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Factors affecting the recovery of abandoned semi-arid fields after legume introduction on the Loess Plateau

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ABSTRACT

The Loess Plateau of China has suffered from soil erosion for several decades. As part of the Chinese "Grain for Green" project, legume species have been introduced to restore degraded ecosystems in this region. However, information on how environmental variables influence the recovery of vegetation after legume introduction is scarce. We characterized the composition of plant communities and different environmental variables 11 years after the introduction of the legumes *Medicago sativa* L. and *Melilotus suaveolens* L. in abandoned fields of the Loess Plateau. The objectives of this research were to evaluate how environmental factors such as duration of experiment, precipitation, soil moisture, soil nutrition, and topography affect the changes in plant species composition, richness and diversity and to identify the key factors driving plant species succession. Multivariate analyses were used to evaluate the relationships between plant communities and environmental variables. These analyses showed that plant species composition varied through time, with annual species being replaced by perennial herbaceous species gradually. The introduction of *Medicago* and *Melilotus* to abandoned fields had different effects on later-successional species and changed the successional trajectory of vegetation in the abandoned fields studied. Time since restoration was the most important factor influencing the composition of vegetation. Slope position, soil moisture content, annual precipitation, and slope/aspect were also key factors driving the composition of the plant community. Our results have implications for studies of secondary succession and the topographic and climatic impacts on vegetation change in restoration ecosystems of the semi-arid Loess Plateau, and emphasize the importance of plant–topography–climate interactions in defining the structure and composition of plant communities.

1. Introduction

There is an increasing interest in developing better restoration methods to guide the restoration of degraded ecosystems, particularly in areas where traditional restoration efforts have often failed (Cortina et al., 2011; Cramer et al., 2008; Maestre and Cortina, 2004; Suding et al., 2004). The Loess Plateau is located in the upper and middle courses of the Yellow River in China, and is known as a global hotspot for soil erosion and dust production (Chen et al., 2007; Zhang, 2005). This region is facing serious deterioration of its environment because of long-term soil erosion and vegetation destruction (Jiang et al., 2013). About 1.64 billion tons of sediment are transported into the Yellow River each year (Liu, 1985), raising the riverbed downstream and thereby causing frequent devastating floods. To tackle these issues, the Chinese government proposed the "Grain for Green" project in 1999 to convert low-yielding farmlands back into forests and grasslands (Chen et al., 2007).

The natural restoration of vegetation in semi-arid environments is particularly challenging (Barberá et al., 2006; Cortina et al., 2011) because of the long time typically required to establish stable vegetation cover, particularly in highly degraded areas (Hobbs et al., 2006; Lesschen et al., 2008; Römermann et al., 2005). Thus, appropriate interventions are often used to accelerate vegetation restoration processes (Cramer et al., 2008; Török et al., 2011; Lengyel et al., 2012). A key question for the "Grain for Green" project is the selection of species to be used for restoring degraded sites (Cao, 2011; Jiang et al., 2013). Afforestation has been shown to contribute to environmental degradation (Cao, 2008; Cao et al., 2011), including low survival rate of trees (Wang et al., 2007), increased soil erosion (Normile, 2007; Wang et al., 2010), exacerbated water shortages (Cao et al., 2009) and deep soil desiccation (Chen et al., 2007). Consequently, some legume species have been used in restoration practices on the Loess Plateau

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(Zhang et al., 2000) because of their high yield, protection of the soil surface, fixation of nitrogen and adaptability to the semi-arid environment conditions (Li et al., 2007; She et al., 2009).

The introduction of plant species could induce changes in soil resources, and these changes could feed back to vegetation succession (Bezemer et al., 2006). Thus, monitoring changes in both soils and vegetation is of particular interest when assessing the overall success of restoration activities (Potthoff et al., 2005). In addition, variables such as climate and age and fine-scale site factors such as slope have been identified as the main environmental factors controlling plant community composition (Aarrestad et al., 2011; Zhang and Dong, 2010). However, the mechanisms responsible for community succession after legume introduction in abandoned farmlands are largely unknown. Thus, it is necessary to know the relationships among vegetation, soil and topographical variables when evaluating vegetation dynamics during the restoration of degraded semi-arid areas.

To evaluate the efficacy of introducing legumes, we performed a study of introducing *Medicago sativa* L. and *Melilotus* suaveolens L. in abandoned farmlands on the semi-arid Loess Plateau over 11 years. The objectives of this study were to monitor changes in plant species composition, richness and diversity, and to evaluate how environmental factors such as duration of experiment, precipitation, soil moisture, soil nutrition, and topography affect such changes, and to identify the key factors driving plant species succession.

