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Effect of rest-grazing management on soil water and carbon storage in an arid grassland (China)

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S U M M A R Y

The appropriate grassland management practices play an important role for sustainable use of grassland. Rest grazing is beneficial to maintain higher grassland productivity and species diversity. However, little knowledge exists about the effects of rest grazing on soil water and carbon storages in arid regions. In the current study, we investigated the above- and below-ground community characteristics of the three-paired rest-grazing and grazing grasslands in an arid region of northern-west China. An 11-year rest grazing grassland and a continuous grazing grassland were studied to understand soil water and carbon storages. The results revealed that soil water content and carbon storage significantly increased after rest grazing, which was mainly attributable to increasing below-ground biomass density. At the 30–50 cm soil layer depth of the continuously grazing grassland, bulk density was higher and below-ground biomass was lower than the rest of the grazing grassland. This layer significantly affected the water cycle by blocking water exchange between the upper and lower soil layers. Soil carbon content did not significantly increase after rest grazing. The results indicated that rest grazing has a great potential for the recovery of soil water storage, and is an effective way to enhance grassland restoration in the arid area.

1. Introduction

The arid region of northern-west China, covering about one-fourth of the land surface, is characterized by its extremely vulnerable water resources (Zhou et al., 2011). The main grasslands in this arid region are known as oasis and oasis-desert ecotones, where contradictions between ecology and industrial and agricultural production are very conspicuous (Su et al., 2005). Over the last 50 years, overgrazing and grassland degradation rates in the Hexi corridor region in northern-west China have reached 69.10% and 46.86%, respectively (Wang et al., 2003). Ecosystem recovery, associated with rest grazing or reducing grazing intensity, has been designed and implemented by China's central government over the past three decades to control grassland degradation (Zhou et al., 2011). The key factor for ecosystem recovery in an arid ecosystem is to maintain soil water content (SWC) and soil organic carbon content (SOC) (Conant et al., 2001).

Water is a key element for building and maintaining regional ecosystems, and governing the number and size of perennial plant species in semi-arid and arid regions (Wang et al., 2003). SWC is affected by land-use type and pasture management, which control plant canopy cover, leaf area, plant evaporation and community composition (Cooper et al., 2006; Chen et al., 2008, 2010; Huang et al., 2013). Due to intensive livestock and agricultural use, the Hexi corridor region faces the consequences of widespread vegetation and soil degradation, such as lower grass yields, grassland desertification, lower carrying capacity, and loss of nutrients via wind erosion during the recent several decades (Li et al., 2009a; Pan and Chao, 2003). Meanwhile, the arid ecosystem is defined by an arid-fed environment and high rates of potential evapotranspiration (Collins et al., 2008). Precipitation in most of the arid region is, on average, less than 200 mm a year, with the lowest of <50 mm (Wang et al., 2003). A warming and drying trend in the Hexi corridor will increase the surface water stress (Piao et al., 2010; Yang et al., 2012). Soil water is the main constraint for the possibilities to permanently control desertification, and choosing the suitable way to protect the water is essential in this arid region.

Soil carbon storage (SCS) is more than twice the size of atmospheric carbon storage, thus a slight change in SCS has a large impact on atmospheric CO_2 concentration (McSherry and

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Ritchie, 2013). Regarding the large area of grassland throughout northern-west China, grassland degradation has had huge impacts on the global carbon cycle and climate change (Yang et al., 2005; Li et al., 2009a). Shifts in disturbance regimes, which are usually caused by human intervention (land use change, urbanization, cropping, pasture management, etc.), can result in long-term regional carbon loss or gain (Wu et al., 2003; Luo and Weng, 2011; Li et al., 2013). High inherent SOC in the grassland can help maintain and improve soil fertility and quality, increase soil aggregation, stabilize soil structure and reduce soil erosion ratio (Conant et al., 2001; Li et al., 2006; Shi et al., 2009). Therefore, maintaining SOC and understanding the impact of land-use change on SOC have aroused the interest for scientific research on this topic.

