Can Shallow Plowing and Harrowing Facilitate Restoration of *Leymus chinensis* Grassland? Results From a 24-Year Monitoring Program

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Abstract

Long-term effects of two mechanical interventions, shallow plowing and harrowing, on degraded *Leymus chinensis* (Trin.) Tzvel. grassland were studied. Species composition and standing biomass of the grassland were monitored at peak biomass each year for 24 yr after application of these two measures, together with grassland in natural recovery and that under public grazing. Results showed a high resilience of degraded grassland, which recovered naturally after excluding grazing animals to a structure similar to the intact *L. chinensis* community. In comparison with natural recovery, harrowing facilitated restoration of *L. chinensis* population and community structure and improved grassland production. Shallow plowing accelerated recovery of *L. chinensis* population to a larger extent than harrowing and led to a flourish of annual species and improvement of herbage production in the years following its application. But the production improvement was unsustainable and was associated with a decrease in grassland species richness and community complexity. We conclude that the best measure for restoring degraded grassland depends on the restoration objectives and severity of grassland degradation. Harrowing is a feasible technique to assist restoration of the degraded grassland. In contrast, shallow plowing is not appropriate for ecological restoration, but may be applied for quick restoration of herbage production.

Resumen

Se estudió el efecto a largo plazo de dos intervenciones mecánicas, un arado superficial y el rastreo sobre un pastizal degradado de *Leymus chinensis* (Trin.) Tzvel. La composición de especies y la producción de biomasa del pastizal se monitorearon cada año al final de la época de crecimiento por 24 años después del uso de estas dos prácticas de manejo, junto con la recuperación natural y pastoreo comunal. Los resultados demostraron una alta resistencia del pastizal degradado, el cual se recuperó naturalmente después de la exclusión del pastoreo por animales logrando una estructura similar a la comunidad intacta de *L. chinensis*. En comparación con la recuperación natural, el rastreo facilitó la restauración de la población de *L. chinensis* y de la estructura de la comunidad y mejoró la producción del pastizal. La aplicación del arado superficialmente aceleró la recuperación de de la población de *L. chinensis* en mayor medida que el rastreo y condujo a la aparición de especies anuales y un mejoramiento en la producción de forraje en los subsiguientes años de uso. Sin embargo, el mejoramiento en la producción fue insostenible y se asoció a una disminución en la complejidad de la comunidad y riqueza de especies del pastizal. Se concluyó que la mejor alternativa para restaurar el pastizal degradado depende de los objetivos de la restauración y de la severidad actual de degradación. El rastreo es una práctica factible para restaurar pastizales degradados. En contraste, el arado superficial no es apropiado para una restauración ecológica, pero puede ser aplicado para acelerar la restauración de la producción del pastizal.

Key Words: biomass, facilitation, long-term effect, species richness, succession trajectories

INTRODUCTION

Leymus chinensis (Trin.) Tzvel. (syn. *Aneurolepidium chinense* [Trin.] Kitag.) grassland is widely distributed in the steppe region of Inner Mongolia and in the northeast China plain (Wu 1980). It is one of the best rangeland types and has been used as grazing land for thousands of years. However, grazing-induced degradation has extended to more than 90% of the grassland areas during the past several decades (Ministry of Environmental Protection of China 2004). This grassland degradation has severely affected the development of a pastoral economy in the region and caused environmental problems in northern China. Restoration of these degraded ecosystems is vital for sustainable management of natural resources in the region.

Many studies have been done on the *L. chinensis* grassland (Jiang 1988, Xiao et al. 1996) and its pattern and dynamics in response to animal grazing (Li 1989, Wang et al. 1996, Li et al. 2008). These studies showed that the major changes during grazing-induced degradation of the grassland were due to species dominance rather than composition. *Leymus chinensis* and other major species such as *Stipa grandis* P. Smirn. and *Agropyron michnoi* Roshev. decreased, whereas grazing-tolerant or grazing-facilitated species such as *Artemisia frigida* Willd., *Potentilla acaulis* L., *Cleistogenes squarrosa* (Trin.) Keng, and *Carex duriuscula* C. A. May increased. Various methods were applied to restore these degraded grasslands, including "fencing the grassland and moving the animals away" to allow natural recovery of the grasslands (Wang et al. 1996; Liu et al 2003) and agricultural techniques to assist or accelerate rehabilitation. The short-term experimental results showed that shallow plowing

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and harrowing were useful in accelerating recovery of the degraded *L. chinensis* grassland because they facilitated vegetative propagation of rhizomatous *L. chinensis* and improved soil conditions (Ma 1982, Chen and Baoyin 1989). However, long-term effects of these mechanical interventions on recovery of degraded semiarid grasslands remains in debate, especially when the high resilience of the degraded grassland (Li et al. 2008) and environmental risk of these agricultural techniques (Liu et al. 2003) were taken into account.

