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The coupling interaction of soil water and organic carbon storage in the long vegetation restoration on the Loess Plateau

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ABSTRACT

Secondary succession can recover the properties of degraded soil. The moisture stored in different soil layers is recognized as an important driver of the productivity and sustainability of semi-arid terrestrial ecosystems, and land-use change has a significant effect on the global carbon (C) cycle through changing soil C accumulation rates. To evaluate the response of soil water storage (SWS) and soil organic carbon storage (SOCS) to long-term natural vegetation succession (~150 a) and the coupling interaction between them, we examined the soil moisture and soil organic carbon content in the land for different restoration ages in the Ziwuling Forest region located in the central part of the Loess Plateau, China. Our results showed that the SWS decreased and the SOCS increased with long-term natural vegetation restoration. The SOCS decreased along with the increase in the soil depth, and it was highest in the topsoil (0–20 cm). In addition, the soil depth at which the SWS intensely varied and at which the SOCS tended to be stable moved downward and upward, respectively, with the vegetation succession. Furthermore, the correlation between SWS and SOCS was significant ($P < 0.05$) in the long-term restoration and gradually weakened with the increase in the soil depth and the vegetation restoration stages. Clay, silt, sand, total porosity (TP), inactive porosity (IP), aeration porosity (AP) and capillary porosity (CP) were important factors that influenced the coupling interaction of SWS and SOCS at the grass restoration stages (<50 a), and BD influenced this interaction in the shrub and early forest restoration stages (<130 a). The effect of soil physical factors on the interaction of SWS and SOCS gradually weakened during the vegetation restoration succession. These results are expected to help improve the understanding of the response of deep soil water and soil organic carbon to long-term natural vegetation restoration and to provide insights into the coupling interaction between soil water and soil organic carbon influenced by vegetation.

1. Introduction

Secondary succession can recover the properties of degraded soil and maintain soil fertility (Wang et al., 2011; Deng et al., 2013). To control soil erosion and ecosystem degradation, China's government has initiated vegetation restoration projects on the Loess Plateau due to its infamous erosion (Deng et al., 2012). The Loess Plateau has thus converted much agricultural land into other uses over the past few decades; for example, farmland has been converted into artificial vegetation of grasslands, shrubs, forests, and natural vegetation (Deng et al., 2014a,b; Feng et al., 2013; Zhou et al., 2012). Understanding secondary forest succession processes in the central region of the Loess Plateau is therefore becoming increasingly important (Jia et al., 2005; Deng et al., 2013).

As global warming progresses, increased water stress in semi-arid regions is becoming an increasing concern (Vörösmarty et al., 2000). A warming and drying trend on the Loess Plateau, in particular, will undoubtedly increase the surface water and soil moisture stress in the region (Piao et al., 2010). Water is fundamental to the biophysical processes that sustain ecosystem functions, particularly in arid and semi-arid regions, where ecosystem productivity, surface energy balance, and water source availability are tightly coupled (Wang et al., 2012a,b). Specifically, the moisture stored in different soil layers is recognized as an important driver of the productivity and sustainability of semi-arid terrestrial ecosystems (Legates et al., 2011; Yang et al., 2014). Vegetation strongly affects the water cycle, and the interactions between vegetation and soil moisture are fundamental for ecological processes in semi-arid regions (Yang et al., 2014). Vegetation restoration is affected

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by, and also affects, SWC both at the surface and at deeper soil layers (Mengistu, 2009; Deutsch et al., 2010). Researchers have more recently focused on understanding the relationship between the spatiotemporal variation of soil moisture and vegetation type, soil texture, soil organic matter, topographic factors, and other factors (Meerveld and McDonnell, 2006; Qiu et al., 2001). For instance, the soil moisture consumption rate was found to be dependent on the vegetation type, such as grass (alfalfa) and shrub (*Caragana korshinskii*) (Wang et al., 2010). The results of Chen et al. (2007) showed that vegetation type has a significant influence on soil moisture dynamics. Vivoni et al. (2008) revealed that vegetation can mediate the soil moisture response to precipitation and change the spatial distribution of soil moisture, and Yang et al. (2012a,b) found that plant growth conditions can change the spatial pattern of shallow and deep soil moisture in semi-arid regions. Vegetation can significantly influence soil moisture and its spatiotemporal patterns. Hupet and Vanclooster (2002) found that vegetation plays an important role in the temporal dynamics of soil moisture through evapotranspiration based on intensive measurements. A decline in soil moisture in the 0–1 m layer was found during the process of ecological restoration, and the soil moisture replenishment by rainfall during the rainy season was not sufficient to recharge the soil moisture storage (Chen et al., 2010). Liu et al. (2010) found a negative relationship between deep soil moisture content and plant age. It is possible that the large-scale vegetation restoration project is limited by the availability of soil moisture resources (Cao et al., 2011; Chen et al., 2008a,b). Yang et al. (2012a,b) found a negative relationship between deep soil moisture content and plant growth conditions. The groundwater in the Loess Plateau is too deep and thus is unavailable for soil evaporation and/or plant transpiration (Mu et al., 2003). Little work has been conducted on soil moisture dynamics for different land use based on observations in deep layers. Thus, the soil moisture stored at different depths is critical for plant growth, and it serves as a key water source for sustaining ecosystems in this region (Chen et al., 2008a,b; Yang et al., 2012b). Understanding the effect of different plant species on moisture dynamics at different soil depths has several important implications. Such information can be useful for land surface models, large-scale climate models and ecohydrological models, such as LSMs and IBIS (El Maayar et al., 2009).

