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Effects of crop abandonment and grazing exclusion on available soil water and other soil properties in a semi-arid Mongolian grassland

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ABSTRACT

Improper cropping and overgrazing have led to land degradation in semi-arid regions, resulting in desertification. During desertification, vegetation changes have been widely observed, and are likely controlled to some extent by soil water. The purpose of this study was to investigate changes in soil physical properties, organic C, and vegetation induced by land-use changes, with special reference to the dynamics of available soil water. We selected four study sites in a typical Mongolian steppe grassland: grassland protected from grazing, grazed grassland, abandoned cropland, and cultivated cropland. Grazing exclusion increased the cover of perennial grass, with little increase in the root weight. Since there was no difference in available water between the grasslands with and without grazing, there appears to be no serious soil compaction due to overgrazing. On the other hand, vegetation cover and the number of species were poor in both abandoned cropland and cultivated cropland. However, the root weight was greater in abandoned cropland. Although the abandonment of cultivation appeared to increase organic C, available water did not differ significantly in comparison with cultivated cropland. The silt contents were significantly lower in abandoned and cultivated cropland than in both grasslands, suggesting the effects of wind erosion. In addition, the silt contents were positively correlated with the volume fraction of storage pores for available water. Therefore, the lower silt contents may constrain the volume of available water in abandoned cropland. Moreover, the unsaturated hydraulic conductivity results indicated that the diameters of storage pores for available water at the present study sites were smaller than those suggested by previous studies. Although the differences in vegetation cover by different land-use types were observed at every site, differences in the volume of available water were observed at between abandoned cropland and cultivated cropland. The reason why the no differences in available water between grazed grassland and grasslands protected from grazing may be short time of grazing exclusion for 2 years for evaluating the effects of exclusion on soil properties.

1. Introduction

Improper cropping and overgrazing are the main factors responsible for soil degradation in semi-arid regions. Overgrazing alters the floristic composition from perennial grasses to annual forbs and from species that are palatable to livestock to non-palatable species (McIntyre and Lavorel, 2001; Pakeman, 2004; Diaz et al., 2007). These changes have also been reported in Mongolia (Fernandez-Gimenez and Allen-Diaz, 1999, 2001; Sasaki et al., 2005, 2007). In addition, improper cropping and subsequent abandonment can decrease the species richness and the cover of perennial grasses (Zhao et al., 2005). Subsequently, it takes a long time to restore the vegetation in abandoned cropland (Dean and Milton, 1995; Cody, 2000; Kosmas et al., 2000; Zhao et al., 2005).

In semi-arid regions, maintaining a high vegetation cover is essential for soil conservation, and vegetation cover is strongly controlled by the soil water regime in semi-arid regions such as Mongolia (Miyazaki et al., 2001). Therefore, the unsaturated hydraulic properties of soils may play important roles in semi-arid regions. Nevertheless, there have been insufficient investigations of the effect of land-use types on unsaturated hydraulic properties, including the effects of grazing exclusion versus overgrazing (Proffitt et al., 1995; Greenwood et al., 1998; Zhao et al., 2007) and

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continuing cultivation versus the abandonment of cultivation (Ahuja et al., 1998; Or et al., 2000; Schwartz et al., 2003). These studies cited above mainly focused on the range of near-saturated hydraulic conductivity, which depends on the sizes and volume fractions of macropores, and have not sufficiently considered the availability of water for plants. In general, plant-available water is held in pores ranging from 0.2 to 30 μm (Kay and VandenBygaart, 2002), 0.5 to 50 μm (Greenland, 1977), or 0.2 to 60 μm (Hermawan and Cameron, 1993). Only a few studies have examined the relationship between the soil pores that hold available water and land-use changes (Greenland, 1977; Hermawan and Cameron, 1993; Pagliai et al., 1995, 2004; VandenBygaart et al., 1999; Kay and VandenBygaart, 2002). However, it is not yet fully understood which pore size classes are most responsible for the availability of water to plants after grazing exclusion and the abandonment of cultivation in semi-arid grasslands.

A positive correlation between soil organic C and available water has been well documented (Hudson, 1994; Emerson, 1995), as has the negative correlation between bulk density and available water in compacted soils (Archer and Smith, 1972; Zhao et al., 2007). These relationships also exist for croplands under continuous tillage (Bowman et al., 1990; Zhao et al., 2005) and for some continuously grazed grasslands (Zhao et al., 2007) in semi-arid regions. For example, declines in organic C and available water are associated with increasing bulk density. Although the effects of land-use changes, such as grazing exclusion and the abandonment of cultivation, on soil organic C and physical properties are significant during the early stages of the change (Zhao et al., 2005), limited quantitative research has been carried out (Martinez-Fernandez et al., 1995; Greenwood et al., 1998; Li and Shao, 2006), and the results of these studies are not always consistent. The purpose of the present study was to investigate the differences in soil physical properties, organic C, and vegetation that result from land-use changes, with special reference to the dynamics of available soil water. Understanding these aspects is important to identify the factors that control the recovery process of vegetation in overgrazed grasslands and abandoned croplands.

