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Factors limiting vegetation recovery processes after cessation of cropping in a semiarid grassland in Mongolia

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ABSTRACT

Land degradation in an abandoned field, such as the loss of palatable species for livestock and low species richness, is a serious problem in Mongolia where the dominant land use is livestock grazing historically. Here, we show the factors limiting vegetation recovery processes after cessation of cropping in a semiarid grassland. We selected fields abandoned in 1990 (CA18), 1999 (CA9), and 2006 (CA2) and continuously grazed grassland (CGG) as a control site. Plant species cover and soil were sampled during summer (June–July) 2008. Soil physicochemical properties were analyzed. Low similarity index of an early succession stage, CA2, with CGG was associated with abundant P and coarse sand. The proportion of coarse sand was not abundant in middle stage (CA9) because of domination by perennial rhizomatous species. In the later stage (CA18), the fine sand proportion did not increase; however, the dominant species were associated with fine sand in CGG. The results suggest the limiting factors of recovery processes in abandoned Mongolian cropland are abundantly available P and coarse sand at an early succession stage (CA2). The small proportion of fine sand in CA18 indicated that the impacts of cropping in Mongolia persist for a long time.

1. Introduction

Environmental and social-economic changes are leading to increased levels of abandoned cropland worldwide (Ramankutty and Foley, 1999). In particular, grassland is the easiest among all vegetation types to clear for cropping. However, cropland in grassland tends to be abandoned at the second highest rate (11%) compared to that in forest land (14%) (Ramankutty and Foley, 1999). Considering grassland is found mainly in semiarid regions, crop abandonment could drastically reduce its potential to recover to a pre-disturbance state. There are many chronosequence studies showing factors limiting the recovery of abandoned cropland in arid regions. For instance, limited seed availability limits recovery in old Australian fields (Scott and Morgan, 2012). Limitations of total P and soil water are factors limiting recovery on the loess plateau of China (Jiao et al., 2008).

In Mongolia, grassland covers 97.4% of the national land area. Nomadic grazing has occurred for over two thousand years (Montsame, 2008), whereas cropping began only in the past 60 years. There are 436,000 ha of abandoned croplands in Mongolia (National Scientific Office of Mongolia, 2007). A loss of typical species composition and small amounts of organic C and available water for plants in a field abandoned 12 years ago, compared with typical rangeland, have been reported (Hoshino, 2010). However, the recovery process of abandoned cropland in Mongolian rangeland is unknown.

There have been attempts at restoration of a degraded Mongolian field abandoned nine years ago, such as by sowing of perennial grass by the Swiss Agency for Development and Cooperation and by creating gaps by removing annual species at different distances from intact vegetation to determine whether the rhizomatous

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species *Leymus chinensis* could invade and grow in abandoned cropland (Hoshino et al., 2009). However, the sowing of perennial grass failed, owing to unexpected drought in summer. The rhizomatous species did not expand into the gaps, although they were adjacent to tracts of the rhizomatous species. These failures of restoration activities result from the selection of inappropriate restoration targets without considering underlying restoration constraints (Hobbs and Harris, 2001). Soil conditions may be limiting if annual species are not removed. However, the recovery process and the factors limiting its recovery are unknown. Moreover, whether limiting factors change during the recovery process is unknown. Therefore, our objective was to characterize the recovery process of vegetation and soil and the factors limiting recovery by sampling across a chronosequence of abandoned Mongolian cropland.

2. Materials and methods

The study was conducted in forest steppe in Hustai National Park (HNP, 47°50′N, 106°00′E), Mongolia (Fig. 1A). The average elevation of HNP is 1240 m a.s.l. The region's climate is semiarid and cold with a short summer. Most of the annual precipitation falls in summer (May–July) and is critical for the growth of grasses. Based on data from the HNP weather station, annual precipitation averaged 232 mm (CV 31% and 76% of rain fall in May to August), and annual temperature averaged 0 °C (the range was −19 °C in January to 20 °C in July) during 1999–2005. The zonal soils were classified as Kastanozems by soil profile morphology and physicochemical properties.