Land-use change has a significant effect on the global carbon (C) cycle through changing soil C accumulation rates and turnover, soil erosion, and vegetation biomass (Deng et al., 2014a,b). Soil organic carbon (SOC) is the largest C stock in the terrestrial ecosystem (Batjes, 1996). Land-use changes resulting from natural vegetation restoration substantially affect SOC stocks and sequestration capacity (Degryze et al., 2004). Globally, 24% of the SOC stock has been lost through the conversion of forestland to cropland (Murty et al., 2002), and 59% has been lost through the conversion of pastureland to cropland (Guo and Gifford, 2002). However, Vesterdal et al. (2002) observed that the afforestation of former arable lands did not increase the SOC over three decades, but it affected its redistribution in the soil profile. Along with vegetation restoration, changes in the plant species composition can alter litter input, root architecture (Schedlbauer and Kavanagh, 2008), and soil aggregation (An et al., 2010). These mechanisms will further control the storage and stabilization of SOC in relation to depth (Blanco-Canqui and Lal, 2004). Rumpel and Kögel-Knabner (2011) concluded that the deeper soil layers play a vital role in SOC storage and sequestration because of their higher SOC stocks and recalcitrance. Knowledge of SOC dynamics in a deeper soil profile is essential to better understand how vegetation restoration affects SOC storage and sequestration. Research on SOC dynamics in a long-term vegetation succession chronosequence is necessary to obtain baseline data of SOC storage and to estimate SOC sequestration potential in the future. Despite the numerous reports on SOC dynamics during vegetation restoration on the Loess Plateau (Deng et al., 2013; Jia et al., 2012), information is lacking on SOC fractions and sequestration potential in deeper soil profiles (~200 cm) under long-term secondary forest succession.

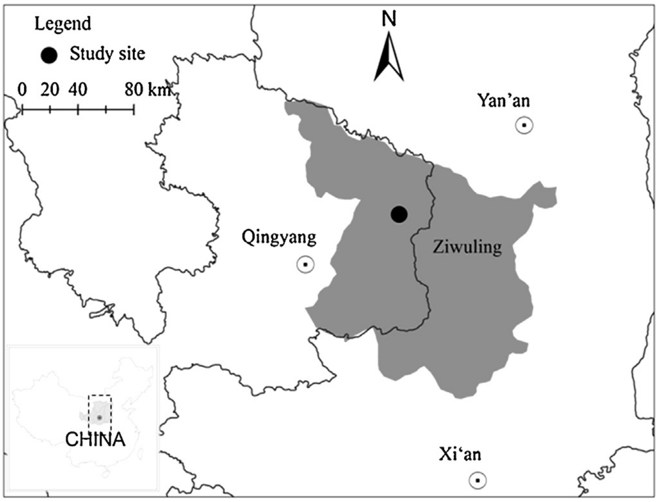

Fig. 1. Location of the study site in the Loess Plateau.

In the study, we hypothesized that the soil water storage and carbon storage varied with long-term natural vegetation restoration ages through succession on the Loess Plateau. In the Ziwuling Forest region of the Loess Plateau, there is an intact series in the naturally recovering vegetation succession on the Loess Plateau. We chose this study area to provide a scientific foundation for constructing the eco-environment and for rehabilitating the water storage and regulating capacity of the soil reservoir and the carbon sequestration capacity of the soil carbon pool. Therefore, the specific objectives of the study were to investigate: (1) the dynamics of deep soil water storage and the SOC storage with the succession of long-term natural vegetation restoration from grassland to forests, (2) the coupling interaction between soil water storage and the SOC storage in the natural vegetation succession, and (3) the soil factors affecting this coupling interaction between soil water storage and SOC storage.

2. Materials and methods

2.1. Study area

The Ziwuling Forest region is in the hinterland of the Loess Plateau. The study was conducted on the Lianjiabian Forest Farm of the Heshui General Forest Farm of Gansu (35°03′–36°37′ N, 108°10′–109°18′E, 1211–1453 m a.s.l.), located the Ziwuling Forest region, covering a total area of 23,000 km^2 (Fig. 1). The altitude of the region's hilly and gully landforms averages 1500 m a.s.l., and their relative height difference is approximately 200 m. The region's soils are largely loessal, having developed from primitive or secondary loess parent materials, which are evenly distributed 50–130 m deep above red earth consisting of calcareous cinnamon soil (Jia et al., 2005). The soil pH ranges from 7.92 to 8.31. The area's annual temperature is 10 °C, the annual rainfall is 587 mm, the accumulative temperature is 2671 °C, and the annual frost-free period is 112–140 days. The area is covered in species-rich uniform forests with a forest canopy density ranging from 80%-95%. The natural biomes of the region are deciduous broadleaf forests of which the climax vegetation is the *Quercus liaotungensis* Koidz forest. Zou et al. (2002) investigated succession throughout the region three times (1962, 1982 and 2000) and revealed that *Populus davidiana* and *Betula platyphylla* forests had been replaced by *Q. liaotun-*

Table 1
Geographical and vegetation characteristics at different restoration stages in the Ziwuling Forest region of the Loess Plateau. G1 and G2 represent the grass restoration stage, S stands for the shrub restoration stage, F1 represents the early forest stage, F2 represents the medium forest stage, and F3 represents the climax forest stage. The numbers in parentheses following the succession stage are the ages after cropland abandonment. G, S and F stand for grassland, shrub and forest, respectively.