Restoring herbivore-disturbed ecosystems solely by reducing herbivore density requires decades to equilibrate (Zhou et al., 2011). Monitoring of vegetation and soil along a chronosequence under similar soil and climate conditions is a basic approach to study soil changes over the natural restoration time. Since there is no historical record of changes in most soil properties due to grassland restoration for the long time, chronosequence approaches offer unique opportunities to use space-for-time substitution to quantify the recovery of soil carbon and water contents (Matamala et al., 2008). Effective ways of maintaining the stability of grassland consisted of recovering the relatively stable ecological zones from the destroyed ecological rift zones, such as the rest grazing, rotational grazing and grazing exclusion for a long term (Pan and Chao, 2003; Deng et al., 2014). Recent studies have described the ecological impact of vegetation restoration on soil carbon storage (Deng et al., 2014; Wang et al., 2014a) and soil available water (Wei et al., 2007; Yang et al., 2012) in different regions, but its impact on carbon–water coupling in the arid region has not yet been described (Newman et al., 2006; Alvarez et al., 2009).

SWC is dynamic and not stored in a stable form for long-terms. However, soil water storage (SWS) is temporally stable in the different land-use types in the arid and semi-arid regions (Li and Shao, 2014). In this study, we use one-time measurement data to compare the SWC difference between in the grazing grassland (GG) and rest-grazing grassland (RGG). Additionally, we also evaluated GG to ascertain the impact of soil water and carbon content, and of the plants and soil properties on the SWS and SCS response to rest grazing in arid regions of the Hexi corridor in northern-west China.

2. Materials and methods

2.1. Study site

The study region (99°22.6′–99°25.8′E, 39°26.8′–39°36.9′N; 1374–1385 m elevation), depicted in Fig. 1, is located in Gaotai county, Hexi corridor, Gansu Province, China, and has a typical desert climate, characterized by cold winter and hot dry summer. According to data from the National Meteorological Information Center of China available for the period from 1992 to 2012, the mean annual air temperature was 8.5 °C and the mean annual accumulated precipitation was 115.9 mm (Fig. 2). The main soil type is classified as grey brown desert soil according to the Chinese Soil Taxonomy, which is equivalent to the Aridisols in terms of the USDA soil taxonomy classification (Group of Chinese Soil Taxonomy, Institute of Soil Science, Chinese Academy of Sciences, 2001).

The study was conducted in three paired RGG sites and GG sites in the flat region without slope (Fig. 1). Rest grazing was started from the year 2002 (Yang, 2004). Before rest grazing, the permanent grasslands were used as grazing land. Both RGG sites and GG sites were in similar initial conditions and had similar characteristics before 2002, such as altitude, soil type, grazing intensity, predominant plant species, and topography. No fertilizer or herbicides had been applied to the grasslands prior to the experiment. The particle size distribution and soil chemical properties before the rest-grazing are listed in Table 1. The grazing intensity of the GG was 2–3.5 sheep ha^{-1} from May to September, and 1–2 sheep ha^{-1} from October to April of the following year. The vegetation coverage ranged from 5% to 25%, and the predominant plant species were *Achnatherum splendens, Agropyron cristatum, Phragmites australis.* In each of the 6 sample sites, five quadrats were set up along a 100-m line transect. The 100-m line transects of each paired GG site and RGG site were parallel, and the distance between the line transects was about 40 m (Fig. 1).

2.2. Plant sampling

In each quadrat, the vegetation was cut to ground level, including plant litter (standing dead parts). The green above-ground plant parts or above-ground net primary productivity (ANPP) and litter were separated. Three soil samplings were taken from each soil layer with depths of 0–5–10–20–30–50–70–100 cm in each quadrat by a 9-cm diameter root auger to measure below-ground biomass (BGB). After the obvious roots were taken out from the soil samples, the rest was isolated using a 0.5-mm sieve. The ANPP, litter and BGB were dried at 65 °C for 48 h and weighed to determine dry mass.