2. Materials and methods

2.1. Site description

To investigate the effects of changes in land use from grazing to grazing exclusion and from cultivation to the abandonment of cultivation, we selected a typical area in which all four land uses were occurred. The study sites were located in the Kherlen Bayan-Ulaan (KBU) of Mongolia, where the meteorological and topographical conditions and the parent materials of the soils were similar among sites.

KBU (47°12′50.3″N, 108°44′14.4″E) is located in the middle reaches of the Kherlen River and has a steppe climate. Based on meteorological data provided by Mongolia's Institute of Meteorology and Hydrology, Ministry of Nature and Environment, mean annual precipitation is about 180 mm (the average from 1993 to 2003), and most of the annual precipitation falls in summer, from May to July. The summer rain is critical for the growth of grasses. Annual potential evaporation is 508 mm (Asano et al., 2007), therefore, KBU is classified as a semi-arid region (index is 0.35). The mean annual temperature is 2.5 °C (the average from 1993 to 2003), with a maximum temperature of about 30 °C in July and a minimum of about −30 °C in January. The dominant grass species are *Stipa krylovii*, *Carex duriuscula*, and *Cleistogenes squarrosa*. The dominant soils are Haplic Kastanozems (FAO/ISRIC/ISSS, 1998) based on the soil profile and the physical and chemical properties of the soils. The soil parent materials are loess deposits. In KBU, the number of grazing livestock (sheep, goat, cattle and house) decrease to a minimum of about 25,500 during the spring, summer and autumn, and increases to a peak of about 115,700 in winter. Since the KBU grassland is used as an overwintering place for local herders, it is under the overgrazing condition in winter time (Onda et al., 2007).

We selected four study sites: Grassland that had been protected from grazing (grazing exclusion, EG) since July 2002 as part of the Rangelands Atmosphere-Hydrosphere-Biosphere Interaction Study Experiment in Northeastern Asia (RAISE). The size of the protected area was 170 m × 200 m. The EG study site was situated within this exclosure, but more than 10 m from the fence used to exclude livestock. Grazed grasslands (GG) had been actively grazed for at least a few hundreds years. The GG study site was located more than 10 m from the fence used to protect the EG sites from grazing. The abandoned cropland (AC) had been cultivated from 1962 until 1991. Wheat and maize had been cultivated using synthetic fertilizer and irrigation from 1972 to 1991. The dominant plant species after 10 years of lying fallow (see Section 2.3 for details) differed from those in the surrounding grasslands. This site was located 50 m from the final site type, the cultivated cropland (CC). The CC site has been managed by Buyant Bulag Co., Ltd. since 1992. Before 1992, the land use was similar to that at the AC site. Since 1992, wheat was sown once per year in the summer, without irrigation or fertilizer. The CC site was 50 m from the AC site. The CC sites was protected from grazing, and the AC site was not.

2.2. Soil and vegetation surveys

The soil and vegetation surveys were carried out in 2004 at each study site. Soil sampling was performed using 20 m × 20 m quadrats at each site. The quadrat was established at each site after using a soil auger to confirm that the soil profile was typical of the study area. Within each quadrat, we obtained 16 bulk soil samples (each 200 cm^3) at 4-m intervals to a depth of 5 cm for chemical analysis and to estimate the total root weight. We also collected 16 core samples (each 100 cm^3) to a depth of 5 cm to assess the soil physical properties adjacent to the locations of the bulk soil samples. Our previous research (data not shown) indicated that the majority (>44%) of the organic C was found with in this layer. Vegetation was sampled in five quadrats (each 1 m × 1 m), which was separated by a minimum distance of 8 m, at each site. In each quadrat, we recorded the cover (%) using the method of Penfound and Howard (1940) and the height (cm) of all plant species.

2.3. Vegetation data analysis

Species richness was determined using the numbers of plant species found in the five quadrats at each site. All plant species were classified by growth form and life history (perennial grass, perennial forbs, annual forbs and shrubs) and their palatability to livestock. These classifications were based on Jigjidsuren and Johnson (2003), Grubov (2001), and information provided by Mongolian botanists. We then calculated the extended summed dominance ratio (E-SDR$_2$; Yamamoto et al., 1995) as follows to permit a quantitative comparison of the study sites.

$$E\text{-SDR}_2 = \frac{100}{2}\left(\frac{\sum_{i=1}^{n} C_i}{\sum_{i=1}^{n} C_i^d} + \frac{\sum_{i=1}^{n} H_i}{\sum_{i=1}^{n} H_i^d}\right) \quad (1)$$

where C_i is coverage level for the plant, and H_i is the height of one for the plant in ith quadrat, n is the number of quadrat (in this study, 5), and superscript d indicates the values of the dominant species. Plant roots were collected by hand from the soil samples used for the soil chemical analysis. These roots were washed with water and oven-dried at 60 °C for 48 h then weighed.