Some parts of the study area had been tilled and then abandoned at different time periods. We consulted the municipal archives and interviewed landowners to determine the abandonment time. We selected fields abandoned in 1990 (CA18), 1999 (CA9), and 2006 (CA2). Wheat with chemical fertilizer and without irrigation was grown since 1977 in CA2, CA9, and CA18. Cropping systems and agricultural materials at each site followed the guidance of the government until 1992, so that the conditions of the abandoned croplands were almost the same from 1977 to 1992. Since abandonment, all fields were moderately grazed as a buffer zone in the park. We also selected continuously grazed grassland (CGG) as a control site in the buffer zone. The size of the buffer zone is 462,000 ha. All four study sites were located in flat locations in the buffer zone, so that only land use history differed among the sites. Although each abandoned cropland site experienced a different duration of cultivation (14, 23, and 30 years in CA18, CA9, and CA2, respectively), half of the change in soil physicochemical properties occurred during the first eight years, and subsequent changes were slow (Zhao et al., 2005). We accordingly assumed minimal effects of different durations of cultivation on our results.

Vegetation and soil were sampled during summer (June–July) 2008, for five fields at each site (CA2, CA9, CA18, CGG) at least 300 m apart, which were randomly selected and located in homogenous subsurface soil on flat land. We sampled the subsurface soil to 50 cm depth with a hand auger. In each field, a 100 × 100 m plot away from the field edges was delineated. We then systematically sampled five 1 × 1 m quadrats along three transects in each plot. Fifteen quadrats in five fields at four sites constituted 300 quadrats in total. Each transect was separated from its neighbor by 30 m, and the distance between the quadrats in each transect was 20 m. In each quadrat, we recorded the percentage cover of each species. The soils were sampled in every alternate quadrat at the depth of 0–15 cm (three samples per transect and nine samples in five fields at four sites, for a total of 180 soil samples). The volumetric water contents were measured at the soil sampling points before sampling with a mobile soil sensor (WET-2, Delta-T Device Ltd, Cambridge, England). The soil was too dry for moisture measurement at some of the points, so the number of data points for volumetric water content were 24, 24, 26, and 28 for CA2, CA9, CA18, and CGG, respectively. Each abandoned field was compared with the control site.

Bulk soil samples were air-dried and sieved (<2.0 mm) for measuring soil properties. Particle size distribution (sieving and hydrometer analysis), soil organic carbon (wet oxidation method), total N (Kjeldahl method), available P (Olsen method), available K (flame photometry), and cation exchange capacity (CEC)