The objective of this study was to examine long-term effects of shallow plowing and harrowing on a degraded *L. chinensis* grassland by comparing vegetation dynamics of treated grasslands with those under natural recovery (animal grazing excluded) and those under continued public grazing. Effectiveness and feasibility of these measures in assisting restoration of the degraded grassland were evaluated considering their impact on both herbage production and ecological structure of grassland communities.

MATERIALS AND METHODS

Experimental Grassland

The experimental grassland is located in Xilingol League of Inner Mongolia (lat 43°26′–44°08′N, long 116°04′–117°05′E). The area experiences a temperate semiarid climate (Fig. 1). *Leymus chinensis* steppe on a sandy loam, dark chestnut soil (or Calcic-orthic Aridisol in the US soil taxonomy classification system) is the zonal vegetation in the region (Jiang 1988; Li et al. 1988). It has been largely degraded due to overgrazing (Li 1989).

The experimental grassland was fenced in 1983 as a permanent monitoring and demonstration site of the Inner Mongolia Grassland Ecosystem Research Station (IMGERS) of the Chinese Academy of Sciences. The degraded grassland was dominated by *Artemisia frigida, C. squarrosa*, and *Agropyron michnoi* when fenced and was a degraded formation of the *L. chinensis* grassland (Wang et al. 1996). The exclosure was 650 m long and 400 m wide and was divided into five sections, among which three adjacent sections were designed for natural recovery (400 × 150 m), restoration by harrowing (400 × 75 m), and restoration by shallow plowing (400 × 75 m). Treatments were applied in July 1983. Plowing depth was set to 18–20 cm, and harrowing depth to 8–10 cm. Distance between harrow blades was 10 cm. The grassland outside the exclosure continued open for public grazing, and a grazing area about 10–30 m distant from the long side of the exclosure and opposite of the inside plowed and harrowed grassland was also studied for comparison purposes. The stocking rate on the open grazing area was unknown, but the average stocking rate of the farm where the experimental grassland was located was 0.7 sheep units $\cdot$ ha^{-1} in 1983, which increased to about 1 sheep unit in 1990 and then varied around that level for the rest of the study period. In addition, vegetation dynamics of a "climax *L. chinensis* community" in a permanent plot of the IMGERS was also included in the analysis as a reference for the intact *L. chinensis* grassland. The plot is about 10 km distant from the degraded grassland, on the same topographic unit and soil type, and experiences the same weather (Jiang 1988; Li et al. 2008). The area had been lightly used (reserved for hay-making) before closing to grazing in 1979 (Jiang 1988).