2.4. Soil organic C and physical properties

Bulk soil samples were air-dried and sieved to prepare samples of two different particle size classes for use in measuring the soil properties: less than 2.0 mm (physical properties) and less than 0.5 mm (organic carbon). The soil properties were determined according to the Soil Survey Laboratory Methods Manual (USDA-NRCS, 2004). Gravel (particles larger than 2.0 mm that did not pass through the sieve) was also collected, and was dried at 105 °C for 24 h, and then weighed. The total carbon content was determined using the dry combustion method and an NC analyzer (Sumigraph NC-900, Sumika Chemical Analysis Service Ltd., Tokyo, Japan). Organic C was determined by subtracting inorganic carbon (Clark and Ogg, 1942) from total carbon.

We used 16 undisturbed core samples to measure bulk densities and saturated hydraulic conductivities. First, we measured the solid and liquid phases of the soil samples using a volumenometer (DIK-1000, Daiki Rika Kogyo Co., Ltd., Tokyo). From the 16 samples at each site, we selected two samples with approximately the same mean solid volume (%) to measure the unsaturated hydraulic conductivity and particle size distribution. The soil core samples were air-dried and sieved to obtain all particles <2.0 mm. The particle size distribution for each site was determined using the pipette method. Each sample was analyzed three times to obtain a mean value for the particle size distribution.

2.5. Hydraulic properties and pore size distribution

Saturated hydraulic conductivity, K_{sat} (cm s^{-1}), was determined using the falling-head method for the 16 samples from each site. The soil's water-retention curve and the unsaturated hydraulic conductivity of two undisturbed core samples were determined using the multistep-outflow method (Fujimaki and Inoue, 2003) at each site. This method gives actual soil water-retention data and hydraulic conductivity data instead of the parameter values for prescribed functions. The water-retention data were fitted with a modified version of Shiozawa's equation:

$$\theta = \frac{\theta\mathrm{sat} - \xi}{\left[1 + (ah)^n\right]^m} + \xi\left\{1 - \left[\frac{\ln(h+1)}{\ln(h_0+1)}\right]^2\right\} \tag{2}$$

where θ is the volumetric water content, θ_{sat} is the saturated θ, h is the suction (cm), and α, ξ, m, n, and h_0 are fitting parameters. The unsaturated hydraulic conductivity data were fitted with Campbell's equation:

$$K = K_{sat}\left(\frac{\theta}{\theta_{sat}}\right)^{\omega} \tag{3}$$

where ω is a fitting parameter. If only one point (θ, K) was obtained, ω could be determined by solving Eq. (3) for ω.

Available water, which is critical for plant growth, is defined as the difference between the water contents at field capacity and wilting point. In this study, we defined field capacity as the volumetric water content at 10^{-6} cm s^{-1} unsaturated hydraulic conductivity. The wilting point, generally defined as the water content at a water potential of −15,000 was estimated using the soil water-retention curves.

Unlike the distribution of inherently independent particle sizes, it is difficult to define the unit of pore, which is inevitably continuous. Therefore, the pore size distribution, $f(D)$, has generally been estimated from the soil water-retention curve based on the assumption that pores are bundles of cylindrical capillaries (Coppola, 2000; Miyamoto et al., 2003). The height to which water in a capillary tube will rise, h (m), is given by

$$h = \frac{2\gamma\cos\phi}{\rho_w g r} = \frac{\xi}{D} \tag{4}$$

where γ is the surface tension (=0.072 N/m), ϕ is the contact angle (rad), ρ_w is the density of water (10^3 kg m^{-3}), g is the gravitational constant (9.8 m s^{-2}), r is the inner radius of the cylinder that represents a capillary (m), D is the diameter of the cylinder (m), and ξ is a bulk coefficient (0.000029 m^2) when ϕ = 0. Eq. (4) implies that a cylindrical pore of diameter D is filled with water until the suction reaches h cm, beyond which it becomes empty. Function obtained by substituting Eq. (4) into a soil water-retention function which is expressed by saturation instead of water content gives a probability, $F(D)$, that an arbitrarily chosen water molecule in a saturated soil is located in a pore smaller than diameter D:

$$F(D) = Y = \int_0^D f(x)dx = \frac{\theta}{\theta_{sat}} \tag{5}$$

In other words, the degree of saturation (θ/θ_{sat}) can be considered as a cumulative distribution function of a probability-density function. Thus, the derivative of Eq. (5) provides the pore size distribution, $f(D)$. In the modified Shiozawa equation:

$$\frac{\theta}{\theta_{sat}} = \frac{1}{\theta_{sat}}\left(\frac{\theta_{sat} - \xi}{\left[1 + (ah)^n\right]^m} + \xi\left\{1 - \left[\frac{\ln(h+1)}{\ln(h_0+1)}\right]^2\right\}\right) \tag{6}$$

