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Soil physical properties response to grassland conversion from cropland on the semi-arid area

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ABSTRACT

Soil physical properties crucially affect vegetation restoration on the semi-arid Loess Plateau. Understanding how converting cropland into grassland affects soil physical properties is essential throughout a long-term natural vegetation restoration chronosequence. The objectives of this study were to determine the effects of naturally restored grassland from cropland (wheat) on soil physical properties over time. Hence, we analysed the effects on various soil physical properties at different restoration ages (0, 5, 15 and 30 years). Our results revealed that soil physical properties changed dynamically in response to the land use change over time. Grassland restoration increases soil texture coarseness in the upper soil layer (0–5 cm). After a 15-year restoration, soil hydraulic conductivity attained the maximum measured value, but in restoration age (to 30 years) did not further improve soil hydraulic conductivity. Restoration increased the field capacity and the soil water content under the restored grassland when compared with the cropland, but increases were not linearly related to the restoration age. Our study suggests that converting cropland into grassland improved the soil structure and soil–water conditions, and that the first 15 years of restoration was sufficient in order to achieve most of the improvements in soil physical properties. Our results will be helpful in providing soil hydraulic parameters to other researchers with the aim of improving the restored grassland to become more effective and sustainable on the semi-arid area. Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS natural regeneration; land use change; soil physical properties; soil–water characteristics; semi-arid region

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INTRODUCTION

Conversion from cropland to grassland has been proposed as an effective method for improving soil properties and promoting vegetation restoration. Conversion from cropland to grassland results in radical changes in vegetation within a short period (Huang *et al*., 2006; Lü *et al*., 2012). Therefore, vegetation restoration of degraded lands on the semi-arid area, where the environmental problem of soil–water and wind erosion is very grievous, was emphasized by the local government in 1991 (Fu *et al*., 2009). Then the large scale of land-use change undertaken for the 'Grain for Green' Program had a dramatic effect on development of soil properties in China. As important soil quality indicators, it is necessary to determine how the soil physical properties respond to a long-term natural vegetation restoration especially on the semi-arid area.

Many studies have reported that the changes of soil physical properties in restored grassland (Li and Shao, 2006), such as soil bulk density (Evrendilek *et al*., 2004; Breuer *et al*., 2006), saturated soil hydraulic conductivity (Bormann and Klaassen, 2008; Wu *et al*., 2013; Zhang *et al*., 2013), soil infiltrability (Zhao *et al*., 2013; Wu *et al*., 2016) and others (Su *et al*., 2005), which were contributed to the variation of total net primary productivity (Jia *et al*., 2011). In farmland, agriculture management practices may lead to a general decrease in soil physical quality and cause a variety of changes on soil–water balance (Gerten *et al*., 2008; Strudley *et al*., 2008). Previous studies have also reported that root activity, the development of biopores, improved aggregate stability resulting from greater carbon sequestration (Unger, 2001), and enhanced wetting-drying cycles mediated by the extraction of soil water by perennial grasses (Schwartz *et al*., 2003). Furthermore, temporal changes in land use and management, or in natural disturbances and cycles, can affect soil physical properties (Zhou *et al*., 2008).

Soil physical properties have a major influence on the transport of water and nutrients in soils. Soil physical properties have frequently been used as indicators when

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assessing the benefits of changing land use to restore vegetation (Wang *et al.*, 2012; Zhang *et al.*, 2013). Conventional soil tillage caused drastic and fast changes in soil physical properties (Logan *et al.*, 1991; Hermawan and Cameron, 1993). For hydrological modelling purposes, soil hydrological parameters are often characterized by constant values, e.g. the saturated hydraulic conductivity, infiltrability or field capacity (Bormann and Klaassen, 2008). In addition soil hydraulic conductivity is, in fact, a highly dynamic soil property (Lin *et al.*, 2005; Lei *et al.*, 2010, 2013).

On the semi-arid area, low precipitation amounts, high potential evapotranspiration and low water retention lead to water shortages which are the main limiting factors for vegetation restoration. Furthermore, severe soil erosion has resulted in soil and nutrient losses, and severe degradation of soil physical properties exhibited by increases in bulk density, and reductions in aggregate stability and water retention in this region (Zha and Tang, 2003; Li and Shao, 2006). Hence, changes in soil physical properties under different land uses can critically affect the success of vegetation restoration projects in this region. Some present studies have reported that the aggregate stability of cropland soils increased to the same levels as those of the natural steppe within 12 years of converting cropland back to grassland (Zhang *et al.*, 2013). Nevertheless the infiltration of rainwater into deeper soil layers decreased over time after restoration, the deepest infiltration and the highest water content occurred in the soils under the grassland that had most recently been converted from cropland (Qiu *et al.*, 2011). When grazing was prevented by fencing off areas of a steppe grassland on the Loess Plateau, the soil structure and soil–water capacity improved to a greater degree after 15 years than after only 5 years of grazing exclusion (Wu *et al.*, 2013). Changes in soil physical properties exhibit diverse patterns during succession after conversion of cropland to grassland (Zhang *et al.*, 2010). Therefore, it is necessary to investigate how soil physical properties change during a long-term conversion of cropland to grassland.

Soil physical properties on the semi-arid Loess Plateau are affected by the changes in vegetation cover and land use. Thus, attention to processes of land use change effect on specific soil properties over time is an important research topic. It could better evaluate the efficiency of the ecosystem restoration strategy. In this study, we assumed that soils from the three cropland before restoration had the same spatial textural homogeneity and followed the same underlying mechanism during restoration. The objectives of this study were to determine the effects of grassland conversion from cropland on soil physical properties after 5, 15 and 30 years of natural regeneration on the Loess Plateau.