2.3. Soil sampling and determination

One soil sample was taken at five points from each quadrat (four corners and the center of the quadrat) by a 4-cm diameter soil drilling sampler at depths of 0–5–10–20–30–50–70–100 cm. Soil samples were air-dried and then passed through a 0.25-mm sieve. A total of 210 soil samples (30 quadrats with 7 soil layers) were measured for bulk density (BD), pH, SWC and soil carbon content. Each RGG and GG has 105 soil samples. Soil pH was determined at a soil–water ratio of 1:5. Soil BD ($g\,cm^{-3}$) of the different soil layers was measured using the soil cores (volume, 100 cm^3) by the volumetric ring method (Wu et al., 2010). Part of the fresh soil samples were dried at 105 °C for 48 h to determine SWC, and then multiplied by bulk density to calculate the volumetric SWC. The SOC was assayed by dichromate oxidation (Nelson and Sommers, 1982). Each analysis was performed in duplicates. We used the following equation to calculate SCS (Deng et al., 2013)

$$\mathrm{SCS} = \mathrm{SOC} \times \mathrm{BD} \times D$$

where, SCS is soil organic carbon storage ($kg\,m^{-2}$); BD is bulk density ($g\,cm^{-3}$); SOC is soil organic carbon content ($g\,kg^{-1}$); and D is soil thickness (cm).

The following equation was used to calculate SWS:

$$\mathrm{SWS} = \mathrm{SWC} \times D \times 100$$

where SWS is soil water storage (mm); SWC is volumetric soil water content ($m\,m^{-1}$); and D is soil thickness (cm).

Below-ground biomass density (BGBD, $g\,m^{-3}$) was calculated by the equation:

$$\mathrm{BGBD} = \mathrm{BGB}/D \times 100$$

where BGBD is below-ground biomass density ($g\,m^{-3}$); BGB is below-ground biomass ($g\,m^{-2}$); and D is soil thickness (cm).