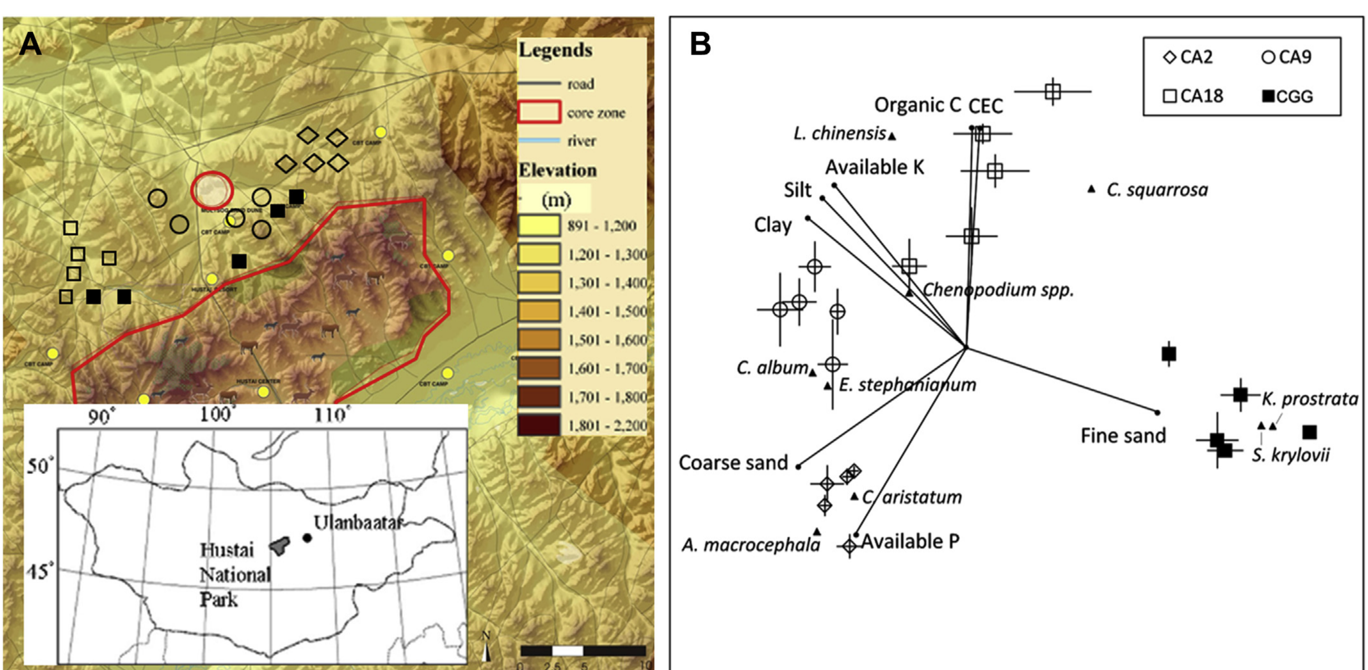

Fig. 1. A. Schematic map of the research site and NMDS of the species composition with soil properties in each plot in each site. B. Significant soil vectors are shown in the ordination (stress = 0.14). The dominant species are plotted in the figure. Vertical and horizontal error bars indicate standard errors of 15 samples in each field (5 fields at each site).

Table 1a
Species composition of each plant life form and family name at each study site The number represents the mean count over all quadrats at each site (n = 300 = 75 samples × 4 sites). The dominant species at each site is indicated in bold. Standard errors of each site are shown in parentheses. Palatability for livestock is shown by H (high), M (medium), or L (low).

Species	Palatability	CA2	CA9	CA18	CGG
Annual Forbs					
Asteraceae					
Artemisia macrocephala	M	22.47 (11.05)	7.10 (3.80)	0.83 (0.50)	
Artemisia palustris	L		0.37 (0.33)		
Artemisia spp.			0.15 (0.13)	0.07 (0.06)	
Bidens pilosa			0.02 (0.02)		
Amaranthaceae					
Chenopodium acminatum	L		5.45 (2.41)		0.04 (0.03)
Chenopodium album	L	0.37 (0.13)	11.81 (2.06)	0.20 (0.11)	0.17 (0.12)
Chenopodium aristatum	L	22.88 (2.56)	2.06 (0.70)	0.36 (0.18)	0.85 (0.31)
Chenopodium spp.	L	14.93 (5.28)	6.30 (1.97)	2.47 (1.72)	0.97 (0.63)
Kochia spp.	L	0.36 (0.21)			
Geraniaceae					
Erodium stephanianum	L	26.41 (4.90)	23.95 (6.28)	11.70 (6.68)	
Polygonaceae					
Fagopyram tataricum	L		0.02 (0.02)	0.41 (0.28)	
Ranunculaceae					
Leptopyrum fumarioides	L				
Chenopodiaceae					
Salsola collina	L	0.64 (0.50)	5.48 (3.43)	3.29 (0.84)	0.05 (0.03)
Salsola spp.		1.93 (0.91)	3.61 (2.37)	0.43 (0.23)	0.05 (0.03)
Brassicaceae					
Arabis spp.		0.32 (0.26)			
Thlaspi arvense	L			0.11 (0.03)	
Annual Grass					
Poaceae					
Eragrostis minor	H	1.04 (0.59)	0.28 (0.23)		
Panicum miliaceum	H	1.72 (0.99)	0.05 (0.04)		
Setaria viridis	H	4.32 (1.70)	0.91 (0.66)	0.97 (0.54)	
Biennial Forbs					
Leguminosae					
Astragals spp.				0.07 (0.06)	
Astragalus dahuricus	M			0.20 (0.11)	
Asteraceae					
Heteropappus altaicus	L			2.40 (1.48)	
Solanaceae					
Hyoscyamus niger	L	0.05 (0.05)			
Brassicaceae					
Isatis oblongata	L			0.11 (0.08)	
Boraginaceae					
Lappula myosotis	L			0.26 (0.12)	0.04 (0.04)
Perennial Forbs					
Amaryllidaceae					
Allium anisopodium	H				0.15 (0.10)
Allium bidentatum	H				9.73 (3.79)
Allium leucocephalum					0.05 (0.03)
Asteraceae					
Artemisia adamsii	L			0.96 (0.77)	0.79 (0.57)
Artemisia mongoica			0.05 (0.04)		
Saussurea amara	L				0.05 (0.04)
Saussurea saclicifolia	L				0.91 (0.63)
Tarxacum spp.				0.56 (0.45)	0.04 (0.04)
Iridaceae					
Iris tigridia	M				0.20 (0.16)
Boraginaceae					
Myostis spp.	L			0.23 (0.07)	0.20 (0.18)
Nonea pulla	L			1.29 (0.69)	
Poaceae					
Poa botryoides			0.11 (0.06)		
Rosaceae					
Potentilla anserina	L		0.11 (0.10)	0.24 (0.13)	
Brassicaceae					
Ptilotrichum canescens	L				0.08 (0.07)
Caryophyllaceae					
Silene repens	L			4.77 (2.04)	0.14 (0.13)
Stellaria spp.			0.02 (0.02)		
Leguminosae					
Thermopsis dahurica	L			0.02 (0.02)	
Thermopsis lanceolata		0.05 (0.03)			0.02 (0.02)
Apiaceae					
Cicuta spp.				0.39 (0.35)	
Perennial Grass					
Poaceae					
Agropyron cristatum	H				0.08 (0.06)
Cleistogenes squarrosa	H		0.11 (0.10)	24.43 (4.13)	3.08 (1.18)
Leymus chinensis	H		30.53 (3.29)	33.03 (2.51)	0.76 (0.42)
Leymus spp.				0.47 (0.42)	
Stipa krylovii	H			1.30 (0.76)	53.80 (6.05)
Stipa spp.				0.62 (0.56)	
Hordeum spp.				0.17 (0.15)	
Cyperaceae					
Carex spp.			0.32 (0.20)	0.89 (0.50)	0.14 (0.06)
Shrub					
Asteraceae					
Artemisia frigida	M			0.91 (0.53)	0.85 (0.76)
Artemisia scoparia	M		1.19 (0.69)	4.91 (3.69)	
Leguminosae					
Caragana microphylla	M				0.66 (0.45)
Caragana stenophylla	M				0.95 (0.63)