Successional stage	Latitude (N)	Longitude (E)	Altitude(m)	Aspect	Slope(°)	Coverage (%)	Main plant species
G1 (10 a)	36°05′04.0″	108°31′37.4″	1348	NE	14	85	*Lespedeza bicolor*
G2 (30 a)	36°05′08.8″	108°31′38.9″	1365	NE	8	85	*B. ischaemum*
S (50 a)	36°04′14.4″	108°32′01.4″	1354	NE	18	90	*H. rhamnoides*
F1 (110 a)	36°02′11.2″	108°31′22.5″	1450	NE	13	90	*P. davidiana*
F2 (130 a)	36°03′05.3″	108°32′31.8″	1437	NE	10	90	*P. davidiana, Q. liaotungensis*
F3 (150 a)	36°02′57.5″	108°32′13.7″	1449	NE	18	95	*Q. liaotungensis*

gensis forests after approximately 50 years. Thus, the recovery period of *Q. liaotungensis* forests was determined to be approximately 150 years. Throughout the region, *Bothriochloa ischaemum* (Linn.) Keng, *Carex lanceolata* Boott, *Potentilla chinensis* (Ser) and *Stipa bungeana* Trin are the main herb species; *Sophora davidii* (Franch.) Skeels, *Hippophae rhamnoides* (Linn.), *Rosa xanthina* Lindl and *Spiraea pubescens* Turcz are the main shrub species; and the *P. davidiana* Dode and *B. platyphylla* Suk communities dominate the pioneer forests (Table 1). Based on previous research, the study chose six communities representing different stages of succession in the Ziwuling Forest region. To measure the age of the communities, two methods were adopted. Local elders and descriptions found in contracts between farmers and local governments established a recovery time for shrub and herbaceous communities of less than 60 years. Forest community recovery times deemed longer than 60 years were calculated by counting the growth rings and consulting related written sources (Wang et al., 2010).

2.2. Experiment design and soil sampling

A field survey was conducted between July 15 and August 15, 2014. The sampling areas were determined according to the size of the communities. There were five 2 m × 2 m plots in the herbaceous communities, five 5 m × 5 m plots in the shrub communities, and five 20 m × 20 m plots chosen in each forest community. The largest relative elevation difference between two plots was less than 120 m. Most plots faced north and had a slope gradient less than 20°. The distance between the soil sites was approximately 1 km. All soils surveyed have developed from the same parent materials and have had vegetation for varying lengths of time. Six soil sites were selected from growing vegetation that was approximately 10, 30, 50, 110, 130 and 150 years old, and all stages of succession we discuss are the result of natural re-vegetation. Basic site information is shown in Fig. 1.

Soil samples were taken at five points, which were the four corners and center of the soil sampling sites, as described above. Soil samples were taken at a depth of 2 m at 20-cm intervals using a drill and stored in sealed aluminum cases to prevent potential moisture loss before they were transported to the laboratory to measure the soil water content. Undisturbed soil cores were collected using a soil bulk sampler with a 5.0-cm diameter and 5.0-cm high stainless steel cutting ring (3 replicates) to measure the soil bulk density and porosity. Disturbed soil samples for measuring soil organic carbon and particle sizes were also taken at a depth of 2 m at 20-cm intervals using a drill and sieved through a 2-mm screen. Roots and other debris were removed, and each sample was air-dried and stored at room temperature.

2.3. Laboratory assay

Soil water content (SWC) was measured gravimetrically and expressed as a percentage of soil water to dry soil weight (Jia et al., 2012). Soil bulk density (BD) was calculated depending on the inner diameter of the core sampler, the sampling depth and the oven-dried weight of the composite soil samples (Jia et al., 2005). Soil organic carbon (SOC) was assayed by dichromate oxidation (Kalembasa and Jenkinson, 1973). Total porosity (TP), inactive porosity (IP), aeration porosity (AP) and capillary porosity (CP) were calculated based on the saturated moisture content, field moisture capacity and wilting water content (Ghanbarian-Alavijeh and Millán, 2009). Soil particle sizes were determined using the MasterSizer 2000 method. The proportions of the clay (<0.002 mm), silt (0.002–0.02 mm), and sand (>0.02 mm) contents were then calculated.