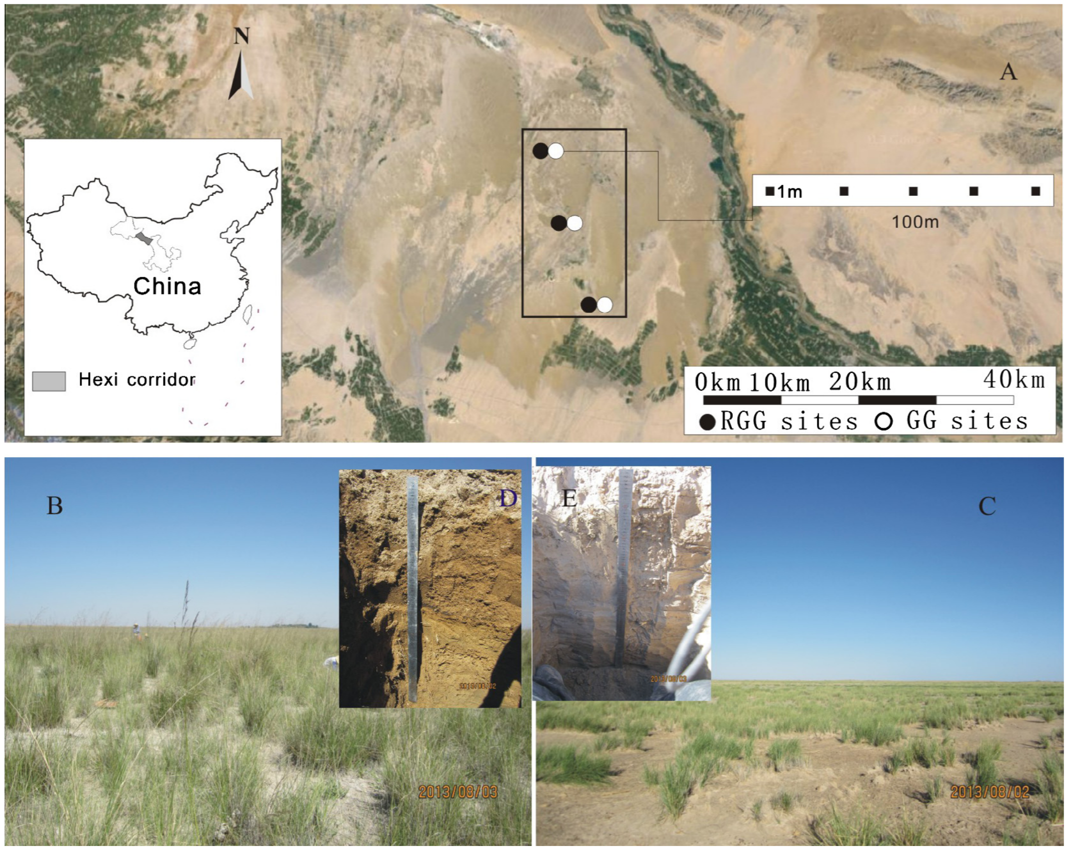

Fig. 1. The study sampling sites located in the Hexi corridor, northern-west of China (A). Six 100 m line transects are selected respectively in three desert rest-grazing grassland (RGG) sites, (B); and three grazing desert grassland (GG) sites, (C); D and E show the soil profiles of the RGG and GG, respectively. Five quadrats (1.0 m × 1.0 m) are selected respectively in each transect. A total of 30 quadrats are included in this study.

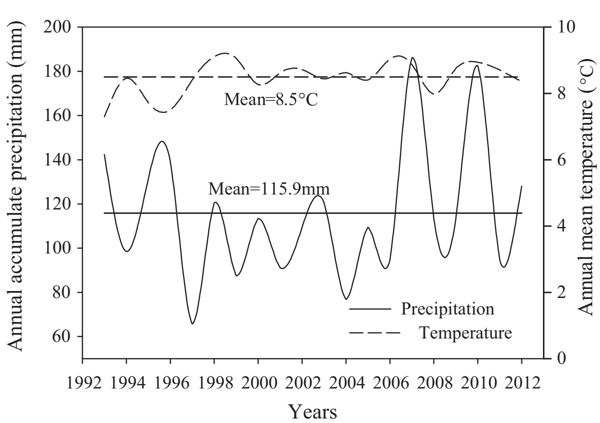

Fig. 2. Annual mean temperature and annual accumulated precipitation in the study site from 1993–2012. Note: the straight lines are the mean values of annual mean temperature and annual accumulated precipitation.

2.4. Statistical analyses

All data are expressed as mean values ± standard error (SE). Soil characteristics in different layers were analyzed to assess the effects of rest grazing. Changes in green above-ground plant parts, BGB, litter, soil carbon content, SWC, SCS, and SWS between RGG and GG were assessed by ANOVA. Significant differences were evaluated at the 0.05, 0.01 and 0.001 level. Figures were plotted by Sigmaplot version 8.0 (Systat Software Inc., San Jose, CA, USA). All other statistical tests were performed by SPSS 11.5 (Chicago, Illinois, USA).

Table 1
Soil physical and chemical properties in the study region before rest-grazing[a].

Soil depth	SOC	TN	TP	Particle-size distribution (%)		
	(g kg^{-1})	(g kg^{-1})	(g kg^{-1})	Sand	Silt	Clay
0–20 cm	10.3	0.8	0.7	49.0	39.0	12.0
20–50 cm	8.9	1.0	0.6	48.0	39.7	12.3
50–90 cm	3.6	0.3	0.7	62.0	30.0	8.0
90–100 cm	2.2	0.2	0.6	62.0	32.9	5.1

[a] Sand (2–0.02 mm), silt (0.02–0.002 mm), clay (<0.002 mm). SOC = soil organic carbon, TN = total nitrogen, TP = total phosphorus.