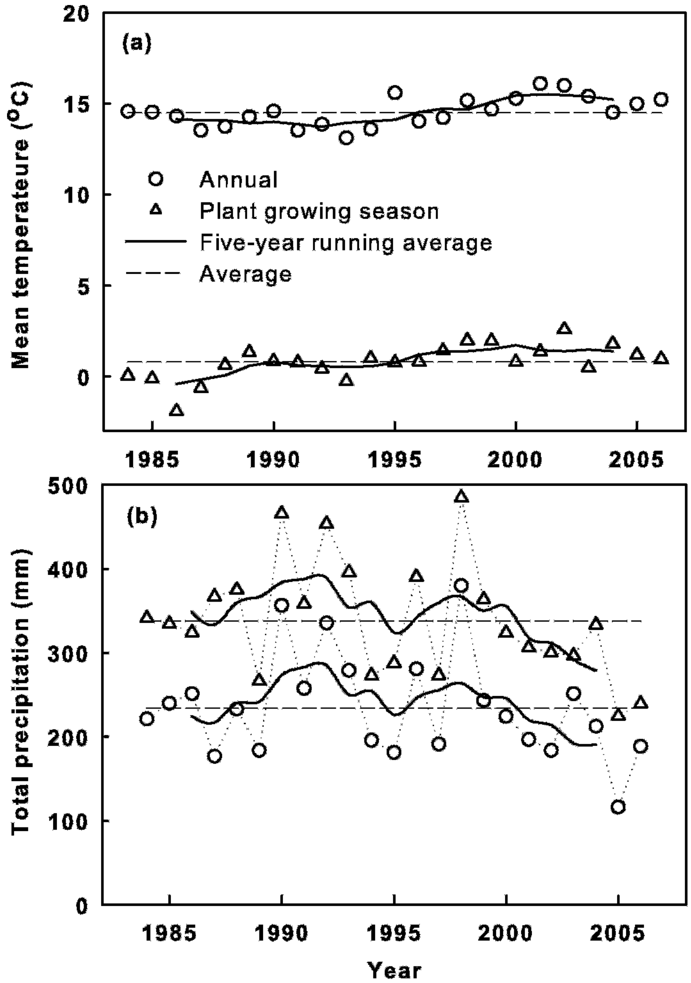

Figure 1. Weather conditions in experimental area during the observation period. **a**, Annual mean temperature (Δ) and mean temperature during plant growing season (O: 1 April–31 August). **b**, Annual precipitation (Δ) and precipitation during plant growing season (O: 1 April –31 August). Solid lines are 5-yr running averages, and dashed lines overall averages during the observation period.

Data Collection and Analysis

The grassland under different treatments (shallow plowing, harrowing, and natural recovery) and that under open public grazing were monitored every year for 24 yr (1984–2007) during the plant growing season using 10 quadrats of 1 m^2 each (five in mid-July and another five in mid-August) within a relatively small area (50 × 50 m) in each treatment. All the species were identified, and the aboveground standing biomass was clipped, species by species, to ground level, oven-dried at 60°C, and weighed. The vegetation dynamics of the "climax" community was monitored using the same method. The first few years' data, focusing on effects of these treatments in improving herbage production, were reported in Chen and Baoyin (1989). Changes in species diversity in plowed and harrowed grassland were also documented separately (Baoyin et al. 2003; Baoyin and Liu 2003) for part of the observed period. This integrative analysis of the complete dataset focuses on long-term effects of these treatments.

The changes in species richness and biomass composition of grassland following different treatments were compared using "before-after-control impact" analysis, similar to that used in analyzing natural events without replicates (Stewart-Oaten et al. 1986, Wiens and Parker 1995, Michener 1997). Total species number recorded in 10 quadrats each year was used as a measure of species richness, whereas the average of species biomass in five quadrats harvested in mid-August (time of peak herbage biomass) was calculated to represent biomass composition of grassland. In order to minimize effects of interannual variation of grasslands caused mainly by climatic fluctuation, the moving averages (of five successive years) of species richness and biomass of grassland under different treatments were used to present their long-term trends. Climate data over the observation period were presented and used in interpretation of vegetation changes. Grassland succession trajectories following treatments were presented using principal components analysis (PCA) and explained by biomass change of major species. Effects of different treatments on species richness and biomass were examined using analysis of variance for different observation periods or the whole observation period. All statistical analyses used GenStat9 (Payne 2006).

RESULTS

Weather Conditions

The daily mean temperature during plant growing season (1 April–31 August) averaged 14.5°C, and had a slight increasing trend during the 24-yr period (Fig. 1a). The annual mean temperature had the same increasing trend with an overall average of 0.8°C. Annual precipitation averaged 338 mm during the observation period, 69% of which fell during plant growing season. Precipitation showed large interannual variation, but no significant increasing or decreasing trend was observed during the 24-yr period (Fig. 1b).

Plant Community Succession Trajectories

Fifty-five species were recorded in total during the 24 yr, but only a few species constituted the bulk of herbage mass at various successional stages following treatments. Grasses were the major component of herbage mass in the climax *L. chinensis* grassland, with *L. chinensis* and *S. grandis* constituting more than 60% of total herbage mass. The degraded grassland had more forbs (> 50% of total herbage mass) than grasses, and dominant species were *Artemisia frigida, Agropyron michnoi, C. squarrosa*, and *P. acaulis*.

