and roots, the soil sample from each soil core was spread to form a thin layer (about 2 cm) over a thick layer of seed-free sand in a nursery pot. Three other pots filled with only seed-free sand were used as controls to monitor the occurrence of airborne seeds. The sand used in the germination test was pre-baked for 4 h at 150 °C in the oven. All pots were randomly arranged in a glasshouse (temperature ranging between 12 and 22 °C) and allowed to germinate under natural light conditions. All pots were watered once or twice daily to keep the surface moist.

As seedlings emerged, they were identified and then removed from the pots, while those that could not be identified were further transplanted to other pots and kept growing until they could be identified. Soil in each pot was mixed once every 2 weeks to maximize possible germination. Germination trials lasted for approximately 4 months.

2.3. Vegetation survey

Vegetation was investigated twice by recording the species present in eight 0.5 m × 0.5 m-quadrats randomly located in each field types. The first survey was conducted on 30 May, 2004 when the steppe plants were still in vegetative growth, and the second was on 4 August when steppe plants were at their reproductive stage.

2.4. Statistical analysis

Differences between sites in the mean number of germinated seedlings in the soil seed bank were analysed using one-way ANOVA followed by Duncan's Multiple-Range Test.

Sorensen's coefficient of community (CC) was calculated to denote similarities between the soil seed bank and the corresponding vegetation in terms of plant species composition (Magurran 1988) as: $CC = 2B/(V+S)$, where B is the number of species common to both the seed bank and the vegetation, V and S represent the numbers of the species detected in the established vegetation and its corresponding soil seed bank, respectively (Tracy and Sanderson, 2000).

3. Results

3.1. Seed bank density

No seedlings were found in the control pots, indicating that there were no airborne seed contaminants. Altogether 3276 seedlings belonging to 34 species were germinated, which resulted in a calculated mean of 6035 seeds m^{-2}. The largest seed bank was found in the abandoned field, the smallest seed bank was found in the grazed steppe, and intermediate in the enclosed steppe (Table 1). Annual grasses only found in the soil seed bank of the abandoned field. Annual forbs dominated in the abandoned field soil seed bank. Perennial grasses occurred more in the soil seed bank of grazed steppe and enclosed steppe, and perennial forbs occurred more in the enclosed steppe soil seed bank.

Table 1
Mean number ± SD of germinated seedlings per m^{-2} in different sites

Mean number of seeds (m^{-2})	Annual grasses	Annual forbs	Perennial grasses	Perennial forbs	Total
Grazed steppe	0^a	11.1 ± 12.8^a	1840.2 ± 282.1^b	1812.6 ± 330.8^a	3663.9 ± 172.5^a
Enclosed steppe	0^a	0^a	1591.5 ± 525.3^b	3547.8 ± 903.2^b	5139.4 ± 645.8^b
Abandoned field	508.4 ± 97.2^b	6603.8 ± 1313.5^b	198.9 ± 65.1^a	1989.4 ± 733.4^a	9300.6 ± 1303.5^c

Different symbols indicate significant differences ($p < 0.05$), assessed by Duncan multiple-range test after one way ANOVA.

Table 2
Total and mean number ± SD of species in the soil seed bank

	Grazed steppe	Enclosed steppe	Abandoned field
Mean number of species per plot in seed bank			
Annual grasses	0^a	0^a	1.25 ± 0.50^b
Annual forbs	0.50 ± 0.58^a	0^a	7.25 ± 0.96^b
Perennial grasses	3.50 ± 1.00^b	4.50 ± 0.58^b	2.00 ± 0^a
Perennial forbs	5.25 ± 1.50^a	8.00 ± 0.82^b	4.50 ± 0.58^a
Total	9.25 ± 1.26^a	12.50 ± 0.58^b	15.00 ± 1.41^c
Total number of species in seed bank	13	16	23
Total number of species in vegetation	31	36	34
Number of species both in seed bank and vegetation	11	16	19
Sorenson's index	0.5000	0.6154	0.6667

Sorenson's index of species similarity comparing seed bank species and established vegetation in different sites. Different symbols indicate significant differences ($p < 0.05$), assessed by Duncan multiple-range test after one-way ANOVA.

3.2. Seed bank flora and resemblance with vegetation

The total number of species and the mean number of species per plot present in the soil seed bank at each site are shown in Table 2. The number of species was the largest in soil samples from the abandoned field, intermediate in the enclosed steppe, and the lowest in soils from the grazed steppe. Perennial forbs and perennial grasses dominated in the soil seed banks of both the enclosed steppe and the grazed steppe, while annual forbs and annual grasses were present almost exclusively in the abandoned field soil seed bank.