2. Materials and methods

2.1. Study area

The study was conducted at the Semi-arid Ecosystem Station of the Loess Plateau (36°02′N, 104°24′E, 2400 m above sea level), owned by Lanzhou University. It is located at Zhonglianchuan, northern mountain region of Yuzhong county, Gansu Province, China. The area is characterized as a semi-arid desert-grassland climate with mean annual precipitation of 301 mm (see Appendix A), of which approximately 60% occurs from June to September. Mean annual temperature is 6.5 °C, ranging from −8.0 °C in January to 19 °C in July. Average annual open-pan evaporation is about 1300 mm. The soil of the study site is a Loess Orthic Entisol, and has gravimetric water content at field capacity of 23% and a permanent wilting point of 4.5% (Shi et al., 2003).

2.2. Experimental design

Two leguminous species, *M. sativa* L. (a perennial herb) and *M. suaveolens* L. (an annual or biennial herb) were used in this research. They are important forage crops and have been cultivated for hundreds of years in China (Deng et al., 2014; Fan et al., 2014). Three sloped fields (which were within 500 m of each other) were selected for this study, which started in April 2003 (Table 1). The fields had been used as croplands to grow spring wheat for several decades before their restoration. In April 2003, each field was divided into three 35 × 40 m plots (next to each other and at the same elevation), which were randomly assigned to one of the following treatments: (i) cessation of cultivation and natural revegetation, (ii) introduction of *M. sativa* L. at a seed density of 22.5 kg ha^{-1}, and (iii) introduction of *M. suaveolens* L. at a seed density of 11.3 kg ha^{-1}. All of the seeds were sown by broadcasting. No grazing, tillage, fertilization, harvesting, or any other management measures took place on the plots after the setup of the experiment.

2.3. Vegetation and soil sampling

In each plot, ten sampling quadrats (1 m × 1 m) were randomly placed in each plot at the beginning of August in each year of 2003–2008 and 2011–2013. To avoid edge effects of plant communities, all of the quadrats in this study were at least three meters apart from the plot boundaries. In each quadrat, the number of individuals of each vascular plant species was counted.

Three 0–20 cm depth soil samples were randomly collected per plot at the end of the growing season (October) in each year of 2003–2008 and 2011–2013. Each soil sample was air-dried for the estimation of soil parameters (Maestre et al., 2009). Soil available P was extracted by the Olsen method (Olsen et al., 1954). Soil total P was measured by the $HClO_4$–H_2SO_4 colorimetric method. Soil organic C 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). Soil moisture content was determined gravimetrically to a depth of 500 cm in increments of 20 cm for three cores per plot in October from 2003 to 2013. The soil variables of the three soil cores within a plot were averaged for conducting the statistical analyses described below. The data of soil moisture content, soil organic C, soil total N, soil total P and soil available P in the first (2003) and the last year (2013) of revegetation are given in Table 2.

2.4. Statistical analyses

We used multivariate analyses to explore the relationships between plant community composition and environmental factors over the 11-year period studied. Detrended correspondence analysis (DCA) was used to determine whether to use linear- or nonlinear- based methods. In this study, the results of DCA ordination showed the gradient lengths ranged from 3.752 on the first axis to 1.797 on the fourth axis. Thus, we performed a nonlinear canonical correspondence analysis (CCA) to explore the relationships between communities and environmental variables. A Monte Carlo permutation test based on 499 random permutations was conducted to test the significance of the eigenvalues of all canonical axes. To identify the contributions of environmental factors to the explanation of species variation, eigenvalues and statistical significance of each variable in the analyses of environmental variables alone (marginal effects) and forward selection of environmental variables (conditional effects) were assessed by Monte Carlo permutation tests (ter Braak and Smilauer, 2002).

The environmental variables used in the CCA analyses were soil nutrients (total N, total P, available P), and organic C and moisture content, duration of experiment, yearly precipitation, restoration treatment, aspect, slope position, and slope. The species data used were the averaged abundance of each plant species in different

Table 1
Physical properties and mean inclination and facing directions of the three studied slopes.

Field	Slope orientation	Slope position	Slope angle	Bulk density (g cm^{-3})	pH
I	North-east facing	Upper slope	10–14°	1.04	8.5
II	South-east facing	Middle slope	12–16°	1.12	8.5
III	South-east facing	Top slope	4–8°	1.14	8.4