Since the derivative of the water-retention function is generally known, the derivative of Eq. (5) can be obtained using the chain rule:

$$\begin{aligned} F'(D) = f(D) &= \frac{dY}{dh}\frac{dh}{dD} \\ &= \frac{1}{\theta_{sat}}\left\{\frac{ma^n n(\theta_{sat} - \xi)(\xi/D)^{n-1}}{\left[1 + (a\xi/D)^n\right]^{m+1}} + \frac{2\xi\ln[(\zeta/D) + 1]}{\left[\ln(h_0+1)\right]^2[(\xi/D) + 1]}\right\}\left(\frac{\xi}{D^2}\right) \end{aligned} \tag{7}$$

The $f(D)$ calculated with Eq. (7) increases with decreasing D. Since it is difficult to compare the dominant pore size from $f(D)$, $f(\log_{10} D)$, is widely used instead of $f(D)$ (Coppola, 2000; Miyamoto et al., 2003):

$$\begin{aligned} F'(\log_{10} D) = f(\log_{10} D) &= \frac{dY}{d(\log_{10} h)}\frac{d(\log_{10} h)}{d(\log_{10} D)} = -\frac{dY}{d(\log_{10} h)} \\ &= -\frac{dY}{dh}\frac{dh}{d(\log_{10} h)} = -\ln(10)h\frac{dY}{dh} \end{aligned} \tag{8}$$

Note that integrating $f(\log_{10} D)$ with respect to D does not give a value of 1. It is $f(D)$ that approaches a value of 1 by integrating with respect to D. To obtain a definite integral that implies the proportion of the total pore space accounted for by a given range of pore diameters, $f(\log_{10} D)$ must be integrated with respect to $\log_{10} D$, not D.

The proportion of the pore size distribution in each pore size class was calculated by integrating $f(\log_{10} D)$ across the range of pore sizes for that class. The real porosity in each pore size class was calculated by multiplying the one calculated in the previous sentence by the total porosity.

2.6. Statistical analysis

Mean soil property data from the 16 samples were compared using a post hoc Scheffé's test. Correlations between the pore size distribution and root weight and other soil properties (n = 8) were expressed using Pearson's correlation coefficient. The number of samples was consisted of two samples at each site. Because of the proximity of the two groups of soil samples obtained from each site, the data for all soil properties was considered to represent the same sampling point when we calculated these correlations. All statistical analyses were performed using version 2.7.2 of the R software for Windows (R Development Core Team, 2008).

3. Results and discussion

3.1. Vegetation

The results of the vegetation survey (Table 1) suggest that the species composition at EG and GG consisted mainly of perennial species, and the value of E-SDR$_2$ was higher in EG than in GG for most species. The grassland vegetation seemed to respond to grazing exclusion by increasing the numbers of shrubs, perennial species, and palatable species (Table 1), as was shown in previous studies of grazing exclusion (Wahren et al., 1994; Pettit and Froend, 2001; Sasaki et al., 2007). Root weights in the top 5 cm of the soil did not differ significantly between EG and GG, suggesting that the primary vegetation change that resulted from grazing exclusion occurred above the ground surface owing to active growth of aboveground plant parts. Although the vegetation at AC and CC had a very low cover, a small number of species, and a low abundance of annual species compared with the grassland sites, root weight was significantly higher at AC than at CC. In addition, the root weight at the AC site did not differ significantly from that at EG and GG. These results suggest that the aboveground vegetation at AC was affected by past cultivation practices, even after 10 years had elapsed (Zhao et al., 2005; Li et al., 2008). On the other hand, it is likely that the soil physical and chemical properties at AC would have been changed by the increased root growth, since roots can create macropores (Tippkötter, 1983) and can increase soil organic matter (thus, organic C) as a result of the decay of dead roots.

3.2. Soil organic C and physical properties

Table 2 shows the organic C and physical properties of the soil samples. Organic C was significantly higher at GG than at EG, AC, and CC, and was significantly higher at AC than at CC, which may indicate the effect of continuous cultivation at the latter site (Wang et al., 2008). The cropland results suggest that organic C increased after the abandonment of cultivation, because it is well known that organic C increases rapidly soon after the abandonment of cultivation (Zhao et al., 2005). The higher organic C contents at EG and GG than at AC and CC were probably caused by a greater input of organic C under the grassland vegetation than would occur under cultivation (Cerri et al., 1991; Guo and Gifford, 2002). The significant difference in organic C between the EG and GG would be caused by a decrease in urine and dung inputs at EG as a result of the grazing exclusion (Carran and Theobald, 2000; Liebig et al., 2006).