(continued on next page)

Table 1a (*continued*)

Species	Palatability	CA2	CA9	CA18	CGG
Amaranthaceae					
Kochia prostrata	M			0.51 (0.40)	24.95 (6.05)
Rosaceae					
Potentilla bifurca	L	2.51 (0.66)	0.01 (0.01)	0.39 (0.22)	0.18 (0.16)

Table 1b
Species richness and similarity index of each plant life form at each study site.

	CA2	CA9	CA18	CGG
Annual Forbs	9	12	10	6
Annual Grass	3	3	1	0
Biennial Forbs	1	0	5	1
Perennial Forbs	1	4	8	12
Perennial Grass	0	3	7	5
Shrub	1	2	4	5
Total Species Richness	15	24	35	29
Sorenson's index	0.36	0.42	0.56	

(ammonium acetate extraction) were evaluated. The CEC value shows the potential of soil capacity of holding water-soluble cation.

To assess the differences in dominant species due to years abandoned, the dominant species were determined based on relative values for plant cover. All species were classified by life form (annual forb, annual grass, perennial forb, perennial grass, and subshrub) and palatability. These classifications followed Sergelenkhuu and Oyuntsetseg (2008) and information provided by Mongolian botanists. The similarity among communities at each abandoned site and the continuously grazed grassland was determined using the similarity coefficient of Sørensen (similarity index). Mean soil property data were compared among the four sites using Tukey's multiple comparison test. We also calculated Pearson's correlation coefficients among soil properties ($n = 180$), except for the data of volumetric water content. The relationship between a subset of soil properties with low cross-correlation with species composition was then analyzed by nonmetric multidimensional scaling (NMDS) to show the relationship between the soil properties and plant species composition across the site.