A PCA of species biomass percentage for grassland vegetation during the 24 yr after treatment showed a clear vegetation divergence caused by different treatments, and a convergence of these treated grasslands toward the climax *L. chinensis* community following treatments (Fig. 2a). Succession of plant community was gradual during natural recovery, whereas a rapid change occurred following the application of the mechanical interventions. Vegetation in the plowed treatment jumped from being degraded to being "overrehabilitated" when compared with the final stage of the restoration succession and with the intact climax *L. chinensis* community. It then returned towards the intact climax community. The harrowed community and the community in natural recovery had similar vegetation trajectories, but the harrowed community recovered much more quickly. The grassland under public

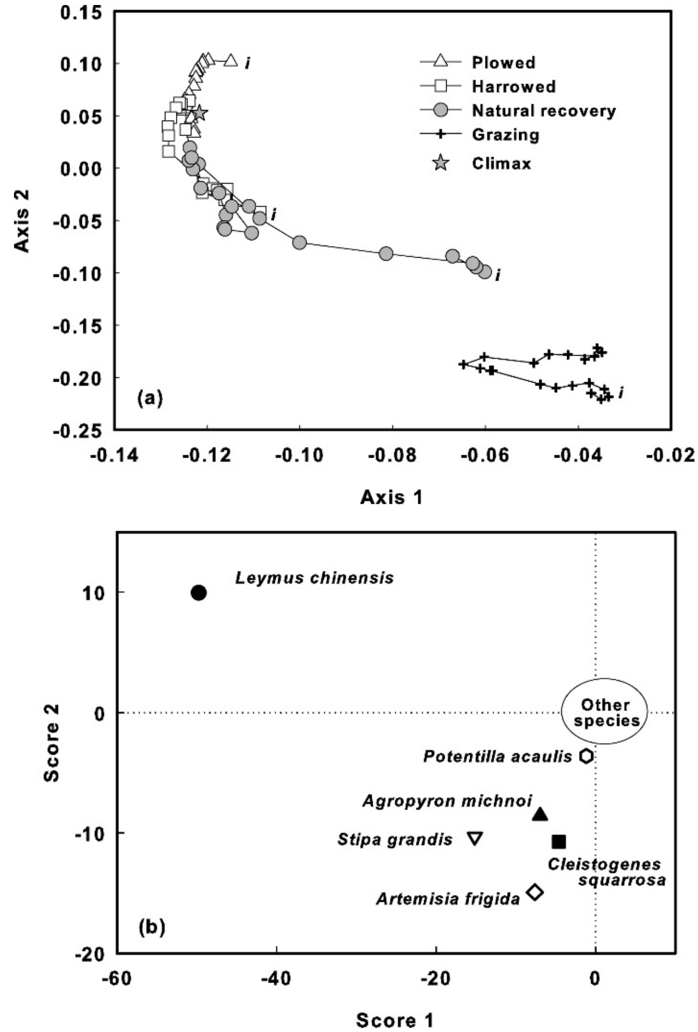

Figure 2. a, Succession trajectories of degraded grasslands following different treatments based on principal-component analysis ordination of species biomass percentage for grassland vegetation during 24 yr after treatment. First and second axes represent 65% and 15% of the variation, respectively. Moving averages of vegetation coordinates over successive 5 yr were plotted to distinguish directional succession from interannual fluctuations. Observations following each treatment are linked sequentially with the first observation marked *i* (representing the average position of the first five successive years: 1984–1988). Climax community of *Leymus chinensis* is included as a reference using its average species biomass percentage over the observation period of 1983–1993. **b**, Plot of the species scores on first and second principal components, indicating roles of dominant species in the ordination.

grazing had little directional change, keeping a relatively stable structure during the 24 yr (Fig. 2a).

Recovery of *L. chinensis* and Other Dominant Species

As indicated by the species scores in the PCA (Fig. 2b), successional trajectories of the community after different treatments reflected mainly the biomass change of several dominant species, namely *L. chinensis*, *S. grandis, Artemisia frigida, C. squarrosa*, *Agropyron michnoi*, and *P. acaulis*. These species constituted 74% (± 14%) of total herbage mass averaged across all treatments over the observation period (ranging from 30% to 94%).