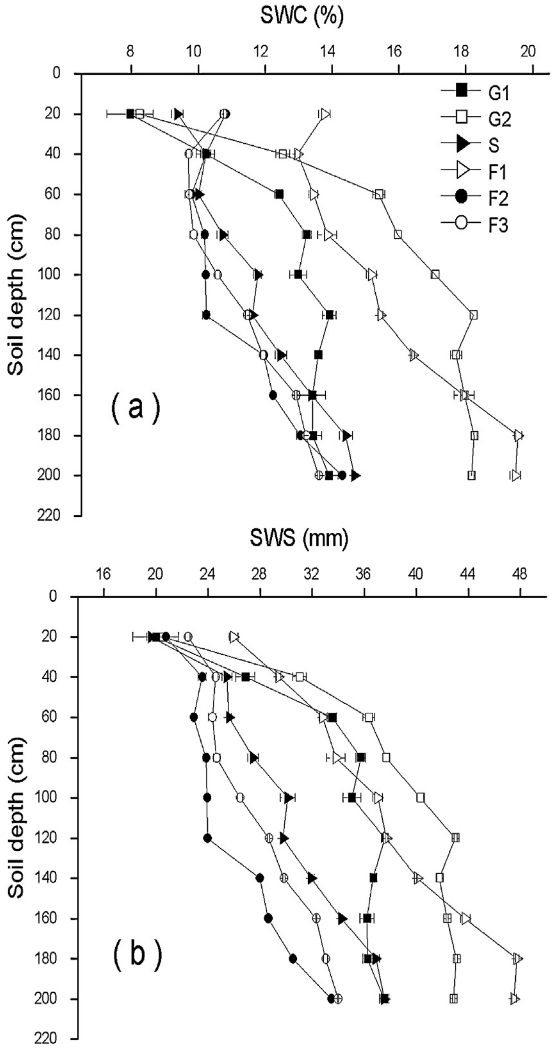

Fig. 2. Vertical variation of (a) soil water content (SWC) and (b) soil water storage (SWS) at the 0–200 cm soil depth in each restoration stage (see Table 1). Values are in the form of mean ± SE, and the sample size n = 5.

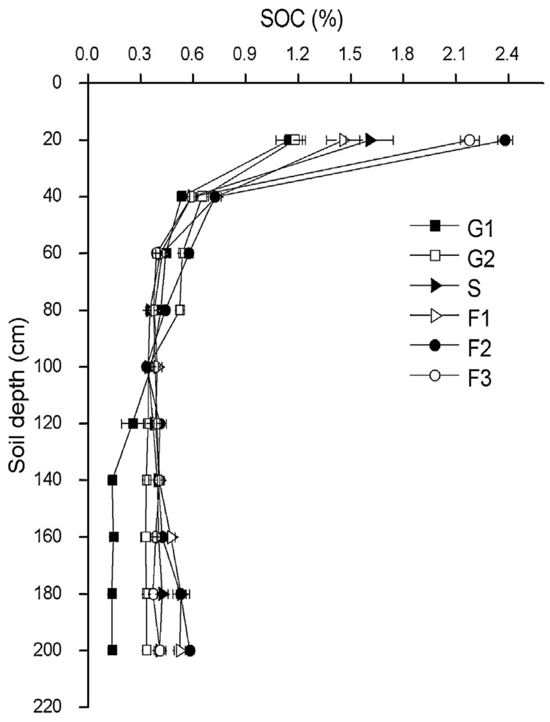

Fig. 3. Vertical variation of (a) soil organic carbon content (SOC) and (b) soil organic carbon storage (SOCS) at the 0–200 cm soil depth in each restoration stage (see Table 1). Values are in the form of mean ± SE, and the sample size n = 6. Different lower-case and upper-case letters above the bars indicate significant differences at the different soil layers in the same restoration stages and in the same soil layers at the different restoration stages (P < 0.05).

2.4. Soil water storage

The study used the following equation to calculate soil water storage (SWS) within a depth of five meters (Jia and Shao, 2013):

$$S = \theta v \times h \times 10$$

where S is the SWS at a specific depth (mm), $\theta v$is the volumetric soil water content at a specific depth ($\mathrm{cm}^3\ \mathrm{cm}^{-3}$), and h is the soil depth increment (cm).

2.5. Soil organic carbon

We clarify that in our sample soils, there was no coarse fraction (soil fraction >2 mm) so that we could avoid inserting (1–coarse fragment (%)) into the formula. Thus, the study used the following formula to calculate soil organic carbon storage (SOCS; Guo and Gifford, 2002):

$$SOCS = BD \times SOC \times D$$

in which SOCS is the soil organic carbon storage ($\mathrm{Mg\ ha}^{-1}$), BD is the soil bulk density ($\mathrm{g\ cm}^{-3}$), SOC is the soil organic carbon content (%), and D is the soil thickness (cm).

2.6. Statistical analysis

One-way ANOVA was used to analyze the means of the same soil layers across the different restoration stages. Differences were evaluated at the 0.05 significance level. When significance was observed at the $P < 0.05$ level, the least significant difference (LSD) test was used to carry out the multiple comparisons. Pearson's test was adopted to determine whether there were significant correlations between soil water storage and the soil properties measured in the study.