MATERIALS AND METHODS

Study site

The study area was located in the Wangdonggou watershed (107°41′E, 35°14′N, 1, 120 m above sea level), at a field station of the National Ecosystem Research Network of China (NERE) in Changwu County, Shaanxi Province, China (Figure 1). The watershed includes a gully system and, since 1984, small watershed comprehensive management practices have been applied within it in order to solve the problem of immense losses of water and soil caused by severe runoff and erosion during rainfall events, as well to address the frequent droughts and low crop yields. Subsequently, the cropland was converted back to natural grasslands in the gully system. Based on climate data from 1984 to 2005, the mean annual precipitation is 584 mm, about 52% of which occurs between July and September. The annual mean temperature is 9.1 °C. The soil is a Heilu soil, which corresponds to a Calcarid Regosol according to the FAO/UNESCO classification system.

Experiment design and sampling

The study was undertaken in July, 2012. Based on the progression of grassland conversion from cropland occurring in the study area, we studied three grassland areas, in which conversion commenced 5, 15 and 30 years ago, respectively, and one cropland (wheat) area nearby about 500 m. The different restoration ages were considered as our treatments, where cropland (CL) was considered to represent a restoration age of 0 years, and the restored grassland (RG) areas had ages of 5, 15 and 30 years denoted by subscripts (i.e. RG_5, RG_{15} and RG_{30}). Conversion of the cropland, which had formerly been under grassland, back to grassland commenced in the RG_5, RG_{15} and RG_{30} areas in 2007, 1997 and 1982, respectively. Images of the four treatment areas are shown in Figure 2 The dominant species, total biomass, litter mass and belowground biomass (BGB) (0–50 cm) details for the different studied sites are given in Table I.

We established randomly three blocks (50 m × 50 m) within each treatment and five plots (10 m × 10 m) were randomly arranged within each block. Fifteen randomly located sampling quadrats (50 cm × 50 cm) in each of the treatment area (one quadrat randomly located in each plot) were established (Figure 1). Samples were collected in mid-July 2012, when the biomasses had reached the seasonal peak values. Undisturbed soil samples were taken from the centre of each sampling quadrat in the four treatments and were removed from different depth intervals (0–5, 5–10, 10–20, 20–30 and 30–50 cm). The litter, which comprised dead plant material, was estimated by harvesting it from square areas (0.25 m^2) in each quadrat located close to the plots. Three belowground core samples were

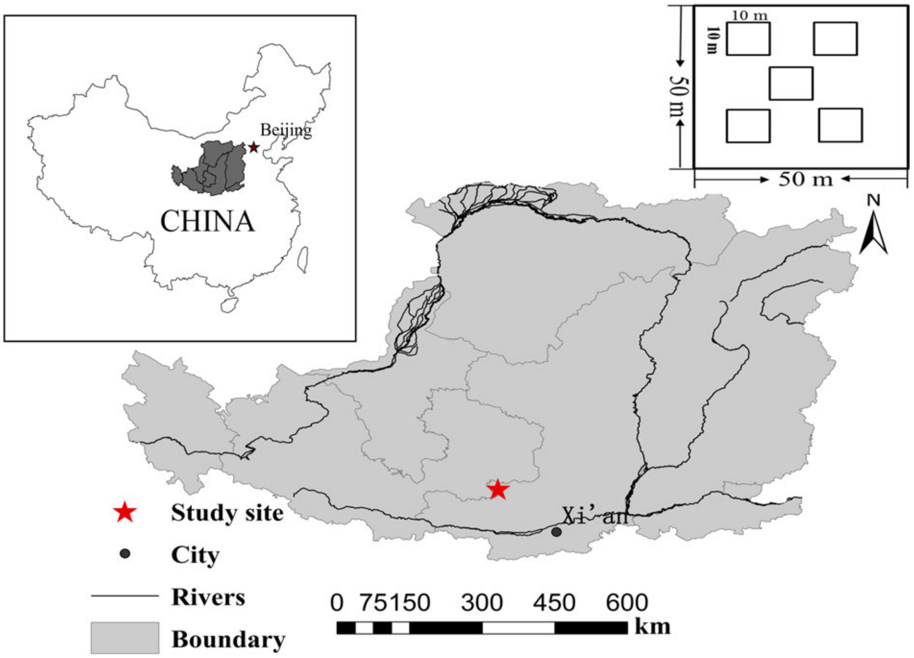

Figure 1. Location of the study site on the Loess Plateau. The shaded area in the upper left corner of the map represents the range of the Loess Plateau in China. The treatment and the arrangement of the blocks shown in the upper right corner.