3. Results

3.1. Plant properties

The ANPP, litter, vegetation coverage, height and root to shoot ratio were significantly ($P < 0.05$) affected by rest grazing, as shown in Table 2. In August 2013, at the peak growing season, the ANPP and litter at the RGG were 103.58 ± 9.20 g m^{-2} and 105.85 ± 10.05 g m^{-2}, respectively, which were about twice those of the GG. The BGB at 100 cm-depth increased from 625.17 ± 114.56 g m^{-2} to 701.06 ± 97.64 g m^{-2} under rest grazing management. Meanwhile, the root to shoot ratio decreased significantly from 8.64 ± 2.52 to 3.75 ± 0.67 by rest grazing. The coverage

Table 2
Mean (standard error) values of annual net primary productivity (ANPP), below-ground biomass (BGB, 0–100 cm), standing dead matter (Litter), coverage, height and ratio of root to shoot for the rest-grazing (RGG) and grazing grassland (GG) communities (n = 15). ANOVA results are shown by F statistic and P.

	ANPP (g m^{-2})	BGB (g m^{-2})	Litter (g m^{-2})	Coverage (%)	Height (cm)	Root/Shoot
GG	46.50(9.33)	625.17(114.56)	42.78(8.44)	10.30(1.78)	108.60(12.14)	8.64(2.52)
RGG	103.58(9.2)	701.06(97.64)	105.85(10.05)	18.73(1.65)	157.60(9.18)	3.75(0.67)
$F_{1,28}$	17.54	0.25	19.87	11.51	10.37	4.99
P	<0.001	0.622	<0.001	0.003	0.003	0.019

and height of the grassland community were also greatly enhanced 82% and 45% after rest grazing (Table 2). The BGBD was decreased 6%, 17% and 1% at the soil depths of 0–5, 5–10 and 10–20 cm, respectively, whereas it was increased 24%, 71% (P < 0.01), 55% and 29% at the soil depths of 20–30, 30–50, 50–70 and 70–100 cm, respectively, after rest grazing (Fig. 3).

3.2. Soil bulk density and pH

Compared with the GG sites, soil bulk density in the RGG sites decreased 21% (P < 0.001), 15% (P < 0.05), 9% (P < 0.01), 2% (P < 0.48), 8% (P < 0.01), 4% (P = 0.634) at the depths of 0–5, 5–10, 10–20, 20–30, 30–50, 50–70 cm, respectively, (Fig. 4a). The highest BD of the GG sites was 1.40 g m^{-3} at the depth of 30–50 cm, while the highest BD of the RGG sites at similar layer depth was only 1.28 g cm^{-3} (Fig. 4a). The significant differences of pH between the RGG and GG sites appeared at the depth of 10–20 cm, 20–30 cm and 30–50 cm (Fig. 4b). However, while the pH at the GG sites varied significantly among the soil layers, the pH did not show significant difference in the RGG sites (Table 3).

3.3. Enhancement of soil water content and storage

Compared with the GG sites, SWC in the RGG sites was increased 8% (P = 0.738), 1% (P = 0.967), 51% (P < 0.05), 84% (P < 0.001), 158% (P < 0.001), 57% (P < 0.05) and 45% (P < 0.05) at the depths of 0–5, 5–10, 10–20, 20–30, 30–50, 50–70 and 70–100 cm, respectively, (Fig 4c). The largest difference of SWC between the RGG and GG sites was found at the soil depth of 30–50 cm, where SWC was significantly decreased by rest grazing from 27.16 ± 1.65% to 10.7 ± 1.54% (Fig 4c). Additionally, SWC increased significantly in the RGG with increasing soil depth