3. Results

3.1. Soil water content and storage

Generally, the soil water content (SWC; Fig. 2a) and soil water storage (SWS; Fig. 2b) in the different soil layers decreased gradually along with the vegetation restoration and differed significantly among the different restoration stages, whereas they increased with the soil depth in 0–200 cm at each restoration stage. The SWC and SWS in the 0–60 cm soil layer significantly increased at the early stage of succession (G1, G2), slightly increased in the 60–120 cm soil layer and then tended to be stable at the soil layer below 120 cm. However, at the S and F1 stages, the SWC and SWS in the 0–80 cm soil layer had not significantly varied but significantly increased in the 100–180 cm layer and tended to be stable. The SWC and SWS remained stable in the 0–120 cm later and then increased gradually until 200 cm at the medium and climax forest stages. This finding showed that the soil depth at which the SWC and SWS intensely varied moved downward with the vegetation succession.

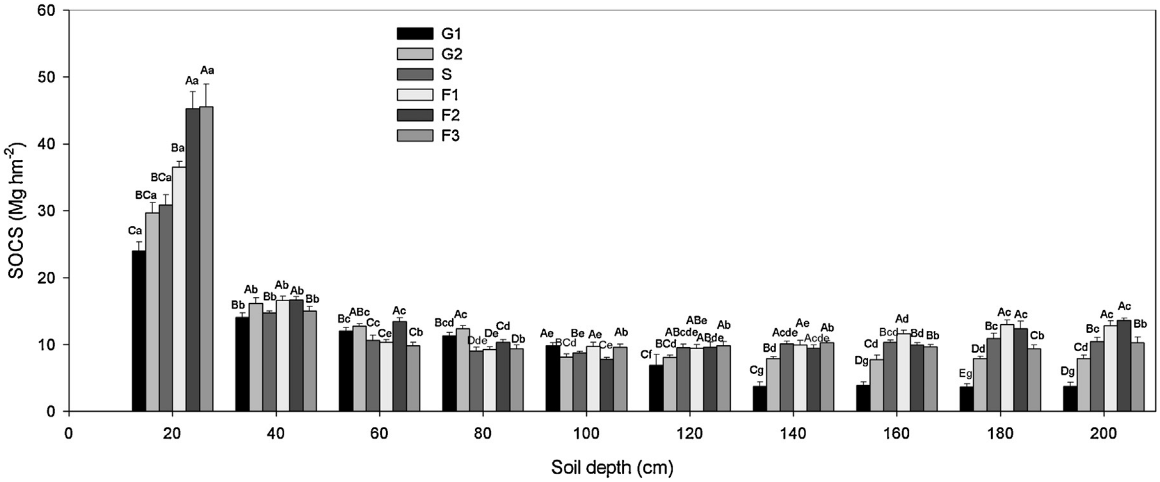

Fig. 4. Vertical variation of soil organic carbon storage (SOCS) at the 0–200 cm soil depth in each restoration stage (see Table 1). Values are in the form of mean ± SE, and the sample size n = 6. Different lower-case and upper-case letters above the bars indicate significant differences in the different soil layers at the same restoration stages and in the same soil layers at different restoration stages (P < 0.05).