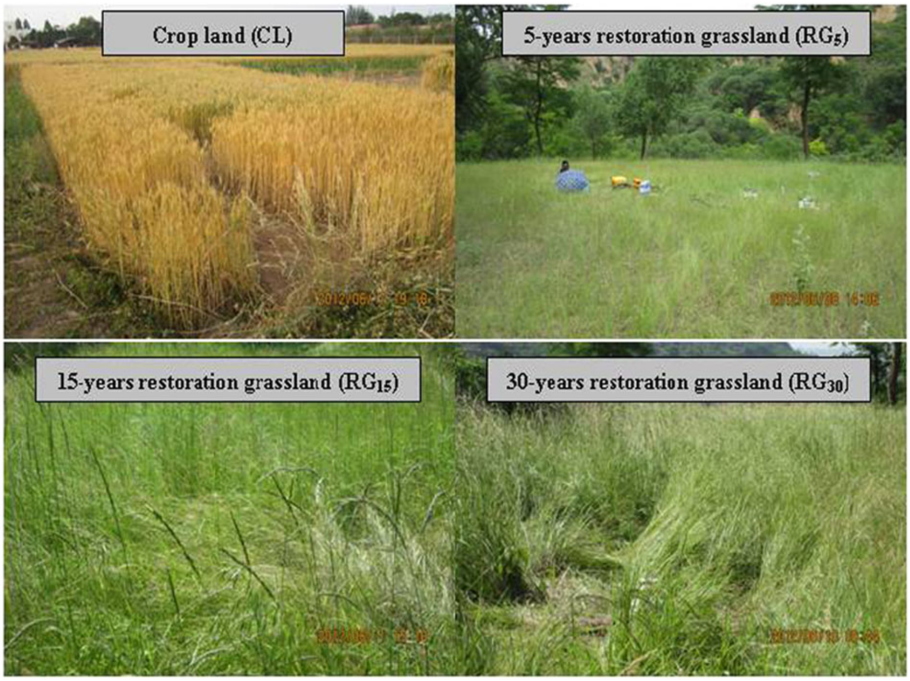

Figure 2. Landscapes of the cropland (CL) and restored grassland sites (RG_5, RG_{15} and RG_{30} represent grassland converted from cropland in 2007, 1997 and 1982, respectively).

extracted from the 0–50 cm soil layer from each quadrat using a cylinder auger, 80 mm in diameter, in order to determine BGB. The cored samples were taken to the laboratory for analysis.

For each BGB sample, plant parts were separated from the soil by washing over a 0.2-mm mesh and were oven-dried at 80 °C for 72 h before weighing in order to obtain the dry BGB.

Table I. Description of dominant species, total biomass, litter mass and belowground biomass (0–50 cm) during a 30-year restoration period when cropland (CL) was converted to restored grassland (RG).

Study sites	Dominant species	Total biomass ($g\,m^{-2}$)	Litter mass ($g\,m^{-2}$)	Belowground biomass ($g\,m^{-2}$)
CL	Cropland (wheat)	—	—	1257 ± 32
RG_5	*Agropyron cristatum Artemisia sacrorum*	161 ± 24	74 ± 6	1697 ± 95
RG_{15}	*Helictotrichon dahuricum Poa subfastigiata*	379 ± 62	103 ± 12	1409 ± 252
RG_{30}	*Poa subfastigiata Vicia amoena f. albiflora*	731 ± 147	342 ± 41	1763 ± 157

Note: Values of biomass and litter are expressed as mean ± standard deviation. Restoration process investigated at four sites representing the restoration chronosequence, and subscripts following RG denote the restoration age.

The 15 undisturbed soil samples obtained from each treatment were used to determine basic soil physical properties. The *in situ* soil core samples were slowly saturated from the base with deionized water before the flow was reversed and measured under a constant head to measure the saturated hydraulic conductivity (Ks) by the constant head method (Klute and Dirksen, 1986).

Soil–water characteristic curves (SWCC), also known as soil–water retention curves, of the soil samples were determined using the centrifugation method (Wu *et al.*, 2013). Each sample was first saturated with water for 24 h and then weighed to determine the soil–water content at saturation before submitting them to step-wise water extraction by applying different centrifuge rotation speeds to induce different suctions. A HITACHI CR21G centrifuge was used at a constant temperature of 20 °C. During the water desorption measurement procedure, the bulk density might change slightly, which could obviously have an influence on the SWCC (Lu *et al.*, 2004). However, the centrifuge method is still considered as an appropriate method for determining the characteristics of field soil–water properties (Reatto *et al.*, 2008). The bulk density at each suction was measured, and the volumetric soil–water content at each stage of the procedure was calculated taking into account the changes in bulk density. All data were expressed as the means of the quadrat values for each block.

A more detailed description of the equations used to derive the SWCC, the software and related methodologies are given by Wu *et al.* (2013). SWCC were fitted to the measured data by the Retention Curve Program (RETC), which was developed by the US Salinity Laboratory. The fitted SWCC gives pertinent soil–water parameters (θr, θs, α, n) that define the SWCC. The derivation of these parameters used the van Genuchten Model $m = 1 - 1/n$ Mualem (van Genuchten, 1980).

Following the *in situ* analyses, the cored soil samples were removed, and particle size distributions over the range of 0.02–2000 μm were measured by a Mastersizer 2000 (Malvern Instruments Ltd. UK), in the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau.

RESULTS

Saturated hydraulic conductivity

The saturated hydraulic conductivity of the soil changed significantly during the restoration process (Table II). In the surface layer (0–5 cm), the mean Ks (22.00–41.51 mm h^{-1}) values for all of the restored grassland soils were higher than those of the cropland soil (21.73 mm h^{-1}), and the maximum mean value in RG_{30}. Furthermore, a clear trend whereby Ks increased with the increase in restoration age was evident. However, in the underlying layers, this trend did not occur although Ks generally increased between the restoration ages of 0 and 15 years. Thus, in the 5–10 cm layer although the maximum mean Ks value was notably higher than that of the 0–5 cm layer, it was observed in the soil under RG_{15} (121.46 mm h^{-1}) rather than under RG_{30} (42.61 mm h^{-1}). In the 10–20 cm layer, the maximum mean value of Ks was observed under RG_5 (73.74 mm h^{-1}), and Ks decreased with the increase in the age of the restoration process. Furthermore, there were few differences among the four treatments in either the 20–30 cm or the 30–50 cm soil layers, and the two maximum values in those layers were both observed under RG_{15}. For the four treatments, the maximum mean Ks value of the profile (0–50 cm) was observed under RG_{15} (69.12 mm h^{-1}), which was 2.94 times greater than that of the cropland profile, and 82.8% greater than that of the RG_{30} profile (Table III and IV).

Field capacity

Field capacity determined from the fitted SWCC at a suction (or equivalent pressure head) of mm H_2O increased significantly after restoration (Table II). Taking the 0–5 cm soil layer as an example, the field capacity increased from 25.0% (cropland) to 33.0% (RG_5), and again to 36.2% (RG_{30}). The field capacities of the deeper soil layers (5–50 cm) followed similar increasing trends as restoration progressed over time. The results illustrated that soil–water holding capacity in the 0–50 cm soil profile was improved by grassland restoration.