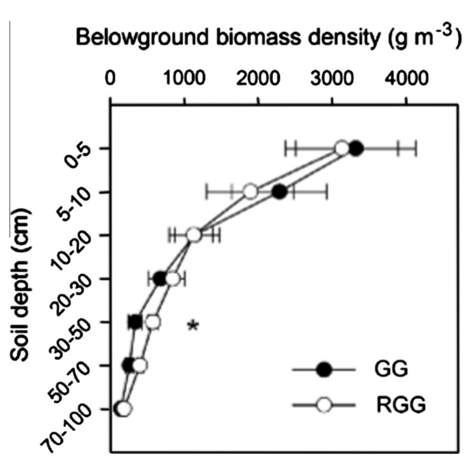

Fig. 3. Effect of rest-grazing grassland (RGG) and grazing grassland (GG) on the below-ground biomass of different soil layers. Note: The values are the mean ± SE (N = 15). Significant differences between rest-grazing and grazing grasslands are indicated by symbols, *P < 0.05, no symbol, no significant difference.

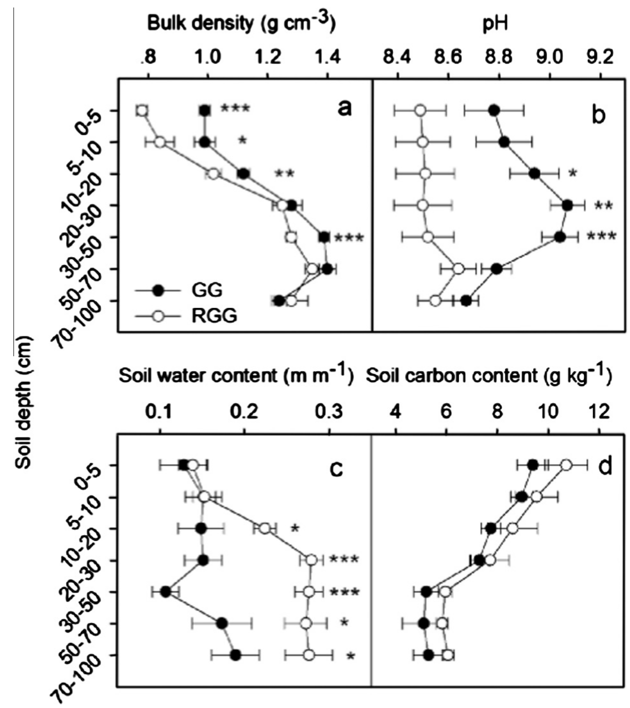

Fig. 4. Effect of rest-grazing grassland (RGG) and grazing grassland (GG) on soil bulk density (BD) (a), pH (b), soil water content (c) and soil carbon content (d). Note: The values are the mean ± SE (N = 15). Significant differences between rest-grazing and grazing grasslands in different soil depth are indicated by symbols, ***P < 0.001, **P < 0.01, *P < 0.05, no symbol, no significant difference.

Table 3
One-way ANOVA results of the soil layers effect on soil bulk density (BD), soil water content (SWC), pH, soil organic content (SOC) and below-ground biomass density (BGBD) both in the grazing grassland (GG) and rest-grazing grassland (RGG).

		BD	SWC	pH	SOC	BGBD
GG	$F_{6,98}$	40.65	1.09	3.08	10.70	8.31
	P	<0.001	0.38	<0.001	<0.001	<0.001
RGG	$F_{6,98}$	51.74	11.76	0.28	8.42	7.22
	P	<0.001	<0.001	0.95	<0.001	<0.001

(Table 3 and Fig. 4c). Rest grazing significantly enhanced SWS, exhibiting a 25 mm increment at the 30–50 cm soil layer (Fig 5a).

3.4. Enhancement of soil carbon content and storage

Rest grazing had no significant effect on the SOC and SCS. Numerically, the SOC showed an increasing trend of 14%, 6%, 11%, 6%, 14%, 14% and 15% at the depths of 0–5, 5–10, 10–20, 20–30, 30–50, 50–70 and 70–100 cm, respectively (Fig. 4d). Meanwhile, the SCS decreased 96 g C m^{-2} at the surface soil (0–20 cm), while it increased 356 g C m^{-2} at the 0–100 cm depth soil (Fig. 5b). Compared with grazing management, soil carbon sequestration rate at the RGG sites was larger by about 32 g C m^{-2} yr^{-1} at a soil depth of 100 cm.

