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Short communication

Interaction of soil water storage and stoichiometrical characteristics in the long-term natural vegetation restoration on the Loess Plateau

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ABSTRACT

Knowledge of the soil water and stoichiometrical characteristics (SC) during long-term natural vegetation restoration is essential for managing the restoration of vegetation. To evaluate the response of soil water storage (SWS), soil organic carbon (SOC), total nitrogen content (TN) and total phosphorous content (TP) to long-term natural vegetation restoration (~160 a), we examined the soil moisture and SC in areas with different restoration ages located in the central part of the Loess Plateau, China. Our results showed that the SWS decreased significantly with vegetation restoration and that the C:P ratio, N:P ratio, TN and TP increased significantly. The SWS increased gradually, whereas the SOC, C:P ratio, N:P ratio, TN and TP in each restoration stage decreased significantly with increasing soil depth in the 0–60 cm soil layer. These parameters tended to be stable in the soil layer below 60 cm. Vegetation acts as a link between SWS and soil SC, and they interact with each other indirectly. SWS and SWC showed an significant positive relationship ($P < 0.01$), whereas SWS and SOC, TN, TP, C:P ratio, and N:P ratio showed significant negative relationships ($P < 0.01$), thus, SOC, TN and TP are the key chemical factors affecting SWS.. These results could help estimating the productivity and sustainability of semiarid ecosystems and improve future eco-environmental reconstructions.

1. Introduction

Soil erosion is a modern global problem that induces severe economic consequences (Montgomery, 2007), environmental effects (Lal, 1995), and accelerated degradation of soil quality (An et al., 2008). In the Loess Plateau of China there are extreme environmental problems (Kimura et al., 2007), especially in the region severely affected by wind and water erosion covering ca. 178 million square meters (35°25′–40°38′N, 103°00′–113°53′E), about 29% of the total area of the plateau in the transitional zone between arid and semi-arid areas (Li et al., 2003). Secondary succession can lead to the recovery of the properties of degraded soil and maintain soil fertility (Wang et al., 2011a; Deng et al., 2013; Zhang and Shangguan, 2016). To control soil erosion and ecosystem degradation, a large area of agricultural land on the Loess Plateau has been converted to other uses during the past few decades. For example, farmland has been converted into grasslands, shrublands and forests with natural vegetation (Zhou et al., 2012; Feng et al., 2013; Deng et al., 2014). Information on the secondary forest succession processes on the Loess Plateau is of great significance, as it could reveal the relationship between the succession of vegetation and the evolution of soil ecological functions, thereby proving guidance for eco-environmental reconstruction (Zhang et al., 2016).

Soil water is a critical variable in studies of hydrological processes and the soil–plant–atmosphere continuum, especially in arid and semi-arid regions of the world such as the Loess Plateau of China where groundwater is buried below the thick unsaturated loessial soil (Jia and Shao, 2014). It directly controls the main source of water consumed by vegetation and the availability of water to plants (Martinez-Fernandez and Ceballos, 2003). Furthermore, soil water is the most limiting factor in the production and restoration of vegetation on the Loess Plateau (Xia and Shao, 2008; Gao et al., 2011; Jia and Shao, 2013a) and heavily influences the spatial and temporal distribution patterns of vegetation. Soil water storage (SWS), which is associated with the soil water content (SWC), is critical for sustaining rain-fed agriculture on the Loess Plateau (Yang, 2001). Long-term vegetation restoration has had significant effects on the SWS in grasslands and forests, and the SWS has decreased significantly with vegetation restoration (Zhang et al., 2016). Information on the dynamics of soil moisture needed for vegetation restoration in arid and semi-arid regions is essential for estimating the productivity and sustainability of semiarid ecosystems.

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Ecological stoichiometry provides a powerful framework for studying how vegetation types affect the balance of essential nutrients (e.g., carbon (C), nitrogen (N) and phosphorous (P)) during long-term natural vegetation succession, in which the cycling dynamics of soil nutrients may affect successional patterns, plant production and ecosystem processes (Peltzer et al., 2010; Osman and Barakbah, 2011; Yuan and Chen, 2012b). Soil organic carbon (SOC) is the largest C stock in the terrestrial ecosystem (Batjes, 1996). Deng et al. (2014) found that changes of land use types have a significant effect on the global C cycle through changing soil C accumulation rates and turnover. The afforestation of formerly arable affected the redistribution of SOC in the soil profile, but the SOC did not increase over three decades (Vesterdal et al., 2002), however, Murty et al. (2002) observed that 24% of the SOC stock has been lost from forestland to cropland and Guo and Gifford (2002) found 59% has been lost from pastureland to cropland globally. As the higher SOC stocks and recalcitrance, the deeper soil layers play a vital role in SOC sequestration and storage (SOCS) (Rumpel and Kögel-Knabner, 2011). Changes in the plant species composition with the vegetation restoration can alter soil aggregation (An et al., 2010), root system and litter input (Schedlbauer and Kavanagh, 2008), which will further change the stabilization and storage of SOC (Blanco-Canqui and Lal, 2004). Galloway et al. (2004) reported that N is the most common limiting element for plant production in the terrestrial biosphere and N dynamics are a key parameter in the regulation of long-term terrestrial C sequestration (Luo et al., 2004). In agricultural ecosystems, soil total nitrogen (TN) and total phosphorus (TP) are the major determinants and indicators of soil fertility and quality, which are closely related to soil productivity. The reduction of TN and TP levels can result in a decrease in soil nutrient supply, fertility, porosity, penetrability, and, consequently, in soil productivity (Wang et al., 2009). Thus, information on the spatial distribution of STN and STP is needed for the purpose of evaluating potential crop yields. Soil C:N:P stoichiometry is essential for understanding the nutrient cycling in terrestrial ecosystems (Tian et al., 2010; Yuan and Chen, 2012a). However, the mechanism of how Soil C:N:P stoichiometry changes with natural vegetation restoration is still unclear for Loess Plateau. The study of ecological stoichiometry is crucial in accelerating scientific understanding of nutrient biogeochemistry and associated behavior during nutrient circulation (Jeyasingh and Weider, 2007; Bradshaw et al., 2012). However, at present, soil C, N, and P stoichiometrical characteristics with respect to vegetation restoration have yet to be fully described (Jiao et al., 2013).