Table II. Soil physical properties under cropland (CL) and three restored grassland (RG) sites at five soil depths. Note: RG is followed by subscripts that denote restoration age; mean ± standard deviation; saturated hydraulic conductivity (Ks).

Restoration stage	Soil depth (cm)	Median of Ks (mm h^{-1})	Ks (mm h^{-1})	Field capacity (%)	Porosity (%)	Bulk density (g cm^{-3})
CL	0–5	16.39	21.73 ± 7.55	24.98 ± 3.64	53.62 ± 1.39	1.23 ± 0.04
	5–10	14.67	20.58 ± 8.36	24.65 ± 2.28	50.25 ± 2.31	1.32 ± 0.06
	10–20	44.88	43.06 ± 2.59	25.96 ± 1.13	49.03 ± 3.00	1.35 ± 0.08
	20–30	3.99	4.13 ± 0.20	28.19 ± 1.51	46.72 ± 3.46	1.41 ± 0.09
	30–50	20.70	27.70 ± 9.91	25.36 ± 2.14	48.52 ± 2.37	1.36 ± 0.07
RG$_{5}$	0–5	22.76	22.00 ± 1.09	32.86 ± 1.62	53.70 ± 1.20	1.23 ± 0.03
	5–10	48.98	65.52 ± 13.38	28.38 ± 1.95	54.64 ± 0.46	1.20 ± 0.01
	10–20	39.97	73.74 ± 17.76	25.95 ± 1.76	53.94 ± 1.39	1.22 ± 0.04
	20–30	29.58	44.77 ± 11.49	25.37 ± 1.89	50.00 ± 2.09	1.33 ± 0.06
	30–50	3.38	4.76 ± 1.95	28.62 ± 0.85	45.06 ± 2.88	1.46 ± 0.08
RG$_{15}$	0–5	41.61	30.83 ± 5.23	32.57 ± 4.66	56.61 ± 1.24	1.15 ± 0.03
	5–10	94.30	121.46 ± 18.47	30.12 ± 3.50	55.54 ± 2.29	1.18 ± 0.06
	10–20	96.79	68.62 ± 9.86	28.36 ± 1.75	56.22 ± 2.94	1.16 ± 0.08
	20–30	96.61	91.79 ± 6.82	28.85 ± 0.64	55.12 ± 3.51	1.19 ± 0.09
	30–50	41.71	32.57 ± 12.92	30.54 ± 2.16	50.82 ± 1.26	1.30 ± 0.03
RG$_{30}$	0–5	55.31	41.51 ± 9.51	36.15 ± 4.68	55.57 ± 0.90	1.18 ± 0.02
	5–10	48.85	42.61 ± 8.82	33.10 ± 3.46	54.50 ± 2.04	1.21 ± 0.05
	10–20	45.14	61.81 ± 13.57	30.24 ± 2.02	52.90 ± 2.11	1.25 ± 0.06
	20–30	23.37	23.76 ± 5.47	29.76 ± 1.82	52.49 ± 2.36	1.26 ± 0.06
	30–50	21.99	18.81 ± 4.49	28.86 ± 1.60	51.46 ± 2.62	1.29 ± 0.07

Table III. Particle size composition of soil under cropland (CL) and three restored grassland sites at five soil depths. Note: RG is followed by subscripts that denote restoration age; mean ± standard deviation.

Restoration stage	Soil depth (cm)	Median diameter (μm)	Clay (<2 μm) (%)	Silt (2–50 μm) (%)	Sand (>50 μm) (%)
CL	0–5	15.35 ± 1.40	25.55 ± 2.63	64.11 ± 0.69	10.34 ± 2.91
	5–10	14.37 ± 1.64	27.71 ± 2.15	62.50 ± 1.70	9.79 ± 0.71
	10–20	14.06 ± 0.87	26.06 ± 1.34	67.23 ± 0.75	6.71 ± 2.04
	20–30	13.86 ± 0.99	27.45 ± 2.03	65.48 ± 1.28	7.07 ± 0.93
	30–50	13.79 ± 0.89	26.75 ± 1.54	67.34 ± 0.54	5.91 ± 1.25
RG$_{5}$	0–5	13.37 ± 2.20	29.07 ± 2.95	63.04 ± 0.33	7.90 ± 3.08
	5–10	16.69 ± 0.78	23.10 ± 0.42	65.41 ± 0.66	11.48 ± 1.02
	10–20	15.29 ± 1.24	24.26 ± 0.73	67.01 ± 0.71	8.73 ± 1.43
	20–30	15.26 ± 0.71	24.05 ± 0.62	68.26 ± 0.26	7.68 ± 0.66
	30–50	15.05 ± 0.93	24.01 ± 0.89	68.66 ± 0.67	7.33 ± 0.70
RG$_{15}$	0–5	17.32 ± 1.97	22.63 ± 1.29	62.44 ± 0.68	14.93 ± 1.95
	5–10	16.82 ± 1.38	23.22 ± 1.95	66.52 ± 2.01	10.27 ± 0.54
	10–20	17.54 ± 1.76	22.79 ± 1.33	65.53 ± 0.76	11.68 ± 2.05
	20–30	16.66 ± 1.40	22.61 ± 2.21	68.11 ± 1.41	9.28 ± 0.91
	30–50	16.43 ± 1.32	23.12 ± 1.49	67.91 ± 0.37	8.97 ± 1.25
RG$_{30}$	0–5	17.04 ± 1.06	23.02 ± 2.48	63.20 ± 0.47	13.78 ± 2.41
	5–10	15.41 ± 1.23	24.04 ± 1.99	66.99 ± 1.86	8.97 ± 1.05
	10–20	15.53 ± 1.75	24.41 ± 0.81	67.05 ± 0.10	8.55 ± 0.91
	20–30	16.17 ± 1.50	22.91 ± 1.93	68.73 ± 1.43	8.36 ± 0.53
	30–50	14.64 ± 1.35	25.30 ± 1.12	67.01 ± 0.71	7.69 ± 0.77