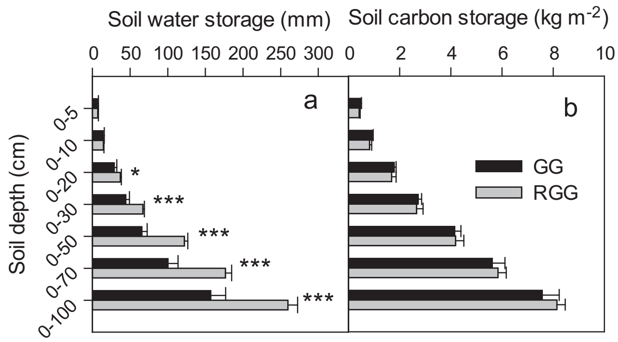

Fig. 5. Effect of rest-grazing grassland (RGG) and grazing grassland (GG) on soil water storage (a) and soil carbon storage (b). Note: The values are the mean ± SE ($N = 15$). Significant differences between rest-grazing and grazing grasslands are indicated by symbols, $^{***}P < 0.001$, $^{*}P < 0.05$, no symbol, no significant difference.

4. Discussions

4.1. Soil water storage

Among paired grazing and rest grazing management, the former has been previously found to have significantly reduced community coverage (from 32.06 to 27.48), infiltration rate (from 9.85 to 6.00 cm h^{-1}), SWC (from 24% to 15%) and greater soil loss to erosion in the arid environment (from 288.74 to 525.91 kg ha^{-1}) (Jones, 2000; Jia et al., 2006; Teague et al., 2011; Giese et al., 2013). In this study, rest-grazing increased the ANPP and coverage (Table 2), which could enhance infiltration and buffer temperatures, while decreasing evaporation and radiation, so that SWC increased (Jones, 2000; Felzer et al., 2011; Merritt and Bateman, 2012; Deng et al., 2014). In addition, in this study, rest-grazing increased coverage and decreased bare ground (Table 1). Bare ground is not protected from the sun and gets much hotter than covered soil, causing a decrease in SWC, additionally the wind erosion risk increases if there is insufficient cover (Teague et al., 2011). Moreover, infiltration rate and SWC are not only affected by vegetation variables but also by soil properties (Castellano and Valone, 2007; Allington and Valone, 2010; Shi et al., 2013). In the present study, rest grazing inhibited excessive herbivory and trampling, and then decreased soil compaction and BD (Fig. 4a). Soil BD, which is negatively related with soil porosity, infiltration rate and water-holding capacity, is a key soil factor that influenced the soil reservoir under natural vegetation recovery (Jones, 2000; Zhao et al., 2010). The results of this study revealed that the changes of coverage, ANPP, litter and BD enhanced the SWC at the RGG sites (Table 2 and Figs. 4a and c). Compared with RGG sites, BD (Fig. 4a) was significantly larger in the GG sites, while SWC (Fig. 4c) and BGBD (Fig. 3) were significantly lower at the soil depth of 30–50 cm in the GG sites. Previous findings revealed that the 30–50 cm soil layer of the GG constrained the soil water distribution and soil pores water content, and negatively influenced the water cycle in soil–plant systems by blocking water interchange between upper soil layers and groundwater (Wang et al., 2010; Moyano et al., 2013). Additionally, BGBD also played a key role in enhancing SWS by increasing the water capacity of the bucket at the RGG (Felzer et al., 2011). More root in the deep soil can enhance the soil–plant systems with more available water, which can buffer the deep soil from climatic fluctuations in these dry environments and allow stable conditions to persist for long periods (Burgess et al., 1998; Seyfried et al., 2005; Li et al., 2009b).