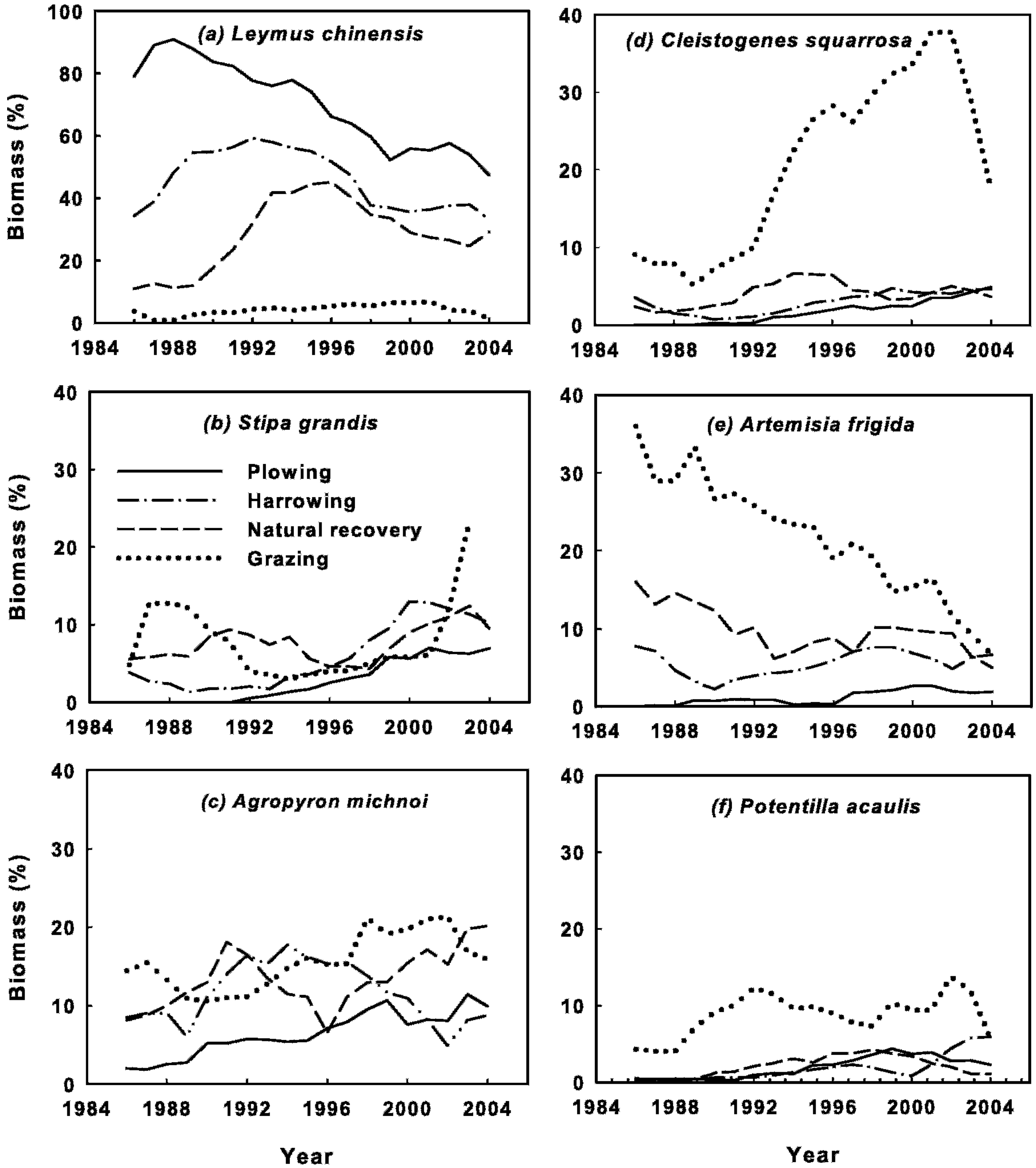

Figure 3. Moving averages (over successive 5 yr) of biomass (%) for major species in degraded *Leymus chinensis* grassland following different treatments. The major species are **a**, *Leymus chinensis*, **b**, *Stipa grandis*, **c**, *Agropyron michnoi*, **d**, *Cleistogenes squarrosa*, **e**, *Artemisia frigida*, and **f**, *Potentilla acaulis.* The four lines represent biomass (%) of each species in grassland following shallow plowing, harrowing, in natural recovery, or open to public grazing, as indicated by the legend in b.