Bulk density and porosity

In the soils under either cropland or restoration grassland, the bulk density increased and porosity decreased with increasing depth (Table II). In general, the bulk density under cropland was higher, and the porosity was lower than under the restoration grasslands for all of the soil layers (Table II). The results illustrate that conversion of cropland to grassland improved the soil properties such that soil bulk density was decreased and porosity was increased overall. The porosity and bulk density of the soils in the study area tended to decline slightly at some time before or after 15 years of restoration as indicated by their values measured after 5 or 30 years, respectively, of restoration. Thus, under RG$_{15}$, the soil porosity was greater than that under either RG$_{5}$ or RG$_{30}$ while, correspondingly, the bulk

Table IV. Parameters derived from the soil–water characteristics curve for soils under the four treatments (Cropland, CL; and Restored Grassland (RG), where subscripts denote the restoration age in years) at five soil depths.

Restoration stage	Soil depth (cm)	Parameter				
		θ_r	θ_s	α	n	R^2
CL	0–5	0	0.5248	0.0117	1.1981	0.9975
	5–10	0	0.5171	0.0156	1.1861	0.9949
	10–20	0	0.4830	0.0062	1.1990	0.9964
	20–30	0.0443	0.4488	0.0019	1.257	0.9988
	30–50	0.0543	0.4842	0.0037	1.2826	0.9985
RG_5	0–5	0	0.4738	0.0019	1.1847	0.9929
	5–10	0.0036	0.4936	0.0048	1.1906	0.9967
	10–20	0.0106	0.5545	0.0281	1.1689	0.9979
	20–30	0.0074	0.5630	0.0515	1.1556	0.9984
	30–50	0	0.4741	0.0197	1.1250	0.9903
RG_{15}	0–5	0	0.4937	0.0028	1.1781	0.9969
	5–10	0	0.4861	0.0075	1.1558	0.9942
	10–20	0	0.4955	0.0096	1.1564	0.9974
	20–30	0	0.5027	0.0105	1.1517	0.9987
	30–50	0.1174	0.4674	0.0013	1.3538	0.9985
RG_{30}	0–5	0	0.4526	0.0007	1.1910	0.9969
	5–10	0	0.4717	0.0022	1.1686	0.9937
	10–20	0	0.4767	0.0048	1.1625	0.9951
	20–30	0	0.4334	0.0022	1.1742	0.9968
	30–50	0	0.4611	0.0045	1.1678	0.9973

Note: Parameters were derived using the van Genuchten Model, $m = 1 - 1/n$ Mualem. θ_r, residual volumetric water content; θ_s, saturated volumetric water content.

density under RG_{15} was less than that under either RG_5 or RG_{30}. This indicated that the changes in soil physical properties were not consistently improved but could also deteriorate as restoration progressed at the study site.

Particle size distribution

Under cropland, clay contents were less in the 0–5 cm soil layer than those in the layers below it while, correspondingly, sand contents were higher than those in the lower layers (Table III). In the 0–5 cm soil layer and when compared with the CL soil, under RG_5 the clay content increased and the sand content decreased but this pattern was inverted under RG_{15} and RG_{30}. For the 0–50 cm profiles, the mean median diameter (Md) was 14.3 μm under cropland, and tended to increase after restoration to become 15.1, 17.0 and 15.8 μm under RG_5, RG_{15} and RG_{30}, respectively (Table III).

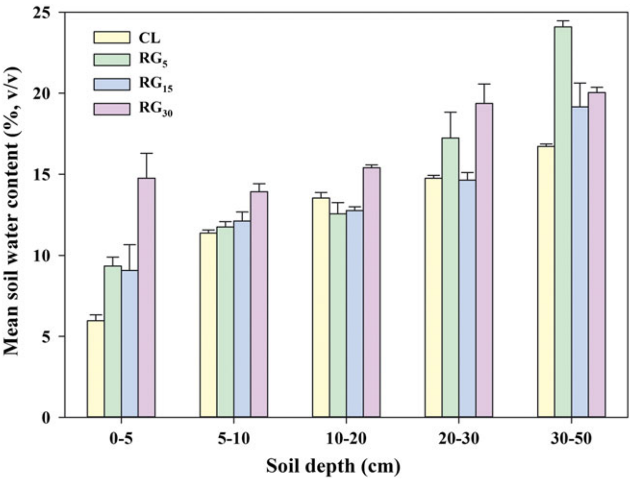

Figure 3. Mean volumetric soil–water content with standard deviation bars for each soil depth under cropland (CL) and three restored grassland plots (restoration ages: 5 years, RG_5; 15 years, RG_{15}; 30 years, RG_{30}).

Soil–water characteristics curve

In the 0–5 cm and 5–10 cm soil layers, the volumetric soil–water contents under all suctions were the lowest under cropland, and increased as restoration progressed over the entire 30-year period (Figure 3). There were significant differences in the water contents between each of the restoration stages ($P < 0.05$) but the difference between RG_{15} and RG_{30} was not significant (Figure 4a,b). In contrast, the effects of restoration on the soil–water holding capacity of the 10–50 cm layer (Figure 4c,d,e) were weaker than that on the 0–10 cm layer. In the three lower soil layers the water holding capacity was not increased with the restoration age, and the soil–water holding capacity of RG_{15} was higher than that of RG_{30}.