Vegetation can affect the SWS, SWC, SOC, TN, TP and other SC through the physiological activity of roots, the addition of leaf litter and the affected soil physical properties, such as soil bulk density, particle composition, hydraulic conductivity, etc. Additionally, soil water and SC inevitably influence plant growth. Thus, although SWS and SC seemingly cannot directly interact, they influence each other indirectly. Information about the change of soil SC in the long-term natural vegetation restoration could provide a powerful framework for studying how vegetation types affect the balance of essential nutrients, help estimating the productivity and sustainability of semiarid ecosystems and improve future eco-environmental reconstructions. In the Ziwuling Forest Region of the Loess Plateau, there has an intact series in the naturally recovering vegetation restoration on the Loess Plateau. In this study, we hypothesized that SWS and soil SC can negatively interact each other and both vary with natural vegetation restoration on the Loess Plateau, and our aim was to reveal the SWS response dynamics and SC to different vegetation restoration stages and the relationships between them. The specific objectives of the study were to investigate (1) the spatio-temporal dynamics of SWS and SC along with vegetation restoration, (2) the relationships between SWS and SC during the conversion of grassland to forestland, and (3) the key chemical factors affecting the SWS.

2. Materials and methods

2.1. Study area

The study was conducted on the Lianjiabian Forest Farm of Heshui County in Gansu Province, China (35°03′–36°37′ N, 108°10′–109°18′E, 1,211–1,453 m a.s.l.). The Ziwuling forest region covers a total area of 23,000 km^2. It has an mean rainfall of 587 mm, mean temperature of 10 °C and cumulative temperature of 2,671 °C. The soils of the region are largely Loessial (Jia et al., 2005). In this area, the forest canopy density ranges from 80% to 95% (Cheng et al., 2012), and secondary forests have naturally regenerated from grassland to shrubland to climax forest (Q. *liaotungensis*) through approximately 160 years (Wang et al., 2010a). Shrub and herbaceous communities recovery times were estimated from the local elders and descriptions found in contracts between farmers and local governments and forest community recovery times were estimated by counting the growth rings and consulting related written sources (Wang et al., 2010b). Throughout the region, *Bothriochloa ischaemum* (Linn.) Keng, *Carex lanceolata* Boott, *Potentilla chinensis* (Ser) and *Stipa bungeana* Trin are the dominate herb species, *Sophora davidii* (Franch.) Skeels, *Hippophae rhamnoides* (Linn.), *Rosa xanthina* Lindl and *Spiraea pubescens* Turcz are the dominate shrub species, *Populus davidiana* Dode and *Etula platyphylla* Suk communities dominate the pioneer forests, and. the climax vegetation is the *Quercus liaotungensis* Koidz forest (Table 1).

2.2. Experiment design and soil sampling

A field survey was undertaken between August 1 and August 15, 2014. Five 20 m × 20 m plots were chosen in each forest community, five 5 m × 5 m plots were chosen in the shrub communities, and five 2 m × 2 m plots were chosen in the herbaceous communities. All of the plots faced northeast and the slope gradient is less than 20°. Four soil sites were selected in areas with vegetation that had been allowed to grow for approximately 10, 50, 110 and 160 years naturally.

Soil samples were taken at five points: the four corners and the center of the soil sampling sites described above. The soil samples were taken at 20-cm intervals to a depth of 2 m using a drill and stored in sealed aluminum cases for measuring the SWC. Undisturbed soil cores were collected using a soil bulk sampler for measuring the soil bulk density at 0–60 cm. To measure SOC, TN and TP, disturbed soil samples

Table 1
Geographical and vegetation characteristics at different restoration stages in the Ziwuling forest region of the Loess Plateau.

Restoration stages	Latitude	Longitude	Altitude	Aspect	Slope	Coverage	Main plant species
	(N)	(E)	(m)		(°)	(%)	
G(10 a)	36°05′04.0″	108°31′37.4″	1348	NE	14	85	*Lespedeza bicolorr*
S(50 a)	36°04′14.4″	108°32′01.4″	1354	NE	18	90	*H. rhamnoides*
F1(110 a)	36°03′05.3″	108°32′31.8″	1437	NE	10	90	*P. davidiana, Q. liaotungensis*
F2(160 a)	36°02′57.5″	108°32′13.7″	1449	NE	18	95	*Q. liaotungensis*

Note: G represents the grass restoration stage, S represents the shrub restoration stage, F1 represents the early forest stage, and F2 represents the climax forest stage. Numbers in parentheses following the restoration stage are the ages after cropland abandonment. G, S and F stand for grassland, shrub and forest, respectively.