Shallow plowing largely facilitated recovery of *L. chinensis* when compared with natural recovery (Fig. 3a). However, facilitation happened at the expense of other species. Most species in the community were severely diminished, including *S. grandis* and *Agropyron michnoi* (the dominant or persistently present species in the climax community) and *Artemisia frigida* and *C. squarrosa* (the grazing-tolerant species dominant in the degraded community; Figs. 3b–3e). Biomass percentage of these species in plowed grassland was much lower than that present during natural recovery and that under continuous public grazing. Biomass percentage of *L. chinensis* gradually declined following treatment, whereas biomass of *S. grandis* and *Agropyron michnoi*, as well as other consistently present species in the natural community, increased.

Harrowing also facilitated recovery of *L. chinensis* when compared with natural recovery, but the facilitation effect was smaller than that of shallow plowing. The vegetation change following harrowing was in the same direction as that in natural recovery. The faster recovery after harrowing reflected the fast change of dominant species. For example, the decrease in biomass percentage of *Artemisia frigida* was much faster in harrowed grassland than in natural recovery (Fig. 3e).

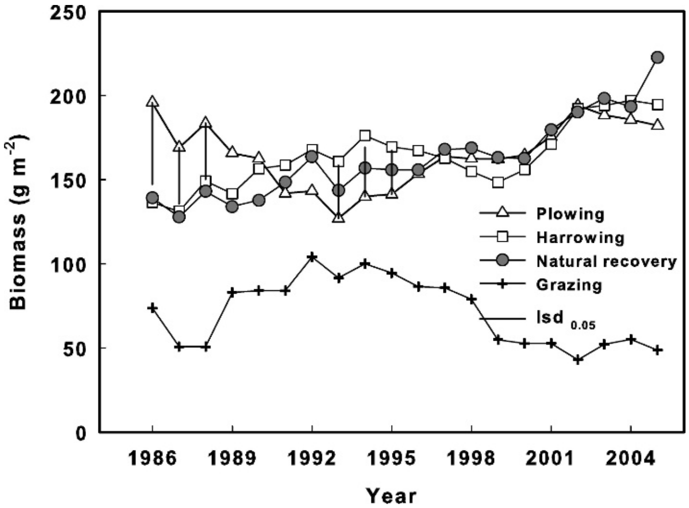

Figure 4. Plant aboveground biomass dynamics during 24 yr following different treatments. Moving averages of five successive years are plotted to show successional trends (e.g., points corresponding to 1986 represent the averages of 1984–1988). Vertical lines are the least significant difference among treatments at $P = 0.05$ ($LSD_{0.05}$) for the corresponding five successive years. Vertical lines are shown only if a significant difference existed among any two of the plowing, harrowing, or natural recovery treatments.

Grassland Production

Moving averages of five successive years were plotted to show the general trends of aboveground biomass for plant communities following different treatments (Fig. 4). The harrowed community showed some evidence of a slightly higher production than the grassland in natural recovery during the first half of the observation period, although the difference was not statistically significant ($P > 0.05$ for any 5-yr periods; Fig. 4). Plant biomass in the first 7 yr following shallow plowing was significantly higher than the harrowed grassland or grassland in natural recovery ($P < 0.05$ for the first three 5-yr periods; Fig. 4). But this plowing-improved biomass production was not persistent. It declined gradually and reached a minimum in about 10 yr, when it was significantly ($P < 0.05$) lower than that of harrowed grassland. Biomass differences among plowed, harrowed, and natural recovery grasslands were minimal after about 14 yr after treatment (Fig. 4).

Succession of the plowed grassland could be clearly divided into two stages (Fig. 5a). The first stage was structurally simple. It was dominated by *L. chinensis* and contained abundant annual forbs but very little abundance of other codominant or common species of the natural grassland. Total herbage mass declined as a consequence of the decrease in *L. chinensis* biomass, whereas recovery of other species was not significant. Second was the community structure recovery stage that was characterized by a gradual recovery of abundance of codominant and consistently present species in natural communities. Total herbage mass increased, although biomass of *L. chinensis* changed little and its biomass percentage declined.

Standing biomass following harrowing and that during natural recovery increased gradually during the succession (Figs. 5b and 5c). The increase was significant, from 138 $g \cdot m^{-2} \pm 30$ SD averaged over the first 5 yr to 195 $g \cdot m^{-2} \pm 51$ SD averaged over the last 5 yr (for harrowed grassland and land in natural recovery). This increase was the result of recovery succession because weather was not better for plant growth in the later than in the earlier observation period (Fig. 1). Standing biomass under public grazing was not actual herbage production due to unknown uptake by grazing animals. Standing biomass was much lower, averaged 69 $g \cdot m^{-2} \pm 39$ SD over the 24 yr.