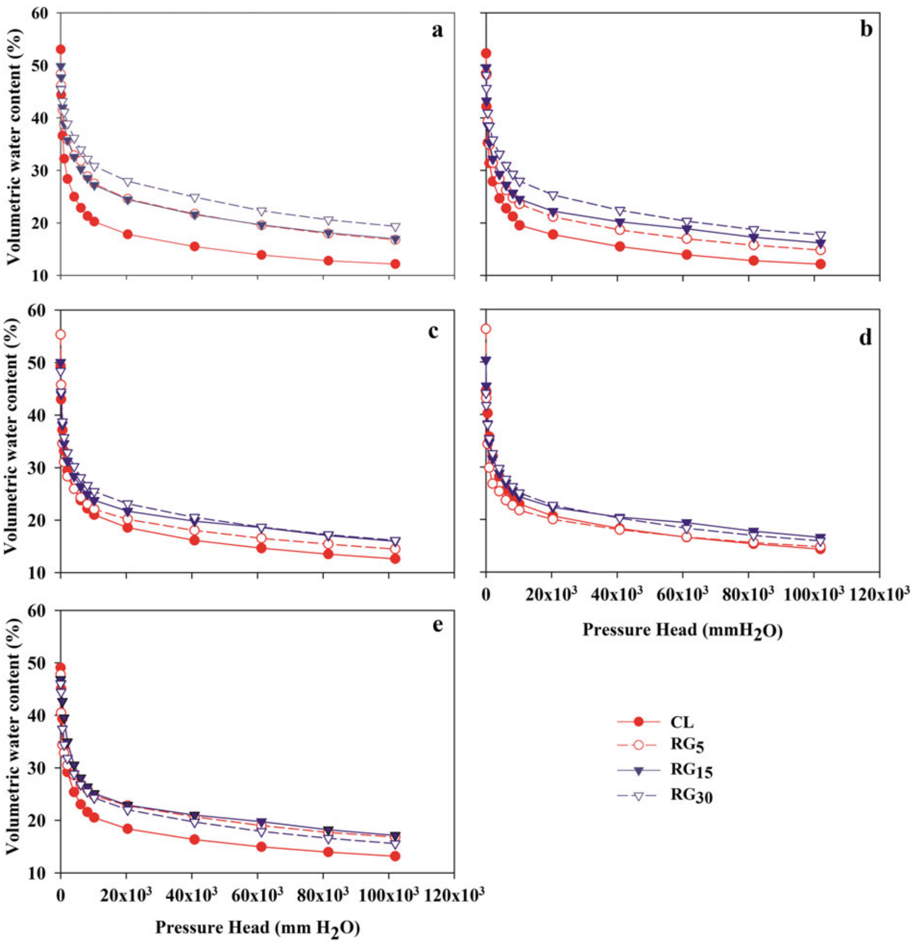

Figure 4. Soil–water characteristic curves for a soil under four treatments (cropland, CL, and restored grassland, RG, where subscripts indicate the restoration age in years) for five soil depths (a, 0–5 cm; b, 5–10 cm; c, 10–20 cm; d, 20–30 cm; e, 30–50 cm).

DISCUSSIONS

Our results showed that converting cropland to grassland had a positive effect on the investigated soil physical properties, such as, in reducing bulk density in the upper soil layer and increasing saturated hydraulic conductivity and plant available water (as indicated by the increased field capacity). In the early period of restoration, changes could occur at a relatively fast rate because of a considerable increase in soil organic matter content (Li and Shao, 2006). This could account for the improvements that we observed during the first 15 years of restoration in the soil properties that we investigated. Our results showed that, after restoration had occurred for some time around 15 years, the hydraulic conductivity of the soil had achieved its maximum value and an additional 15 years of restoration did not improve it further. Saturated soil hydraulic conductivity is an integrating parameter for several physical characteristics such as bulk density, porosity and mechanical composition. The conclusion that the land use changes during restoration had induced the differences in soil hydraulic conductivity is reasonable because previous studies have also reported that changes in soil properties such as various soil chemical properties and bulk density as well as pore volume were affected by land use or land use change (e.g. Murty *et al*., 2002; Bewket and Stroosnijder, 2003; Neves *et al*., 2003; Bronson *et al*., 2004; Hu *et al*., 2009).

Soil porosity is a highly dynamic property subject to numerous natural and human influences. Therefore, knowledge of its temporal variability is fundamental to accurately describing soil processes during restoration (Bodner *et al*., 2013). In this study, the soil porosity increased in the upper 10-cm soil layer after grassland restoration had continued for 15 years. The main reasons for the increased porosity might be that: (1) greater amounts of litter were incorporated into the soil after restoration commenced, which means that soil organic matter increased during this period that improved the soil structure so that it became less dense with more and bigger pore spaces; and (2) the reduction in trampling by humans and in agricultural machinery traffic would prevent further compaction and allow the soil structure to expand in the absence of these compaction forces. Consequently, soil bulk density was reduced and porosity increased. For example, Savadogo *et al.* (2007) reported increases in porosity when grazing intensity was reduced in the savanna woodlands of Burkina Faso. However, it was inconsistent with other studies conducted in the semiarid steppe zone of Inner Mongolia, China (Zhang *et al.*, 2013).

Induced by restoration, improved soil structure could store more water, even at high suction values (>60 × 103 mm H_2O). The water content of the soil, whether restored for 5, 15 or 30 years, was consistently greater than that of the cropland soil and the water contents became greater with restoration age, although the relationship was not linear. Moreover, we conclude that a restoration age of about 15 years was sufficient to attain the best improvements in soil–water holding capacity and soil structure, which is agreement with the conclusions of Wu *et al.* (2013). For the 0–50 cm profiles, the mean median diameter (Md) was 14.3 μm under cropland, and tended to increase after restoration to become 15.1, 17.0 and 15.8 μm under RG_5, RG_{15} and RG_{30}, respectively. This indicated that the soil became coarser as the restoration process progressed for the first 15 years, which differed from the findings of some previous studies (Li *et al.*, 2011; Wu *et al.*, 2013). To explain this phenomenon needs accurate soil texture data before the onset of grassland restoration, so needing further studies that should include investigating potential relationships with environmental factors and their spatial distributions in this area.