The clay and silt contents at EG and GG were clearly higher than those at AC and CC. Since our four study sites were located at sites with comparable geomorphic features and similar soil profiles, these results may indicate the influence of wind erosion at AC and CC. Because croplands generally have longer periods when bare earth is exposed, especially after plowing, these sites are more vulnerable to wind erosion, which is well known to reduce the clay and silt contents of exposed soils (Kokubun, 1960). Increased wind erosion has also been observed in cultivated land in northern-east Asia (Su et al., 2004). Wind erosion may be responsible for the high gravel weights and high bulk density, especially at CC. Although the silt content was lowest at AC, there were no clear differences in bulk density and the weight of gravel between AC, EG, and GG. However, this result suggests that although the particle size distribution was not greatly changed during the 10 years following the abandonment of cultivation, soil bulk density was apparently decreased by this land-use change. Bulk density did not differ obviously between EG and GG, which suggests that the soil was not greatly compacted by grazing.

3.3. Soil hydraulic properties and pore size distribution

Fig. 1 shows the unsaturated hydraulic conductivity results for the soils at the four sites. For EG, the unsaturated hydraulic conductivity at $\theta = 0.2$ (near field capacity) was smaller than that of GG, but became greater than that of GG at $\theta = 0.35$. Similar results were reported for the near-saturated hydraulic conductivity in a study in which unsaturated hydraulic conductivity increased after 2.5 years of grazing exclusion (Greenwood et al., 1998). However, water contents greater than field capacity would be rare in semi-arid regions such as our study area. Data collected by the RAISE project suggests that θ ranged between 0.1 and 0.2 $cm^3\ cm^{-3}$ to a depth of 5 cm at the study site in the summer of 2005 (http://raise.suiri.tsukuba.ac.jp/new/index.html). This suggests that the K value at EG would usually have been the same as or lower than that

Table 1
Vegetation cover, number of species, and the five most abundant species at each site.

Study site			EG	GG	AC	CC
Mean vegetation cover (%)			60	48	0.6	26
Number of species			10	11	2	4
Weight of roots (g L^{-1})			3.21a	4.83a	2.32ab	0.69c
Species	Life form	Palatability	E-SDR$_2$			
			EG	GG	AC	CC
Stipa krylovii	PG	P	100	55		
Carex duriuscula	PG	P	51	47		
Cleistogenes squarrosa	PG	P	42	30		
Convolvulus ammannii	PF	N	24	17		
Caragana stenophylla	S	N	23			
Artemisia frigida	PF	N		15		
Chenopodium aristatum	AF	N			2	
Potentilla bifurca	PF	P			2	
Species A						45
Artemisia dracunculus	AF	N				8
Species B						7
Artemisia adamsii	AF	N				5

EG, grassland with grazing exclusion; GG, grazed grassland; AC, abandoned cultivation; and CC, continuing cultivation. The vegetation results represent the means of five (1 m × 1 m) quadrats at each site, except for root weight, which represents the mean of 16 soil samples to a depth of 5 cm. E-SDR$_2$ represents the degree of dominance of each species at the four study sites. Life form abbreviations: PG, perennial grass; PF, perennial forb; S, shrub; AG, annual grass; and AF, annual forb. Palatability for livestock: P, palatable; N, non-palatable. Means labeled with different letters differ significantly ($P < 0.05$, Scheffé's post hoc test, $n = 16$). Species A and B were not identified species.

Table 2
Organic C concentration and physical properties of the soil samples.

Site	Organic C ($g\,kg^{-1}$)	Dry weight of gravel (>2 mm) ($g\,L^{-2}$)	Bulk density ($mg\,m^{-3}$)	Particle size distribution (%)			
				Clay	Silt	Fine sand	Coarse sand
EG	0.21b	39.70b	1.27b	9.08	23.26	11.64	56.01
	(0.01)	(5.79)	(0.02)	(1.80)	(0.26)	(1.10)	(0.96)
GG	0.25a	29.63b	1.22b	14.16	20.42	14.58	50.83
	(0.01)	(3.07)	(0.02)	(2.97)	(0.21)	(3.66)	(6.42)
AC	0.18b	38.35b	1.21b	9.54	5.56	32.18	52.71
	(0.01)	(2.94)	(0.042)	(0.97)	(0.19)	(2.36)	(3.15)
CC	0.10c	63.12a	1.42a	3.70	8.85	26.82	60.62
	(0.01)	(3.17)	(0.02)	(0.41)	(0.60)	(1.07)	(0.88)

EG, grassland with grazing exclusion; GG, grazed grassland; AC, abandoned cultivation; and CC, continuing cultivation. Values of organic C, dry weight of gravel, and bulk density are the means of 16 samples, and the particle size distribution data is the mean value of two samples. Means for a given variable labeled with different letters differ significantly ($P < 0.05$, Scheffé's post hoc test, $n = 16$). Values represent mean values followed by standard errors in parentheses. Each soil sample was analyzed three times, except for the dry weight of gravel and bulk density.

of GG in 2005, and that serious soil compaction did not occur as a result of livestock trampling at GG. For AC, the unsaturated hydraulic conductivity at $\theta = 0.2$ (near field capacity) was smaller than that at CC, possibly because of the greater gravel content at CC.