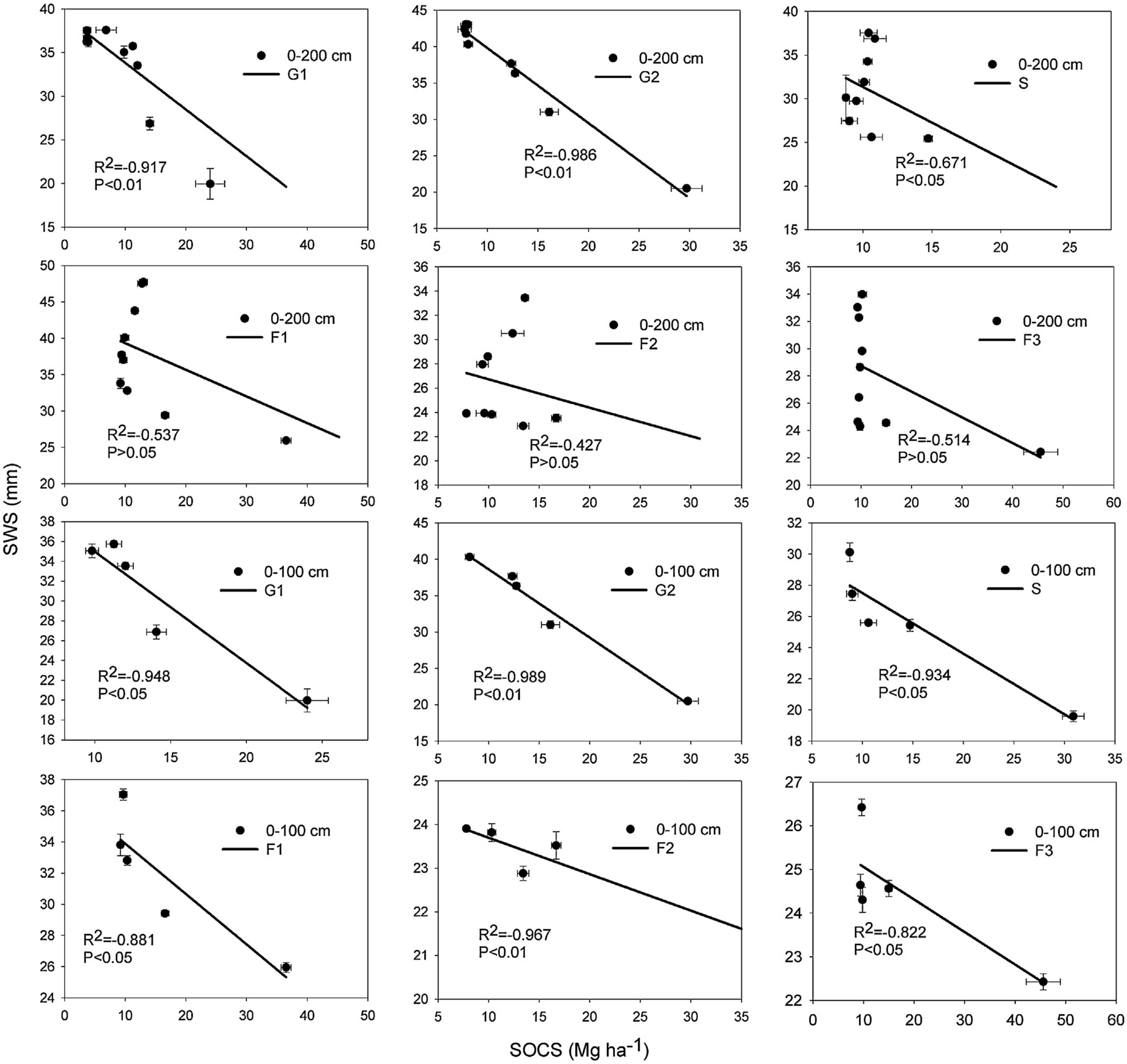

Fig. 5. Relationship between soil water storage (SWS) and soil organic carbon storage (SOCS) in 10 and 5 soil layers with the vegetation succession gradient at 0–200 cm and a 0–100 cm soil depth, respectively. Capped horizontal and vertical lines indicate the SE.

3.2. Soil organic carbon content and storage

Generally speaking, the soil organic carbon content (SOC; Fig. 3) and soil organic carbon storage (SOCS; Fig. 4) in the different soil layers increased gradually along with vegetation restoration and differed significantly among the different restoration stages. Both of them were highest in the topsoil (0–20 cm) and tended to decrease along with the increase of the soil depth. The SOC in the 0–60 cm soil layer significantly decreased at each stage of succession and tended to be stable in the soil layers below 60 cm (Fig. 3).

The SOCS in the 0–20 cm soil layer increased gradually with the vegetation restoration, which had not significantly varied during 50 years of restoration ($P > 0.05$; G1, G2, S; Fig. 4) but increased significantly at the F1 stage (~100 a). After 130 years of vegetation restoration, it tended to be stable. In the 40–100 cm soil layers, the SOCS varied significantly ($P < 0.05$) and irregularly among the restoration stages (Fig. 4). The SOCS in the soil layers below 120 cm increased significantly at the early restoration stages (G1, G2, S; $P < 0.05$). The SOCS tended to be stable at the soil layers below 120 cm, 80 cm, 60 cm, 40 cm, 40 cm and 20 cm at the G1, G2, S, F1, F2 and F3 stages (10 a, 30 a, 50 a, 110 a, 130 a and 150 a), showing that the soil depth at which the SOCS tended to be stable moved upward with the vegetation restoration stages.

3.3. Relationship between soil water storage and soil organic carbon storage

The soil water storage (SWS) and soil organic carbon storage (SOCS) showed different correlations both at the different vegetation restoration stages (G1, G2, S, F1, F2 and F3) and in the

Table 2
Pearson's correlation between SOCS, SWS and soil properties in 0–200 cm soil layer.

Factor									
Restoration stage		BD	Clay	Silt	Sand	TP	IP	AP	CP
G1	SOCS	−0.941**	−0.680*	0.784**	−0.845**	0.810**	0.830**	0.734*	0.811**
	SWS	0.960**	0.743*	−0.587	0.710*	−0.781**	−0.776**	−0.766**	−0.781**
G2	SOCS	−0.904**	−0.739*	0.762*	−0.768**	0.790**	0.783**	0.793**	0.790**
	SWS	0.926**	0.816**	−0.831**	0.835**	−0.844**	−0.842**	−0.845**	−0.844**
S	SOCS	−0.970**	−0.598	0.592	−0.590	0.604	−0.589	0.601	0.605
	SWS	0.689*	0.987**	−0.983**	0.981**	−0.988**	0.979**	−0.988**	−0.988**
F1	SOCS	−0.981**	−0.549	0.556	−0.561	0.544	0.522	−0.546	−0.544
	SWS	0.673*	0.983**	−0.978**	0.974**	−0.986**	−0.556	0.985**	−0.986**
F2	SOCS	−0.938**	−0.572	0.573	−0.573	0.572	0.563	0.573	0.572
	SWS	0.475	0.944**	−0.944**	0.945**	−0.944**	−0.940**	−0.945**	−0.944**
F3	SOCS	−0.977**	−0.598	0.599	−0.595	0.513	−0.584	0.534	0.514
	SWS	0.450	0.985**	−0.985**	0.985**	−0.951**	0.983**	−0.963**	−0.951**

Note: SOCS is soil organic carbon storage, SWS is soil water storage, BD is bulk density, TP is total porosity, IP is inactive porosity, AP is aeration porosity, and CP is capillary porosity.