4.2. Soil carbon storage changes

A recent study has reported that long-term (30 years) grazing exclusion significantly ($P < 0.01$) improved soil carbon content and carbon storage, compared with grazing grassland in the temperate grasslands of northern-west China (Deng et al., 2014). However, in this study site there was no significant increase of SOC and SCS with rest grazing of more than 10 years under the arid climate (Fig. 4d and Fig. 5b). Soil carbon sequestration is a long term process, and the little response of soil carbon in this study might reflect the relatively short time since rest grazing, which was insufficient for carbon to accumulate (Marrs et al., 1989; Shrestha and Stahl, 2008; Medina-Roldán et al., 2012). Furthermore, soil carbon sequestration rate was positively related with precipitation. Indeed, precipitation in this study (115.9 mm) was lower than in the other studies, which ranged from 366 to 937 mm (Conant et al., 2001; Deng et al., 2014; Wang et al., 2014a). Lastly, livestock dung deposition and urine input as well as nitrification rates are increasing at grazing grassland, and these increase soil carbon sequestration rate (Augustine et al., 2003). All these reasons could account for the soil organic carbon without significant increment after rest grazing.

4.3. Carbon–water coupling

Rest grazing significantly increased SWC in the current study (Fig. 4a). SWC has been regarded as the most important driving factor that controlled soil carbon cycle in the grassland (Lai et al., 2013; Wiesmeier et al., 2013). Many soil processes are affected by SWC and soil water movement, including microbial activity, leaching of minerals and biochemistry cycles (Manzoni et al., 2012). Firstly, the higher SWC enhanced the substrate and oxygen diffusion, and thus improved the microbial growth and activity, which in turn increased the decomposition (Manzoni et al., 2012; Linkosalo et al., 2013). Additionally, with soil drying out, the ratio of microbial and enzymatic activity decreased (Or et al., 2007), and rest grazing increased the microbial carbon and promoted enrichment of the labile soil carbon pool by enhancing SWC (Shrestha and Stahl, 2008). Secondly, organic matter input to the soil were supplied by root, which was significantly affected by SWC in the natural environment (Jones, 2000; Lai et al., 2013). In addition, the productivity could be improved by the higher availability of plant water in RGG (Su et al., 2005) and as shown here (Figs. 4c and 5a). Furthermore, even a slight increase of SWC in the topsoil might reduce wind erosion and freeze-thaw erosion, which could then retain the soil nutrients and soil organic matter in the arid region (Wang et al., 2014b). Accordingly, SOC was higher with the higher SWC in the RGG below the depth of 10 cm soil compared with the GG (Moyano et al., 2013).

On the other hand, the higher SOC also could increase the SWC. Previously, the relative microbial respiration rate was found to be positively related with the SWC (Manzoni et al., 2012), and rest grazing was found to supply more substrates and nutrients for microbial growth and activity, which would influence the water retention (Manzoni et al., 2012). Meanwhile, soil organic carbon was shown to play a key role in determining soil physical properties, soil quality and preserving plant nutrients (An et al., 2010). Additionally, the improvement of soil structure also influenced the pore geometry and size distribution, which then controlled the soil water holding capacity. Moreover, vegetation productivity, which was limited by soil nutrients (such as SOC) in the barren soil, exerted a positive effect on infiltration rates and soil hydraulic conductivity (Bonell et al., 2010; Germer et al., 2010).

5. Conclusion

SWC and SWS were significantly increased after 11-years rest grazing, which can be attributed to the increase of ANPP, litter, coverage and BGBD, and to the decrease of soil BD. The soil layer at the depth of 30–50 cm in the GG sites constrained soil water distribution and negatively impacted the water cycle in the soil–plant systems by blocking water interchange between the upper and lower soil layers. The results suggested that rest grazing exhibited a great potential to improve SWS and enhance the water holding capacity, attributable to an increment of below-ground biomass and a slight increase of SOC. Rest grazing treatment was only 11 years in this study, longer term rest grazing effect should be evaluated in future studies.

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