Fig. 2 shows the water-retention curves for the soils at each site. Although soil compaction due to livestock trampling is known to reduce the amount of water available to plants (Zhao et al., 2007), our results showed no obvious reduction in available water at GG. As noted previously, there did not appear to be serious soil compaction due to livestock trampling at GG. However, grazing pressure may be quite heterogeneous, and effects of grazing on soils by livestock appear only after integrating the less pressure for many years. Therefore, it may thus take several more years before differences in soil physical properties become clear between these two sites (Steffens et al., 2008). At low suction values, the water content at a given suction was smaller at CC than at the other sites. This result disagrees with those of previous studies (Ahuja et al., 1998; Schwartz et al., 2003), which reported increased water-retention at low suction as a result of tillage. However, these previous studies also observed a decrease in bulk density as a result of tillage, which was not observed in the present study; instead, we found an increase in the content of coarse materials in the cultivated cropland, which has been frequently observed in Mongolia (e.g., Pankova, 1994). Therefore, it seems reasonable that the low water content of the CC soil at low suction was caused by continuous cultivation. On the other hand, the similarity of the water contents at the EG, GG, and AC sites at low suction suggests that the effect of past cultivation was diminishing. The water contents at field capacity (θ at $K = 10^{-6}$ cm s^{-1}; Fig. 1) were lower for the AC and CC soils than for the EG and GG soils. In addition, the four study sites had similar water contents at the wilting point (θ at $h = 15{,}000$ cm; horizontal line in Fig. 2). Therefore, the EG and GG soils had more available water than the AC and CC soils (Table 3). The differences in available water between AC and CC and between EG and GG were not significant. Moreover, the water contents of the AC soil at $50 < h < 600$ cm were lower than those of the EG and GG soils, indicating that the effects of past cultivation can still be detected at high suction and that these effects may have led to the lower available water at AC.

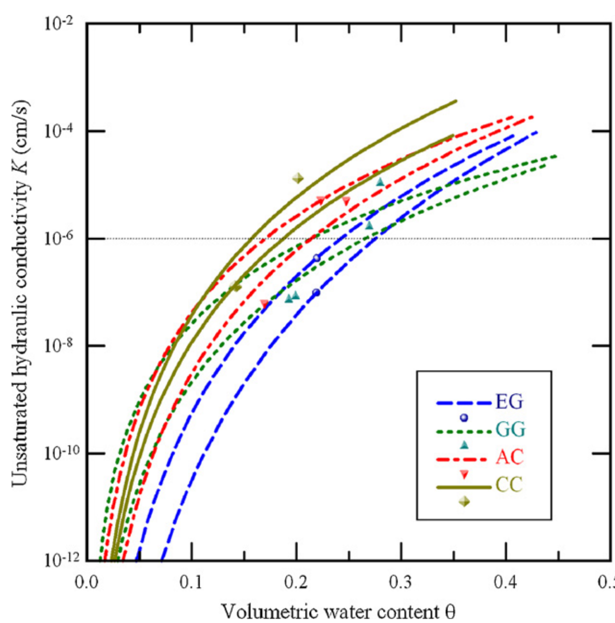

Fig. 1. Unsaturated hydraulic conductivity of the soil samples as a function of the volumetric moisture content EG, grassland with grazing exclusion; GG, grazed grassland; AC, abandoned cultivation; and CC, continuing cultivation. Every site have the repetition, the two curves with the same style represent the hydraulic properties from the same site. Each point was obtained from the direct method, and each curve was determined by fitting the points and saturated hydraulic conductivity.

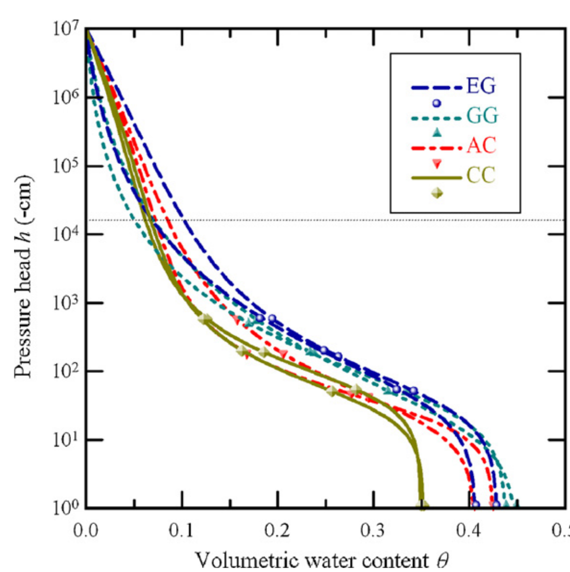

Fig. 2. Soil water-retention curves for the soil samples from the four sites: pressure head as a function of the volumetric moisture content. EG, grassland with grazing exclusion; GG, grazed grassland; AC, abandoned cultivation; and CC, continuing cultivation. The horizontal line represents the wilting point ($h = 15{,}000$ cm). Every site have the repetition, the two curves with the same style represent the water-retention properties from the same site. Each point (retention datum) was directly obtained from equilibration under the multistep-outflow experiment, and each curve was determined by fitting the retention data.