Comparisons of the species similarity between the seed bank and the vegetation for the three sites were made by employing Sorenson's index for community similarity. It can be seen from Table 2 that the species similarity indices between the soil seed bank and the established vegetation in the three sites ranged from 50% to about 67%.

3.3. Seed bank composition

Detailed data of this glasshouse germination test are given in Table 3. The dominated species in the soil seed bank of the abandoned field were *Artemisia sieversiana, Polygonum divaricatum* and *Chenopodium aristatum*, accounting for 68.1% of the total seedlings for the site, while in the grazed steppe and the enclosed steppe the most abundant species were

Table 3
Seed density of individual species in the seed bank

Species		Abandoned field		Grazed steppe		Enclosed steppe	Sum
Annual grasses							
Panicum miliaceum	+	2	+	0	+	0	2
Setaria viridis	+	90	+	0	+	0	90
Annual forbs							
Cannabis sativa	+	2	+	0	+	0	2
Polygonum aviculare	+	2	+	0	+	0	2
Fagopyrum sagittatum	+	25	+	0	+	0	25
Salsola collina	+	68	+	0	+	0	68
Chenopodium glaucum	+	84	+	2	+	0	86
Chenopodium aristatum	+	122	+	0	+	0	122
Fagopyrum tataricum	+	29	+	0	+	0	29
Thlaspi arvense	+	2	+	0	+	0	2
Lappula myosotis	+	1	+	0	+	0	1
Sphallerocarpus gracilis	+	16		0	+	0	16
Artemisia sieversiana	+	844		0	+	0	844
Perennial grasses							
Poa angustifolia	+	0		0	+	4	4
Stipa krylovii	+	9		180	+	154	343
Agropyron cristatum	+	17		9	+	53	79
Leymus chinensis	+	10		6		55	71
Cleistogenes squarrosa	+	0		138		22	160
Perennial forbs							
Artemisia scoparia	+	93		47		41	181
Polygonum divaricatum		180		0		0	180
Potentilla acaulis		0		55		111	166
Potentilla bifurca		49		23		1	73
Potentilla tanacetifolia		0		8		15	23
Melilotoides ruthenica		0		1		0	1
Astragalus galactites		34		1		7	42
Geranium wilfordii		1		0		0	1
Artemisia frigida		0		190		334	524
Artemisia argyi		2		0		0	2
Heteropappus altaicus		0		0		3	3
Carex korshinskyi		1		0		10	11
Allium bidentatum		0		0		106	106
Allium tenuissimum		0		0		3	3
Allium neriniflorum		0		0		11	11
Allium ramosum		0		3		0	3
Total		1683		663		930	3276

Expressed as the total number of germinated seedlings of the 16 soil samples in total for different sites. Plus mark denotes species which occurred also in the above-ground vegetation of the respective sites.

Artemisia frigida and *Stipa krylovii,* accounting for 55.8% and 52.5% of their respective totals.

The species composition in the soil seed bank of the abandoned field was different from that of both the grazed steppe and the enclosed steppe, only 7 of the 23 species in the soil

seed bank of the abandoned field were found in that of both the grazed steppe and the enclosed steppe. *Artemisia sieversiana, P. divaricatum* and *C. aristatum*, the dominated species in the soil seed bank of the abandoned field, were not found in grazed steppe and enclosed steppe. *Artemisia frigida* and *Stipa krylovii* were the dominated species in the seed bank of both grazed steppe and enclosed steppe, but no seeds of *Artemisia frigida* and only 9 seeds of *Stipa krylovii* were found in the soil seed bank of the abandoned field. The grazed steppe and the enclosed steppe were relatively similar in soil seed bank composition, 10 species occurred both in the soil seed bank of grazed steppe and that of enclosed steppe, and the dominated species were the same.

