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Factors affecting lucerne-rich vegetation under revegetation in a semi-arid environment

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A B S T R A C T

Understanding the factors contributing to spatial variation in the functional structure of plant is crucial for revegetation and ecosystem management of the Loess Plateau, China. As one of the measures in the "Grain for Green" project, lucerne (*Medicago sativa* L.) has been widely planted in this seriously-eroded region to improve revegetation and conserve soil and water. However, information on how environmental factors influence the long-term development of lucerne-rich vegetation is scarce. This study aimed to identify the main environmental variables controlling the lucerne-rich vegetation through multivariate analyses. Vegetation and soil surveys were performed in 28 fields containing 11-year-old lucerne. Vegetation variables were total aboveground biomass, aboveground biomass of lucerne, total cover, lucerne cover, total abundance, species richness, Shannon–Wiener's diversity index, Simpson's predominance index, and evenness index. Topographic variables were slope, slope position, and slope aspect. Soil variables were soil total nitrogen (N) and phosphorus (P), available P, mineral N, organic carbon (SOC), moisture content (SMC), microbial biomass C and N. Analyses verified that vegetation variables, soil variables, and topographic variables were significantly correlated. One of the most important factors that influence lucerne revegetation process was SOC. SMC, total P, slope, and mineral N were also key factors that influenced vegetation variables. The obtained values of total aboveground biomass and cover were still high after 11 years planting. The fields that in the north– and south–facing slopes did not significantly differ in terms of total cover, and total and lucerne aboveground biomass. The results suggest that soil properties (such as SOC, TN, and mineral N, etc.) and topographic variables (i.e., slope) interacted with each other and acted on plants simultaneously in the lucerne-rich vegetation. To revegetation the degraded ecosystems by lucerne planting, we should consider the effects of the changes of soil properties, such as SOC, SMC, and soil P, on vegetation development.

1. Introduction

The Loess Plateau of China is a seriously-eroded region in the world (Chen et al., 2007; Turner et al., 2011). In this region, soil erosion is induced by highly-eroded soil, hill-gully terrain, unmanaged land use, and low vegetation coverage. Soil is highly erodible by wind and water because cropping practices, such as tillage, have reduced the levels of soil organic matter and consequently result in poor soil structure (Yang and Shao, 2000). Vegetation cover and biomass are extremely low because of very limited rainfall and severe human disturbances, such as overgrazing; as a result, less protection against soil erosion in provide (Chen et al., 2007; Wang et al., 2011). With population expansion in the region, tillage practices have been intensively applied, but this procedure has exacerbated soil erosion and arable land degradation (Guan et al., 2013). To address these issues, the Chinese government proposed the "Grain for Green" project in 1999 to convert arable land into forests and pasture lands and thus reduce soil erosion and improve environmental quality (Chen et al., 2007). Some legume species, such as *Medicago sativa* L., *Astragalus adsurgens* Pall. and *Lespedeza davurica* S., have been used to revegetate the Loess Plateau (Wang et al., 2015) because of their high yield and adaptability to semiarid environmental conditions (Yuan et al., 2016a).

Lucerne (*Medicago sativa* L.), a perennial legume species, has emerged as an important agricultural forage species in the world (Russelle, 2001; Ventroni et al., 2010). This species has been widely used for the "Grain for Green" project on the Loess Plateau because it can protect soil from wind and water erosion. In 2003, lucerne species was grown on 1 million ha in China, and this coverage increase by 32% from the value obtained in 2001 (Jia et al., 2006). As food for livestock, lucerne was mown once a year by local farmers at the end of the growing season. However, the continuous growth of lucerne on abandoned lands has promoted the rapid development of plant communities and has formed diverse plant communities in which lucerne coexists with but dominates other native plant species (Török et al., 2011; Yuan

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et al., 2015a,b). According to Yuan et al., 2016a, lucerne can produce a maximum pasture yield of 6.5 t ha^{-1} $year^{-1}$, which is higher than that of natural revegetation. Vegetation cover and biomass are necessary to control soil erosion. In addition, high species diversity likely results in high community productivity and stability (Tilman et al., 1996; Hector, 1999). Although this parameter is essential for the revegetation of the "Grain for Green" project, lucerne-rich vegetation has been rarely investigated.

The development of vegetation on arable land is a complex process and it is simultaneously influenced by various environmental factors, such as topography factors, soil properties (Cimalová and Lososová, 2009), and human activities (Yuan et al., 2015). Understanding the relationships between environmental and vegetative variables is a key step to managing degraded ecosystems (Liu et al., 2012). Therefore, abiotic factors that limit revegetation should be understood (Walker et al., 2006; Walker and del Moral, 2009). The productivity and diversity of plant communities have been described as the outcome of available resource, such as nutrients, water, and light (Grime et al., 1997). Changes in soil carbon (C) and nitrogen (N) can provide feedback on plant community succession (Deng, Shangguan and Sweeney, 2014). Phosphorus (P) (Jiao et al., 2007, 2008; Liu et al., 2012) and water (Moeslund et al., 2013) in soil are also considered primary limiting factors of plant production. The long-term planting of lucerne can increase soil C and N contents, decrease P, and cause water deficiency in deep soil on the Loess Plateau (Jiang et al., 2006; Yuan et al., 2016a,b; Guan et al., 2016). However, the specific factors, including soil water, SOC, N or P, affecting lucerne-rich vegetation have yet to be determined. In addition, it has been identified that fine-scale site factors, such as slope and slope aspect, playing key roles in controlling plant community composition (Zhang and Dong, 2010; Aarrestad et al., 2011). Therefore, changes in plant community characteristics, such as aboveground biomass, cover, diversity index, and the factors controlling these characteristics in lucerne-rich vegetation on the Loess Plateau should be evaluated (Yuan et al., 2015a,b).