Table 3
Hydraulic and porosity properties of the soil samples.

Site	Saturated hydraulic conductivity (cm s^{-1})	Available water (cm^3 dm^{-3})	Pore size at field capacity (μm)	Porosity of each pore size class (%)				Total porosity (%)
				Micropores	Storage pores for available water	Mesopores	Macropores	
EG	3.49×10^{-3} a	0.17	9.02	11.74	15.98	9.28	15.40	52.44
	(6.98×10^{-4})	(<0.01)	(1.96)	(1.28)	(0.14)	(1.34)	(1.15)	(1.24)
GG	4.60×10^{-3} a	0.17	9.67	8.78	15.74	9.54	19.41	53.38
	(1.23×10^{-3})	(0.02)	(3.65)	(1.34)	(0.87)	(4.25)	(0.21)	(2.26)
AC	3.00×10^{-3} a	0.11	9.06	10.33	10.40	8.18	24.64	53.51
	(4.96×10^{-4})	(0.02)	(0.55)	(1.41)	(2.39)	(0.31)	(2.06)	(1.43)
CC	3.93×10^{-3} a	0.11	7.29	7.94	8.60	10.05	15.82	42.54
	(2.67×10^{-4})	(0.02)	(0.75)	(0.76)	(0.90)	(0.10)	(2.74)	(2.51)

EG, grassland with grazing exclusion; GG, grazed grassland; AC, abandoned cultivation; and CC, continuing cultivation. Values of saturated hydraulic properties represent the means of 16 samples; the values of other properties represent the means of two samples. Means for a variable labeled with different letters differ significantly ($P < 0.05$, Scheffé's post hoc test, $n = 16$). Mean values are followed by standard errors in parentheses. Pores with an equivalent diameter of <0.1 μm, 0.1 μm to field capacity, field capacity to 30 μm, and >30 μm are referred to as micropores, storage pores for available water, mesopores, and macropores, respectively.

Fig. 3 illustrates the estimated pore size distributions of the four soils, and Table 3 shows the total porosity and the pore size distribution. Here, we have chosen a simple system with four classes of pore size (micropores, storage pores for available water, mesopores, and macropores) based on the functional relationship between these pores and soil water. Although we chose a range of pore sizes from 0.1 μm to field capacity (7.29–9.67 μm) to represent available soil water, previous studies have classified pores of diameters ranging from 0.2 to 30 μm (Kay and VandenBygaart, 2002), 0.5 to 50 μm (Greenland, 1977), or 0.2 to 60 μm (Hermawan and Cameron, 1993) as storage pores for available water. These authors assumed that field capacity occurred at a single suction value. However, Hillel (1988) and William and Robert (2004) demonstrated that field capacity will differ among soils with different conditions. Therefore, we chose to use the pore size at the suction that occurs at field capacity (using Eq. (4)) to more clearly express the differences in available water among the sites.

Pores with equivalent diameters <0.1 μm are referred to as micropores. Water in these pores is generally not available to plants (Kay and VandenBygaart, 2002). Pores with an equivalent diameter between 0.1 μm and field capacity are storage pores for available water, and are particularly important for the storage of water that is capable of supporting plant growth in semi-arid regions. The pore sizes of storage pores for available water in our study were smaller than those in previous studies (Greenland, 1977; Hermawan and Cameron, 1993; Kay and VandenBygaart, 2002). The difference between "storage pores for available water" and "available water" is that the former pores are controlled by the total porosity value. Pores with an equivalent diameter between field capacity and 30 μm are referred to as mesopores, and are also important for the storage of water for plant growth, but these pores are only important immediately after rain falls in semi-arid regions. Pores with diameters >30 μm are referred to as macropores. Water flows primarily through these pores during infiltration and drainage, and consequently these pores exert a major control on soil aeration (Kay and VandenBygaart, 2002).