Species Richness

Species richness (number of species recorded in 10 quadrats each year) had no significant directional change over the 24-yr period either in natural recovery (27 ± 4 SD, range 17–36) or after harrowing (27 ± 3 SD, range 18–33). The harrowed community also had evidence of slightly but not significantly higher species richness than that in natural recovery during the first 8 yr after treatment (Fig. 6). Species richness was

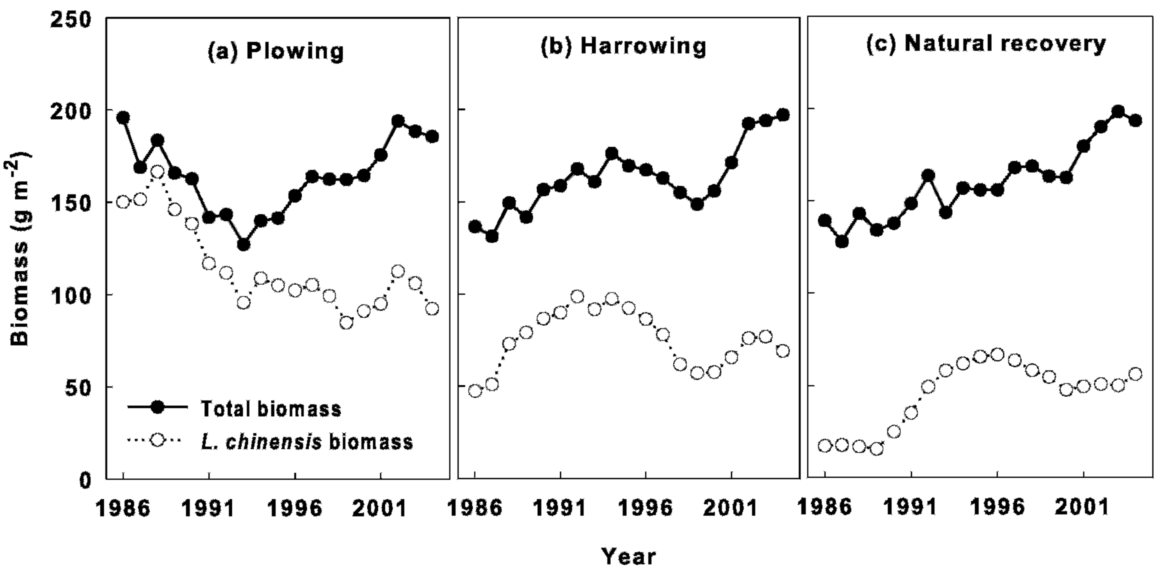

Figure 5. Dynamics of total plant aboveground biomass and biomass of *Leymus chinensis* of grasslands following different treatments: **a**, plowing; **b**, harrowing; and **c**, natural recovery. Moving averages of five successive years are plotted to show trends (e.g., points corresponding to 1986 represent the averages of 1984–1988).

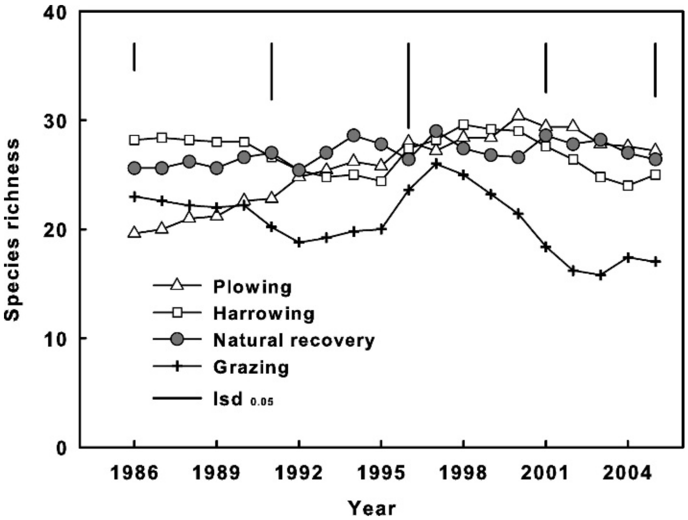

Figure 6. Plant species richness in recovering grasslands following different treatments. Moving averages of five successive years are plotted (e.g., points corresponding to 1986 represent averages of 1984–1988). Length of vertical lines are least significant difference among treatments at $P = 0.05$ ($LSD_{0.05}$) for the corresponding five successive years.

significantly reduced by shallow plowing. It was significantly lower in plowed than in harrowed and in natural recovery grassland during the first 8 yr after treatment, but it recovered in about 10 yr after plowing (Fig. 6). Species richness in the community under grazing was lower (21 ± 5 SD, range 13–26) than in fenced communities over the 24 yr.