Conversion of cropland to grassland increased soil–water significantly. This might be because of the increases in soil organic matter after restoration that would be accompanied by increases in substances that could cement or bind mineral particles together. These substances are mainly lignins, proteins, carbohydrates, adipose and other components of humus that can help bind soil particles together in an organic–mineral complex that enhances soil aggregation and increases the water content both within soil aggregates as well as within the pore spaces between aggregates. It has been shown that soil aggregation is essential to the soil–water holding capacity (van Eekeren *et al.*, 2010; Krupenikov *et al.*, 2011). In contrast, the effects of restoration on the water holding capacity of lower soil layers (10–50 cm) were considerably less than those observed in the upper soil layers (0–10 cm). The main reasons could include: (1) that farming and grazing mainly affected the upper soil layers (0–20 cm), while having relatively little effects on soil layers below that; and (2) that the root system of the grasses and earthworm activity are mainly concentrated in the upper layers and lesser amounts of root exudates and litter are incorporated into the lower layers. Therefore, restoration of grasslands did not so notably change the physical properties of the lower soil layers unlike in the upper soil layers.

CONCLUSIONS

We analysed the effects of converting cropland into grassland on soil physical properties. Our results revealed after grassland restoration had occurred for about 15 years, the hydraulic conductivity of the soil was close to being the highest achievable based on the observed changes in conjunction with the restoration age; after 15 years, the hydraulic conductivity was not observed to improve. The soil porosity, soil–water storage, and water content all increased but, while the increases were not linearly related to the restoration age, the values of these parameters tended to consistently increase. The soil texture of the 0–10 cm profile became coarser after restoration, as indicated by the increases in median diameter, because these increases may be caused by changes in the deposition of windborne particles because of the changes in vegetation cover; further research is required into this phenomenon. We concluded that restoration for about 15 years was sufficient achieve most of the improvement in the soil–water holding capacity and soil structure. Our study shows the necessity to consider time dependence of soil hydrological properties when converting cropland to grassland, which notably improved the soil structure and soil–water holding capacity during the first 15 years of restoration on the Loess Plateau.

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REFERENCES

Bewket W, Stroosnijder L. 2003. Effects of agroecological land use succession on soil properties in Chemoga watershed, Blue Nile basin, Ethiopia. *Geoderma* **111**: 85–98.

Bodner G, Scholl P, Loiskandl W, Kaul HP. 2013. Environmental and management influences on temporal variability of near saturated soil hydraulic properties. *Geoderma* **204-205**: 120–129.

Bormann H, Klaassen K. 2008. Seasonal and land use dependent variability of soil hydraulic and soil hydrological properties of two Northern German soils. *Geoderma* **145**: 295–302.

Breuer L, Huisman JA, Keller T, Frede HG. 2006. Impact of a conversion from cropland to grassland on C and N storage and related soil properties: analysis of a 60-year chronosequence. *Geoderma* **2006**(133): 6–18.

Bronson KF, Zobeck TM, Chua TT, Teresita T, Veronica AM, van Pelt RS, Booker JD. 2004. Carbon and nitrogen pools of southern high plains cropland and grassland soils. *Soil Science Society of America Journal* **68**: 1695–1704.

Evrendilek F, Celik I, Kilic S. 2004. Changes in soil organic carbon and other physical soil properties along adjacent Mediterranean forest, grassland, and cropland ecosystems in Turkey. *Journal of Arid Environments* **59**: 743–752.

Fu XL, Shao MA, Wei XR, Horton R. 2009. Effects of two perennials, fallow and millet on distribution of phosphorous in soil and biomass on sloping less land, China. *Catena* **77**: 200–206.

Gerten D, Rost S, von Bloh W, Lucht W. 2008. Causes of change in 20th century global river discharge. *Geophysical Research Letters* **35**: L20405.

Hermawan B, Cameron KC. 1993. Structural changes in a silt loam under long-term conventional or minimum tillage. *Soil and Tillage Research* **26**: 139–150.

Hu W, Shao MA, Wang QJ, Fan J, Horton R. 2009. Temporal changes of soil hydraulic properties under different land uses. *Geoderma* **149**: 355–366.

Huang ZL, Chen LD, Fu BJ, Lu YH, Huang YL, Gong J. 2006. The relative efficiency of four representative cropland conversions in reducing water erosion: evidence from long-term plots in the Loess hilly area, China. *Land Degradation & Development* **17**: 615–627.

Jia XX, Shao MA, Wei XR, Horton R, Li XZ. 2011. Estimating total net primary productivity of managed grasslands by a state-space modeling approach in a small catchment on the Loess Plateau, China. *Geoderma* **160**: 281–291.

Klute A, Dirksen C. 1986. Hydraulic conductivity and diffusivity, laboratory methods. In *Methods of Soil Analysis*, Klute A (ed) Part 1, Agronomy Monograph. 9. Verlag American Society of Agronomy - Soil Science Society of America: Madison (Wisconsin).

Krupenikov I, Boincean B, Dent D. 2011. *Soil Structure, Soil Water and Drought, the Black Earth*, International Year of Planet Earth. Springer Netherlands: Dordrecht; 69–75.

Lei TW, Chuo RY, Zhao J, Shi XN, Liu L. 2010. An improved method for shallow water flow velocity measurement with practical electrolyte input. *Journal of Hydrology* **390**: 45–56.