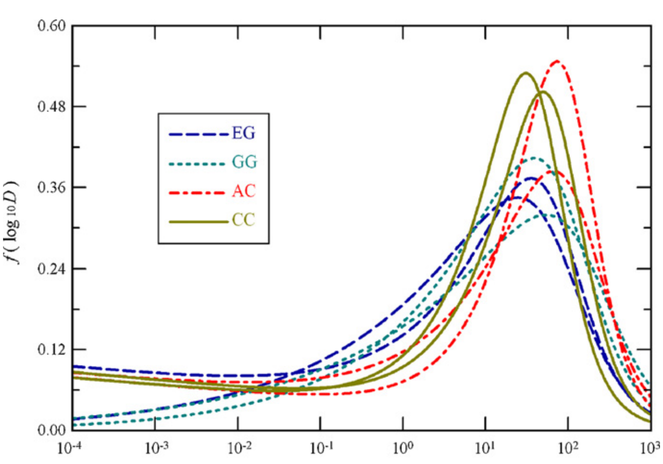

Fig. 3. Pore size distributions for the soil samples from the four sites as a function of pore size. EG, grassland with grazing exclusion; GG, grazed grassland; AC, abandoned cultivation; and CC, continuing cultivation. Every site have the repetition, the two curves with the same style represent the pore size distributions from the same site.

There were no significant differences in total porosity, storage pores for available water, and mesopores between the EG and GG soils (Table 3). However, macropores were more abundant at GG than EG. These results suggest that drainage conditions may not have been degraded by livestock trampling.

Total porosity at AC was approximately the same as at EG and GG, but was considerably greater than that at CC. In addition, the volume fraction of macropores was significantly greater at AC than at CC. On the other hand, the volume fractions of storage pores for available water were only slightly greater at AC than at CC. These results suggest that porosity consisting of macropores has increased at this relatively early stage after the abandonment of cultivation. In contrast, it appears to be difficult to improve the soil's microstructure, which consists of the storage pores for available water, after it has been damaged by cultivation. In addition, there were no significant difference in mesopores among the four sites, which suggests that the relatively larger mesopores may not have been affected by grazing and cropping.

3.4. Correlations among pore size distribution, root weight, and soil properties

Table 4 shows the Pearson's correlation coefficients among pore size distribution, root weight, and soil properties. The proportion of storage pores for available water was significantly correlated with several other soil properties. This demonstrates that storage pores for available water were an important factor for plant roots and depended on other soil properties. However, the positive correlation between root weight and storage pores for available water differed from the results of previous reports of correlation between root density and macropores (Pagliai and De Nobili, 1993; Kay and VandenBygaart, 2002). Our results indicate that the root weight depends directly on the volume fraction of storage pores for available water; that is, roots may preferentially exploit pores of this size. There was a non-significant negative correlation between bulk density and storage pores for available water, in contrast to the results of previous studies (Archer and Smith, 1972; Zhao et al., 2007). This result may have been caused by the lower available water content in the AC soil (Table 3), despite the bulk density of

Table 4
Pearson's correlation cofficients among soil properties and root weight data for all sites combined.

	Root weight	Organic C	Weight of gravel	Bulk density	Clay	Silt	Fine sand	Coarse sand
Micropores	0.247	0.359	−0.476	−0.389	0.142	0.282	−0.212	−0.167
Storage pores for available water	0.766*	0.828*	−0.773*	−0.646	0.649	0.856**	−0.823*	−0.383
Mesopores	0.410	−0.122	0.102	0.015	−0.333	0.116	−0.311	0.620
Macropores	−0.178	0.141	−0.215	−0.449	0.264	−0.497	0.538	−0.395

Pores with an equivalent diameter of <0.1 μm, 0.1 μm to field capacity, field capacity to 30 μm, and >30 μm are referred to as micropores, storage pores for available water, mesopores, and macropores, respectively.
*$P<0.005$, **$P<0.01$, $n=8$.

AC soils was not different significantly with those of the EG and GG soils (Table 2). The pores for storing available water were also significantly and positively correlated with the silt content and organic C. The increased organic C content may result from the increased root weight. However, once the silt fraction decreases as a result of wind erosion, it does not appear to recover. Therefore, the volume fraction of pores for available water seemed to be constrained by silt contents in the AC soil. This may explain why the AC and CC soils did not differ in available water (Table 3), but the organic C content was significantly higher at AC (Table 2). Thus, small silt contents may be caused by land-use changes that have a strong effect on available water.

4. Conclusions

Although grazing exclusion did not significantly increase root weight or available water, and rather decreased organic C, it increased the dominance of perennial grasses and other life forms at the study site. On the other hand, vegetation cover increased and the number of plant species did not change greatly as a result of grazing exclusion. Further studies would be necessary to demonstrate effects of grazing exclusion on soil properties. In the croplands, the root weight was significantly increased after abandoning cultivation, but the coverage of vegetation and number of species both decreased obviously. The organic C content increased remarkably as a result of the abandonment of cultivation. However, available water did not differ clearly between abandoned and cultivated cropland. The decreased silt content that would have resulted from wind erosion under continuous cultivation appears to have affected these results.

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