The percentage cover of each species data were $\ln(y + 1)$-transformed where needed (Sokal and Rohlf, 1995). The level of significance was $P < 0.05$. All statistical analyses were performed with R software (R Development Core Team, 2008).

3. Results

A total of 58 species were identified across all study sites. Species richness increased with time since abandonment and was highest in CA18. The index of species similarity comparing abandoned croplands and the reference CGG site was increased with the years since abandonment. The index of CA9 was 6% higher than CA2 and that of CA18 was 14% higher than CA9 (highest for CA18). The proportion of annual species was highest in CA2 (Table 1a and 1b).

The dominant species changed from nonpalatable annual species to palatable perennial species with increasing years since abandonment. The dominant species in CGG, *Stipa krylovii* and *Kochia prostrata*, were not dominant perennial species in abandoned fields. The dominant perennial species was rhizomatous *L. chinensis* in CA9 and CA18.

Table 2 describes the soil physicochemical properties at each site. The contents of available P and coarse sand and volumetric water content were highest in CA2, significantly ($P < 0.05$). Contents of fine sand and clay were highest and lowest in CGG, significantly. Available K was highest in CA9.

Fig. 1B shows an NMDS ordination of species composition across the sites. The cluster of plots at CA2 was typified by available P and coarse sand and that at CA18 was typified by organic C and CEC (Cation Exchange Capacity). Fine sand typified the cluster of plots in CGG.

4. Discussion

The recovery process at the study sites was slower than that of abandoned cropland in other semiarid lands (Mora et al., 2012; Scott and Morgan, 2012; Zhao et al., 2005). The similarity index was 0.9 in a 14-year site compared with natural grassland in China (Zhao et al., 2005), but the index at the present study site was low (0.56) for the 18-year site (CA18). The ability of the native community to adapt to cultivation disturbance can be an important constraint on recovery. The location of a site on the agro-pastoral ecotone appears to have been one of the reasons for the higher value of the index in the Chinese study (Zhao et al., 2005). The agro-pastoral ecotone is a transition of land-use practices (livestock-grazing and cropping) in places where grassland and cropland are interspersed in Northern China. There is a long history of grazing and cropping. While in the current research site, there is grazing without cropping until 1977. Because the adaptation level of the native community to cultivation disturbance is low in the current research site, the similarity index is low in the abandoned sites.

The low similarity index means that the species observed in abandoned cropland did not overlap with those observed in CGG. *Caragana* and *Allium* species were observed in CGG but not in CA18 (Table 1a and 1b). High contents of fine sand in CGG were associated with *S. krylovii* and *K. prostrata* (Fig. 1). Considering that a high content of fine sand forms a macropore-dominated-soil structure, the amount of available soil water stored in micropores is small. Soil water and nutrients in the soil may have been limited in CGG. *S.*

Table 2
Physicochemical properties of soil samples. Means labeled with different letters differ significantly (P < 0.05). Values represent mean values followed by standard errors in parentheses ($n = 160 = 40$ samples × 4 sites) except for volumetric water content. The numbers of data points for volumetric water content are 24, 24, 26, and 28 for CA2, CA9, CA18, and CGG, respectively.

	Total N		Organic C		Available P		CEC		Available K		Coarse sand		Fine sand		Silt		Clay		Volumetric Water Content	
	(%)		(%)		(mg kg^{-1})		(cmol(+) kg^{-1})		(mg kg^{-1})		(%)		(%)		(%)		(%)		(cm^3 cm^{-3})	
CA2	0.16 (0.02)	B	1.19 (0.18)	b	28.71 (4.28)	a	20.50 (3.06)	b	198.89 (29.65)	bc	16.70 (2.49)	a	56.68 (8.45)	b	17.78 (2.65)	b	8.83 (1.32)	a	0.08 (0.00)	a
CA9	0.18 (0.03)	ab	1.34 (0.20)	a	23.89 (3.56)	b	21.85 (3.26)	ab	306.56 (45.70)	a	8.47 (0.00)	c	59.52 (8.87)	b	23.05 (3.44)	a	8.95 (1.33)	a	0.06 (0.01)	b
CA18	0.19 (0.03)	ab	1.45 (0.22)	a	17.56 (2.62)	d	23.57 (3.51)	a	234.22 (34.92)	b	12.13 (1.81)	b	58.14 (8.67)	b	19.83 (2.96)	b	9.89 (1.47)	a	0.04 (0.00)	c
CGG	0.17 (0.03)	ab	1.29 (0.19)	ab	20.09 (2.99)	c	21.25 (3.17)	b	152.00 (22.66)	c	7.26 (1.08)	c	69.08 (10.30)	a	17.07 (2.54)	bc	6.59 (0.98)	b	0.03 (0.00)	c