Lei TW, Yan Y, Shi XN, Chuo RY, Zhao J. 2013. Measuring velocity of water flow within gravel layer with electrolyte tracer method under pulse boundary model. *Journal of Hydrology* **500**: 37–44.

Li YQ, Zhao HL, Zhao XY, Zhang TH, Li YL, Cui JY. 2011. Effects of grazing and livestock exclusion on soil physical and chemical properties in desertified sandy grassland, Inner Mongolia, northern China. *Environmental Earth Sciences* **63**: 771–783.

Li YY, Shao MA. 2006. Change of soil physical properties under long-term natural vegetation restoration in the Loess Plateau of China. *Journal of Arid Environments* **64**: 77–96.

Lin H, Bouma J, Wilding LP, Richardson JL, Kutilek M, Dielsen DR. 2005. Advances in hydropedology. *Advances in Agronomy* **85**: 1–89.

Logan TJ, Lal R, Dick WA. 1991. Tillage systems and soil properties in North America. *Soil and Tillage Research* **20**: 241–270.

Lu DQ, Shao MA, Horton R, Liu CP. 2004. Effect of changing bulk density during water desorption measurement on soil hydraulic properties. *Soil Science* **169**: 319–329.

Lü YH, Fu BJ, Feng XM, Zeng Y, Liu Y, Chang RY, Sun G, Wu BF. 2012. A policy-driven large scale ecological restoration: quantifying ecosystem services changes in the Loess Plateau of China. *PLoS ONE* **7**: e31782.

Murty D, Kirschbaum MUF, McMurtrie RE, McGilvray H. 2002. Does conversion of forest to agricultural land change soil carbon and nitrogen? A review of the literature. *Global Change Biology* **8**: 105–123.

Neves CSVJ, Feller C, Guimaraes MF, Medina CC, Tavares FJ, Fortier M. 2003. Soil bulk density and porosity of homogeneous morphological units identified by the cropping profile method in clayey oxisols in Brazil. *Soil and Tillage Research* **71**: 109–119.

Qiu GY, Xie F, Feng YC, Tian F. 2011. Experimental studies on the effects of the “Conversion of Cropland to Grassland Program” on the water budget and evapotranspiration in a semi-arid steppe in Inner Mongolia, China. *Journal of Hydrology* **411**: 120–129.

Reatto A, Silva EMD, Bruand A, Martins ES, Lima JEFW. 2008. Validity of the centrifuge method for determining the water retention properties of tropical soils. *Soil Science Society of America Journal* **72**: 1547–1553.

Savadogo P, Sawadogo L, Tiveau D. 2007. Effects of grazing intensity and prescribed fire on soil physical and hydrological properties and pasture yield in the savanna woodlands of Burkina Faso. *Agriculture, Ecosystems & Environment* **118**: 80–92.

Schwartz RC, Evett SR, Unger PW. 2003. Soil hydraulic properties of cropland compared with reestablished and native grassland. *Geoderma* **116**: 47–60.

Strudley MW, Green TR, Ascough JC II. 2008. Tillage effects on soil hydraulic properties in space and time: state of the science. *Soil and Tillage Research* **99**: 4–48.

Su YZ, Li YL, Cui JY, Zhao WZ. 2005. Influences of continuous grazing and livestock exclusion on soil properties in a degraded sandy grassland, Inner Mongolia, northern China. *Catena* **59**: 267–278.

Unger PW. 2001. Total carbon, aggregation, bulk density, and penetration resistance of cropland and nearby grassland soils. In *Carbon Sequestration and the Greenhouse Effect*, Lal R (ed) **57**, SSSA Special Publication. Soil Science Society of America: Madison, WI; 77–92.

Van Eekeren N, de Boer H, Hanegraaf M, Bokhorst J, Nierop D, Bloem J, Shouten T, de Goede R, Brussaard L. 2010. Ecosystem services in grassland associated with biotic and abiotic soil parameters. *Soil Biology & Biochemistry* **42**: 1491–1504.

Van Genuchten MT. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal* **44**: 892–898.

Wang L, Mu Y, Zhang QF, Jia ZK. 2012. Effects of vegetation restoration on soil physical properties in the wind–water erosion region of the northern Loess Plateau of China. *Clean – Soil Air Water* **40**: 7–15.

Wu GL, Yang Z, Cui Z, Liu Y, Fang NF, Shi ZH. 2016. Mixed artificial grasslands with more roots improved mine soil infiltration capacity. *Journal of Hydrology* **535**: 54–60.

Wu TN, Wu GL, Wang D, Shi ZH. 2013. Soil-hydrological properties response to grazing exclusion in a steppe grassland of the Loess Plateau. *Environmental Earth Sciences* **71**: 745–752.

Zha X, Tang KL. 2003. Change about soil erosion and soil properties in reclaimed forestland of Loess hilly region. *Acta Geographica Sinica* **58**: 464–469.

Zhang KR, Dang HS, Tan SD, Wang ZX, Zhang QF. 2010. Vegetation community and soil characteristics of abandoned agricultural land and pine plantation in the Qinling mountains, China. *Forest Ecology and Management* **259**: 2036–2047.

Zhang ZH, Li XY, Jiang ZY, Peng HY, Li L, Zhao GQ. 2013. Changes in some soil properties induced by re-conversion of cropland into grassland in the semiarid steppe zone of Inner Mongolia, China. *Plant and Soil* **373**: 89–106.

Zhao YG, Wu PT, Zhao SW, Feng H. 2013. Varuation of soil infiltrability across a 79-year chronosequence of naturally restored grassland on the Loess Plateau, China. *Journal of Hydrology* **504**: 94–103.

Zhou X, Lin HS, White EA. 2008. Surface soil hydraulic properties in four soil series under different land uses and their temporal changes. *Catena* **73**: 180–188.