[*] Correlation significant at the 0.05 level (two-tailed).

[**] Correlation significant at the 0.01 level (two-tailed).

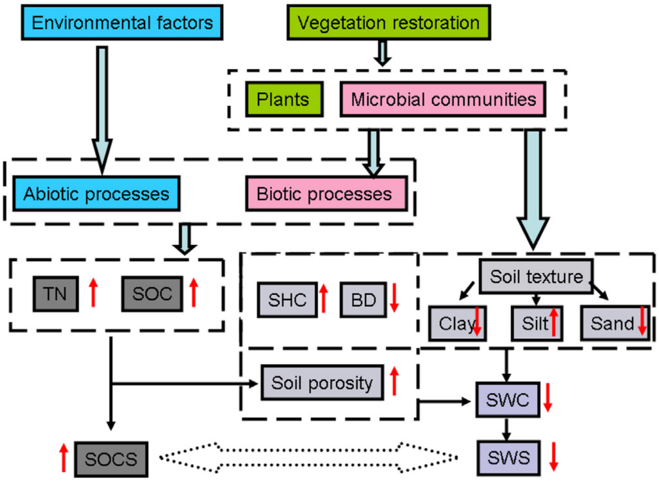

Fig. 6. Relationship between soil water storage (SWS) and soil organic carbon storage (SOCS) and other factors (e.g., soil bulk density (BD), total nitrogen (TN), saturated hydraulic conductivity (SHC), soil water content (SWC), and soil organic carbon content (SOC)). Vegetation restoration can change the plant type and microbial communities. The accumulation of nutrients and organic matter in topsoil results from complex interactions between biotic processes regulated by plants and soil biota and abiotic processes driven by environmental factors. With the vegetation succession, TN and SOC increased, followed by an increase in the SOCS, which in turn changed the soil porosity. The soil texture was improved, resulting from the diminished clay and sand content and the increased silt content. In addition, BD decreased and SHC increased; as a result, SWC and SWS decreased. SOCS and SWS likely affect each other.

different soil layers (0–100 cm and 0–200 cm; Fig. 5). The correlation between the SWS and SOCS was highly significant in the 0–200 cm soil layer at the G1 and G2 stages (10 a and 30 a; $P < 0.01$) and was significant at the S stage (50 a; $P < 0.05$). However, the correlation was not significant in the 0–200 cm soil layer at the F1, F2 and F3 stages (110 a, 130 a and 160 a; $P > 0.05$), whereas it was significant at the F1 and F3 stages ($P < 0.05$) and highly significant at the F2 stage ($P < 0.01$) in the 0–100 cm soil layer. In general, the correlation between SWS and SOCS gradually weakened with the increase in the soil depth and vegetation restoration stages.

4. Discussion

Vegetation types and structures can significantly influence soil water content (Wang et al., 2012a,b). The study indicated that the SWS in the 0–200 cm soil layers significantly decreased with the vegetation succession stages, whereas it increased with the soil depth of 0–200 cm at each restoration stage (Fig. 2b). This result likely occurred because the SWC showed the same pattern with the vegetation restoration and had a significantly positive relationship with the SWS. In general, the vertical variation of the soil moisture at each restoration stage tended to be higher near the soil surface due to the frequent exchange of water and energy (Jia and Shao, 2013). Our study also showed that the SWC in the 0–200 cm soil layer was highly variable. In contrast, Chen et al. (2008a,b) showed that the SWC was less variable in the 0–400 cm soil layer at the plot scale, where there was less variability in, e.g., soil types, plants and topography. Soils at the grass stage had a significantly higher SWC than those at the shrub stage or forest stage ($P < 0.05$), which was partly in agreement with the results of Wang et al. (2006). Soils at the forest stage tended to have lower water contents due to the higher root densities of trees at these depths compared with grasses and the resulting greater transpiration ability (Wang et al., 2010). Because the root depth was becoming deeper and the root density was becoming higher at the restoration stages from grass to shrub to forest, the soil depth at which the SWS intensely varied moved downward with the vegetation succession. In the Loess Plateau, porosity is a key attribute of the soil structure affecting the soil reservoir under natural vegetation recovery (Zhao et al., 2010). In this study, the SWS was highly and negatively related to total porosity (TP), aeration porosity (AP) and capillary porosity (CP) at each restoration stage in the 0–200 cm soil layer ($P < 0.01$) and positively related to soil bulk density (BD), except stages F2 and F3. The correlation between SWS and BD, silt and sand were significant ($P < 0.05$) at stage G1 and highly significant ($P < 0.01$) at the other stages (Table 2), which indicated that BD, TP, AP, CP, silt and sand were important factors influencing SWS during the restoration succession.