This study aimed to analyze the effects of environmental factors, such as topography and soil properties, on aboveground biomass, density, and diversity of lucerne-rich vegetation on the Loess Plateau. This study also aimed to identify the key factors controlling the characteristics of plant communities. This study was mainly designed to provide a scientific basis for improved management and revegetation decisions regarding revegetation in semi-arid region of the Loess Plateau.

2. Materials and methods

2.1. Study area

This study was conducted at the Ecological Research Station of Lanzhou University in the northern mountainous region of Yuzhong County, Gansu, China (104°24′E, 36°02′N; 2400 m above sea level). Mean annual temperature is 6.5 °C, ranging from −8.0 °C in January to 19 °C in July. The area experiences a semi-arid steppe climate with a mean annual precipitation of 305 mm. An approximately 60% of all precipitation occurs from June to September. The average annual open-pan evaporation is about 1300 mm. The soil in the site is Heima (Calcic Kastanozems, FAO Taxonomy), with a field water holding capacity of 23% by weight and a permanent wilting point of 4.5% by weight (Shi et al., 2003). The growing season of vegetation in the area is from April to October.

2.2. Experimental design

Twenty-eight lucerne-rich hillslope fields were randomly selected near the Ecological Research Station of Lanzhou University on August 2013. Lucerne has been planted in these fields since April 2003 at a seed density of 22.5 kg ha^{-1}, as relayed by the village head who conducted the lucerne planting. All of the 28 lucerne fields were planted in the same year (2003). The 28 lucerne fields were mown to soil surface every October from 2004 onwards; the aboveground biomass is removed and no additional management (such as grazing, tillage, and fertilization) was conducted until harvest in August 2013. For the 28 fields, 8 fields were in top slope, 6 fields were in upper slope, 8 fields were in middle slope, and 6 fields were in bottom slope. There were 15 and 13 fields were in the north–facing and south–facing slopes, respectively.

2.3. Vegetation and soil sampling

On August 2013, four sampling quadrats (1 m × 1 m) were randomly placed in each of the 28 lucerne-rich fields. In each quadrat, the numbers of individual species were counted, and aboveground biomass and cover were also measured. The Shannon–Wiener diversity index (*H*), Pielou's evenness index (*E*), and Simpson's predominance index (*D*) were determined by using the numbers of individual species in each quadrat (Zhang, 2005). Total plant aboveground biomass was measured by cutting all plants at the soil surface and after oven-drying to constant weight at 80 °C for 48 h. The aboveground biomass of lucerne was also measured. The heights of all lucerne plantings were measured by a tape. Total vegetation canopy cover (%) and lucerne cover (%) were assessed visually in each quadrat. The slope, slope aspect and position of each quadrat were also measured.

Three soil samples at a depth of 0.2 m were randomly collected in bulk in each field. Soil moisture was determined gravimetrically by drying the samples at 105 °C for 10 h to at a depth of 2.0 m. After removal of roots, each composite soil sample was sieved (< 2 mm) and split into two sub-samples. One sub-sample was kept at 4 °C for analyses of soil microbial biomass carbon (MBC) and nitrogen (MBN), and mineral N. The other sub-sample was air-dried at room temperature for measurement basic soil properties.

Soil organic C (SOC) was determined by the Walkley–Black method (Nelson and Sommers, 1982). Total soil N was determined by using the K_2SO_4–$CuSO_4$–Se distillation method (Bremner and Mulvaney, 1982). Available P was extracted by the Olsen method (Olsen et al., 1954), white total P was determined by molybdate colorimetric method after perchloric acid digestion and ascorbic acid reduction (O'Halloran and Cade-Menun, 2006). Soil mineral N (NH_4^+–N and NO_3^-–N) was extracted with 2 M KCl (soil: solution ratio of 1:5) and determined using the San^{++} Automated Wet Chemistry Analyzer (Skalar, Breda, Netherlands). Soil microbial biomass was extracted by the chloroform fumigation-extraction method (Voroney et al., 1993). Contents of organic C and N in filtered extracts were analyzed with the Multi C/N 3100 (Analytik Jena AG, Germany). MBC and MBN were estimated by the difference between C or N concentration in the fumigated and non-fumigated extracts, and by dividing the difference by 0.38 (K_{EC}) for C and N. In each soil sample, the ratio of SOC to total N (C/N) and the ratio of SOC to available P (C/P) were calculated.

2.4. Statistical analyses

Multivariate analyses were performed using CANOCO 4.5 to explore the relationships between vegetation variables and environmental variables in these 28 lucerne fields (ter Braak and Smilauer, 2002). In each of the fields, the data in each quadrat were used. The vegetation variables used in the analyses were total aboveground biomass, total cover, lucerne aboveground biomass, lucerne cover, species richness, *H*, *E*, *D*, and abundance. The environmental variables used for soil properties were SOC, total N, mineral N, total P, available P, soil moisture content at 0–2 m, C/N, C/P, MBC, MBN, slope aspect, slope position, and slope. The multivariate analysis used four classes of slope position: 1 (top), 2 (upper), 3 (middle) and 4 (bottom) (Yuan et al., 2015a,b) and eight classes of aspects: 1 (337.6°–22.5°), 2 (22.6°–67.5°), 3 (292.6°–337.5°), 4 (67.6°–112.5°), 5 (247.6°–292.5°), 6 (112.6°–157.5°),