4. Discussion

In this study, the soil seed bank size of the *Stipa krylovii* steppe is of the same magnitude as that of a typical steppe in Horqin grasslands (Zhao and Bai, 2001) and that of a *Artemisia frigida* steppe in the Xilingol grasslands (Sudebilige et al., 2000). The species number recorded in our study is slightly larger than that found in the other two reports. However, species composition in the soil seed bank of the abandoned field is different from that of both the grazed steppe and the enclosed steppe. The seed banks of grassland species have been impoverished by agricultural intensification and tend to be replaced by annual and weedy species in the abandoned field, a result similar to the finding of Walker et al. (2004). The lack of seeds of desirable perennial grasses has usually been the key factor limiting for restoring diverse grassland communities from an abandoned field (Pywell et al., 2002). The introduction of desirable species by sowing seed (Coulson et al., 2001), cutting and grazing management (Coulson et al., 2001; Pywell et al., 2002; Walker et al., 2004) and some other techniques should be applied to overcome this biotic constraint in restoration of *Stipa krylovii* steppe from the abandoned field.

High proportions of annual forbs in both the soil seed bank and in the vegetation of the abandoned field suggest that it is still in the early stage of succession. The lack of seeds of desirable perennial grasses in the abandoned field may prevent the restoration of this land back to the original steppe. The impoverishment of desirable grassland species in the soil seed bank has not occurred in the overgrazed steppe. Therefore, we incline to partially accept our working hypothesis-I that the impoverished seed bank in the abandoned field limit the restoration of the degraded *Stipa krylovii* steppe.

Compared to the enclosed steppe, we can see the decrease in seed density in the soil seed bank in the grazed steppe. Based on this results we accept our working hypothesis-II: stop grazing in the enclosed field increases the overall density and species richness of the soil seed bank as compared to the grazed treatment. Similar results have been reported by other studies (Bertiller, 1992; Russi et al., 1992; McDonald et al., 1996). The seed bank of *Chenopodium glaucum* benefited from grazing. This is in agreement with the results from an earlier study (Kinucan and Smeins, 1992), in that grazing increased the proportion of annual forbs in the seed bank.

Artemisia frigida and *Stipa krylovii* were abundant, *Leymus chinensis* and some other desirable species were also presented in the soil seed banks of the grazed steppe and the enclosed steppe, indicating that restoration of this heavily grazed steppe is not seed-limited. Stop livestock grazing for 3 years increased the number of perennial forbs in the seed bank. After enclosing for 3 years, the vegetation in the enclosed steppe was obviously taller and richer in litter, which was in contrast to the thin and short vegetation in the

grazed steppe. Similar results are reported by other studies (Andresen et al., 1990; Jutila, 1997).

Unlike some previous studies, which reported striking differences between the soil seed bank and the corresponding vegetation (Douglas, 1965; Johnston et al., 1969; Rabinowitz, 1981; Hassan and West, 1986; Bertiller, 1992; Jutila, 1998), our results showed a relatively high similarity for each of the three sites. Our working hypothesis-III is generally accepted; the structure and species richness of the soil seed bank is closely related to the species composition of the current vegetation. This is consistent with the findings from an experiment on the grasslands of the North-east United States (Tracy and Sanderson, 2000) and from a study of a typical steppe in the Xilingol grasslands of the Inner Mongolian Plateau (Sudebilige et al., 2000). Cultivation and grazing might have caused this high degree of similarities (Henderson et al., 1988).

In similar studies on grasslands, the species composition of the corresponding above-ground vegetation was assessed only once at the time of the maximum plant diversity (O'Connor and Pickett, 1992; Pugnaire and Lázaro, 2000). As ephemeral plants accomplish their life histories in a very short time, they are often missed in a one-time only assessment, causing an under estimate of the actual species diversity. Therefore, it is necessary that vegetation assessment should be performed at least twice in the growing season.

In our study, more plant species were found in the above-ground vegetation than in the soil seed bank for both the enclosed steppe and the grazed steppe. This result indirectly suggested that asexual reproduction was a primary mean of reproduction in the two sites. If this is true for all steppe ecosystems, the preservation of perennial vegetation may play a more important role in grassland recovery than soil seed banks. This further implies that there might a threshold in remaining vegetative storage for natural recovery. Once the remaining vegetative storage for asexual reproduction drops below a certain threshold, natural recovery is severely hindered. Finding this threshold in remaining vegetative storage for reproduction should be an important task for future research.

The species composition and the dominant species in the soil seed bank in the grazed steppe are similar to that in the enclosed steppe. This result implies that it might be easier to restore the bunch grass steppe damaged by over grazing than to restore the abandoned field back to the native vegetation status by natural means. For the abandoned field, manipulated measures, e.g. reseeding desirable species, cutting and grazing management, etc, will be required to speed up the restoration after a long period of intensive cultivation in the agro-pastoral eco-tone of north China.

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