Depending on land use, soil acts as either a carbon source or a carbon sink. Changes in land-use change the function of the source or the sink (Deng et al., 2013). In this study, the SOCS in the different soil layers increased gradually with vegetation restoration and differed significantly among the different restoration stages. This observation is consistent with previous findings (Schedlbauer and

Kavanagh, 2008; Zhao et al., 2015) likely because vegetation recovery facilitated SOC accumulation from biomass input (Tang et al., 2010). The SOCS was highest in the topsoil (0–20 cm) and tended to decrease with the increasing soil depth. This finding is in agreement with the results of a resent study conducted in the same area (Deng et al., 2013) likely because the accumulation of nutrients and organic matter in topsoil results from complex interactions between biotic processes regulated by plants and soil biota and abiotic processes driven by environmental processes (Hooper et al., 2000). The SOC in the 0–60 cm soil layer significantly decreased at each stage of succession and tended to be stable in the soil layers below 60 cm. This finding was attributed to organic material inputs in the form of the roots and root exudates of the more deeply rooting species (Nelson et al., 2008). In natural restoration, plant litter increasingly decomposes and with time is transformed into soil organic matter (Castro et al., 2010); thus, the SOCS in the 0–20 cm soil layer increased gradually with the vegetation restoration, which had not significantly varied during 50 years of restoration ($P > 0.05$; G1, G2, S). This finding is consistent with a previous study (Deng et al., 2013) likely because the complex effect of vegetation types on the SOC changes following land-use changes: Woody plants may produce a greater amount of litter, and grass may develop enormous root systems (Zhang et al., 2010). However, it increased significantly at the F1 stage (~100 a), and after 130 years of vegetation restoration, it tended to be stable. The SOCS tended to be stable at soil layers below 120 cm, 80 cm, 60 cm, 40 cm, 40 cm and 20 cm at the G1, G2, S, F1, F2 and F3 stages (10 a, 30 a, 50 a, 110 a, 130 a and 150 a). This finding shows that the soil depth at which the SOCS tended to be stable moved upward with the vegetation restoration stages. In this study, the SOCS was highly and negatively related to BD at each restoration stage in the 0–200 cm soil layer ($P < 0.01$), and the correlation between SOCS and clay, silt, sand, TP, IP, AP and CP were significant at only the G1 and G2 restoration stages in the 0–200 cm soil layer ($P < 0.05$), which indicated that BD was an important factor influencing SOCS during the restoration succession.

Broadly speaking, the SWS was negatively related to the SOCS in different degrees in the 0–200 cm soil layer at different vegetation restoration stages. In natural restoration, the increasing plant litter decomposer resulted in increased soil organic matter accumulation, and soil porosity changed as a result (Zhao et al., 2010). Organic matter is the most important coagulating substance in the soil aggregate formation (Kay, 1998). Different organic matter compositions likely result in different soil particles or aggregate bindings, which cause different soil solid states characterized by different soil porosity (Zhao et al., 2010); thus, it follows that natural vegetation succession increases soil organic matter accumulation, thereby also exerting important influences on the characteristics of soil porosity (Deng et al., 2013). In the Loess Plateau, porosity is a key attribute of soil structure affecting the soil reservoir under natural vegetation recovery (Zhao et al., 2010). Thus, the SWS is an indicator for soil organic matter accumulation. Soil organic matter determines SOCS (Jangid et al., 2011; Smith, 2008), making SWS a reflection of SOCS. A correlation analysis of the parameters of the 0–200 cm soil layer showed that both SWS and SOCS were strongly related to other physical properties of soil ($P < 0.05$; Table 2, Fig. 6). In general, clay, silt, sand, TP, IP, AP, and CP were the important factors influencing the coupling interaction of SWS and SOCS at the grass restoration stages (<50 a), and BD influenced this coupling interaction at the shrub and early forest restoration stages (<130 a). The effect of soil physical factors on the coupling interaction of SWS and SOCS gradually weakened during the vegetation restoration succession.

In our study, information on the dynamics of soil water and carbon following long-term vegetation restoration is essential for managing the water resources and reducing the SOC losses through runoff and the transport of sediments, and for evaluating the capacity of the soil water reservoir and carbon pool, this would be helpful for adjusting relevant governmental policies. The long-term restoration of vegetation meant the soil could sequester SOC, this would affect the carbon cycle and mitigate global climate change.

5. Conclusions

The soil water reservoir and carbon pool were significantly influenced by the long-term vegetation restoration from grassland to forest. The SWS in the different soil layers gradually decreased along with the vegetation restoration and increased with the soil depth (0–200 cm) at each restoration stage. However, the SOCS increased gradually along with vegetation restoration and tended to decrease along with the increase in soil depth; it was highest in the topsoil (0–20 cm). In addition, the soil depth at which the SWS intensely varied and at which the SOCS tended to be stable moved downward and upward, respectively, with the vegetation succession. The correlation between SWS and SOCS was significant ($P < 0.05$) in the long-term restoration and gradually weakened with the increase in the soil depth and vegetation restoration stages. Clay, silt, sand, TP, IP, AP, and CP were the important factors influencing the coupling interaction of SWS and SOCS at the grass restoration stages (<50 a), and BD influenced this interaction at the shrub and early forest restoration stages (<130 a). The effect of soil's physical factors on the interaction of SWS and SOCS gradually weakened during the vegetation restoration succession. Further research is required to understand what factors other than BD mainly affected the coupling interaction of SWS and SOCS, as well as the corresponding functional mechanism of this interaction.

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