DISCUSSION

Shallow Plowing

Shallow plowing improved grassland herbage production immediately after treatment. The improvement was realized by a large and rapid biomass increase of *L. chinensis* and by a flush of growth from the annual forbs *Artemisia sieversiana* and *Salsola collina*. These results are consistent with previous observations (Chen and Baoyin 1989) and suggested that plowing stimulates germination of annual species with large seed banks in soil. However, plowing damaged existing bunchgrasses and stoloniferous forbs, inhibiting their quick recovery through clonal growth, and destroyed some perennial forbs. The quick recovery in herbage mass after plowing was followed by an inhibition to recovery toward a natural community. Thus, plowing slowed ecological restoration towards a natural ecosystem of high function and complexity (Bradshaw 2002). Also, our long-term monitoring results showed the initial herbage mass improvement was unsustainable. It decreased significantly to a level lower than the grassland in natural recovery between 10 yr and 14 yr after plowing (Fig. 4). The reason for this herbage mass decline was not certain, but it might be related to the elimination of native legume species and exhaustive use of soil nutrients by the flourish growth at the first several years. Shallow plowing should not be used for ecological restoration of the degraded grassland, but may be used for a quick restoration of herbage yield. In addition, shallow plowing should be used cautiously because it may cause wind erosion of soils in the semiarid steppe area (Dong et al. 2000; Wu and Ci 2002; Wen et al. 2005).

Harrowing

Harrowing significantly accelerated the recovery of rhizomatous *L. chinensis* and the bunchgrass *Agropyron michnoi*, improved soil compaction, and facilitated seed germination and clonal growth of other perennial species. Its acceleration on the recovery of both grassland production and community structure suggests it is a feasible technique for assisting restoration of degraded grasslands toward a natural community of high production and stability.

Restoration Approaches and Severity of Grassland Degradation

Dynamics of the studied vegetation following different treatments was mainly a recovery process after their release from grazing pressure. Different treatments changed vegetation recovery trajectories but did not result in other stable states. The state-and-transition model (Westoby et al. 1989, Laycock 1991) is a powerful concept that describes vegetation dynamics in response to multiple drivers (Briske et al. 2005). The state-and-transition framework of ecosystem degradation and restoration identifies two types of restoration threshold, one controlled by biotic interactions and the other by abiotic limitations (Hobbs and Norton 1996, Whisenant 1999). The degraded ecosystems recover by management changes only if degradation does not go beyond the threshold of biotic interactions. The studied *Artemisia frigida* grassland, derived from the *L. chinensis* grassland, is the most widely distributed grassland type associated with high grazing pressure in open public grazing areas (Li 1991). Results drawn from this long-term monitoring research are most applicable to the *Artemisia frigida* type of degraded grassland. They suggest that the degraded grassland is within the threshold of biotic interactions and has the potential to recover by excluding grazing animals, although its recovery can be accelerated with human intervention such as harrowing. More severely degraded grassland, such as grazing-derived *P. acaulis* grassland on sandy soils with extremely low population density of *L. chinensis* and *S. grandis* and a limited seed bank (Sudebilige et al. 2000, Li et al. 2005) might be in a state beyond its natural regeneration potential, and plowing and sowing native species might be more justifiable.

MANAGEMENT IMPLICATIONS

The appropriateness of a technique for restoring a degraded grassland site depends on the degradation severity of the site and the objective of the restoration. For the grazing-induced *Artemisia frigida* grassland in the semiarid steppe area, harrowing is a recommended technique to aid the grassland restoration toward a natural community of high production and stability. Shallow plowing should be applied only if the objective of grassland management is to restore a high herbage yield, not a natural community. Natural recovery by removing grazing animals only might be superior to any mechanical interventions on less-degraded grassland, whereas shallow plowing and sowing native species might be more justifiable for more severely degraded grassland. Application of these techniques on grasslands at various degradation stages deserves further study.

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