krylovii tolerates water-limited environments, as do the shrub species (*K. prostrata* and *Caragana* species) (Ma et al., 2008). Thus, these species have an advantage in water-limited environments in CGG. Moreover, seed banks of *Allium* species and *S. krylovii* are limited in abandoned cropland (Zhan et al., 2007).

In contrast, the species observed in CA18 but not in CGG were mainly annual and biennial species. This result agrees with observations in abandoned communities in China, where species able to preempt soil resources grow quickly and acquire high biomass (Feng et al., 2007).

In an early succession stage of abandoned cropland (CA2), the annual species (*Artemisia macrocephala*, *Chenopodium aristatum*, and *Erodium stephaniaum*) are dominant. These species habitat are debris and sandy steppes. These species are associated with coarse sand. The coarse sand content in CGG was the lowest in all four sites, and the dominant species in CGG are associated with fine sand. We infer that the differences in dominant species between abandoned fields in early succession stages and CGG were associated with the differences in coarse sand content.

The high coarse sand content in abandoned fields appears to be an effect of erosion due to dust storms. Several dust storms usually occur during April–June (Natsagdorj et al., 2003), when abandoned fields dominated by annual species only in the growing season become bare. Dust storms transport materials lighter than the coarse sand fraction. Thus, a high coarse sand fraction is observed in CA2. In contrast, as soils of CGG may be retained by roots of perennial species, erosion due to dust storms appears to be limited in CGG. The perennial species *L. chinensis* had started to dominate in CA9. Because this species is rhizomatous, it can invade abandoned cropland without being affected by wind erosion. Owing to domination by this perennial species, the fraction of coarse sand was smaller in CA9 than that in CA2. *L. chinensis* predominates in habitats with relatively abundant water (Yanagawa et al., 2015), so that the species first invades abandoned cropland and does not dominate in CGG. As observed in many arid and semiarid landscapes, *L. chinensis* invasion causes aeolian deposits by dust storms and changes soil water conditions that are responses called negative soil–plant feedbacks (Ravi et al., 2010). Wind borne fine soil particles are deposited onto *L. chinensis*, which results in considerable changes in soil texture around the *L. chinensis* and has low rates of infiltration and high nutrient content. This explains the preferential establishment of new vegetative grass growth around *L. chinensis* and the mortality of *L. chinensis*.

Abundant available P resulting from past fertilization may account for the low species richness in CA2. The negative relationships between species richness and soil available P ($r = -0.996$) are consistent with previous studies (Lambers et al., 2013). Phosphorus readily leaches to the subsoil. In semiarid land, however, leaching of available P in the surface soil is slow, owing to the low precipitation. Thus, available P contents were significantly higher in CA2 and CA9 than that in CGG. P limitation promoted species-rich plant communities in low-producing plant communities (Olde Venterink, 2011). The content of soil available P was originally limited in semiarid Mongolian grassland. Species from the most P-impoverished soils are also very poor competitors at higher P availability, giving way to more competitive annual species when the soil P concentrations are increased (Lambers et al., 2013). These changes in the phosphorus availability were the limitations of the recovery process (i.e., low species richness and similarity index) in CA2 and CA9.

We thus suggest that factors limiting recovery processes in abandoned Mongolian cropland in early succession stages are abundantly available P and coarse sand. The low fine sand content in CA18 indicates that the impacts of cropping persist for a long time in Mongolia. These soil properties may slow the recovery of species composition in abandoned Mongolian cropland. Characterizing the impact of dust storms on the relationship between these soil physicochemical properties and vegetation recovery process is warranted in future. Since leguminous grass planting could be ascribed to high plant uptakes and possibly to high sequestrations of P in plant biomass (Wang and Wang, 2013), leguminous grass planting is one of options to restore abandoned cropland.

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