Ecological Engineering 79 (2015) 86–93

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

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

Zi-Qiang Yuan [a], Howard Epstein [b], Feng-Min Li [a,*]

[a] State Key Laboratory of Grassland Agro-Ecosystem, School of Life Sciences, Lanzhou University, Lanzhou, Gansu 730000, China
[b] Department of Environmental Sciences, University of Virginia, Charlottesville, Virginia 22904, United States

ARTICLE INFO

Article history:
Received 4 August 2014
Received in revised form 6 February 2015
Accepted 31 March 2015
Available online 8 April 2015

Keywords:
Alfalfa
Drylands
Precipitation
Revegetation
Succession
Topography

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

* Corresponding author. Tel.: +86 13609309731; fax: +86 931 8912848.
E-mail address: fmli@lzu.edu.cn (F.-M. Li).

http://dx.doi.org/10.1016/j.ecoleng.2015.03.012
0925-8574/

(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

Table 2
The data (mean ± standard deviation) of soil moisture content (SMC, mm), soil organic C (SOC, g/kg), total P (TP, g/kg), available P (AP, mg/kg) and total N (TN, g/kg) in October of the first (2003) and the last (2013) years of revegetation used in the canonical correspondence analysis. NR, natural revegetation; MED, abandoned field introduction of *Medicago sativa*; MEL, abandoned field introduction of *Melilotus suaveolens*. For Fields I–III see Table 1.

		Field I			Field II			Field III		
		NR	MED	MEL	NR	MED	MEL	NR	MED	MEL
2003	SMC	506 ± 64	530 ± 64	494 ± 47	445 ± 38	485 ± 46	517 ± 40	546 ± 74	471 ± 65	526 ± 62
	SOC	7.18 ± 0.96	7.68 ± 0.4	7.34 ± 0.55	8.81 ± 0.45	9.82 ± 0.46	8.67 ± 0.34	9.92 ± 0.87	11.18 ± 0.93	10.01 ± 1.24
	TP	0.58 ± 0.005	0.60 ± 0.005	0.67 ± 0.004	0.58 ± 0.008	0.58 ± 0.003	0.53 ± 0.004	0.56 ± 0.007	0.51 ± 0.011	0.58 ± 0.007
	AP	3.44 ± 0.65	3.15 ± 0.95	3.44 ± 1.01	5.86 ± 0.53	5.66 ± 0.64	6.24 ± 0.78	5.37 ± 0.82	4.76 ± 1.02	3.73 ± 1.22
	TN	0.83 ± 0.04	1.37 ± 0.06	1.17 ± 0.03	1.05 ± 0.04	1.10 ± 0.03	1.02 ± 0.2	1.01 ± 0.1	1.28 ± 0.07	0.82 ± 0.06
2013	SMC	462 ± 60	394 ± 45	468 ± 55	398 ± 48	294 ± 35	378 ± 53	444 ± 57	296 ± 50	354 ± 62
	SOC	7.75 ± 0.91	14.01 ± 0.31	9.27 ± 0.64	8.55 ± 0.56	10.14 ± 0.55	8.48 ± 0.23	8.77 ± 0.6	7.71 ± 0.87	12.82 ± 2.40
	TP	0.52 ± 0.008	0.69 ± 0.004	0.54 ± 0.035	0.65 ± 0.01	0.65 ± 0.001	0.63 ± 0.006	0.63 ± 0.01	0.567 ± 0.015	0.63 ± 0.012
	AP	3.19 ± 0.68	3.45 ± 1.2	2.45 ± 0.3	5.68 ± 0.58	5.27 ± 0.53	4.54 ± 1	3.42 ± 1.2	3.45 ± 0.97	4.04 ± 1
	TN	0.81 ± 0.03	1.58 ± 0.03	1.14 ± 0.06	1.12 ± 0.05	1.35 ± 0.02	1.03 ± 0.04	0.96 ± 0.16	0.63 ± 0.1	1.37 ± 0.06

quadrats at each plot. The rare species were down-weighted in order to reduce their influence on the analysis, and the species data were square-root transformed. All multivariate analyses were conducted using CANOCO 4.5 (ter Braak and Smilauer, 2002).

Species diversity was calculated by the Shannon–Wiener diversity index (Pielou, 1966). Correlations of species richness and diversity with duration of the experiment were performed by Pearson's correlation analysis. Correlations among environments factors (i.e., soil total N, soil total P, soil available P, soil organic C, soil moisture content, duration of experiment, and yearly precipitation) in the CCA were adjusted by multiple correlations, and we only presented those significant correlations in the results. A linear mixed model was used to assess the effect of treatment on species richness and diversity in each field each year. The plot effect was assumed random while the main effect of treatment was assumed fixed. Multiple comparisons further discussed in the text were made using the method of least significant differences (*LSD*) at significance level of 0.05. The analyses were carried out using GenStat 17th Edition (VSN Int. 2014).

3. Results

The CCA results showed that there was a strong correlation between vegetation and environmental factors (Table 3). The Monte Carlo permutation test indicated that the environmental variables significantly explained the total variance (Trace = 0.476, F-ratio = 14.638, p = 0.002) and the variation along the first ordination axis (Trace = 0.978, F-ratio = 3.904, p = 0.002). The eigenvalues of sum of all canonical and sum of all were 0.978 and 2.657, respectively. Changes in the composition of the vegetation through time were significantly correlated with environmental factors (Fig. 1). The environmental variable most correlated with the first CCA axis was duration of experiment (Fig. 1). It was clear that the first CCA axis represents a restoration gradient of time since abandonment, i.e. duration of experiment increases from left to right. The first CCA axis was also correlated with precipitation. The second CCA axis was related to slope position, slope angle, soil total P and available P, restoration treatment, and soil moisture content.

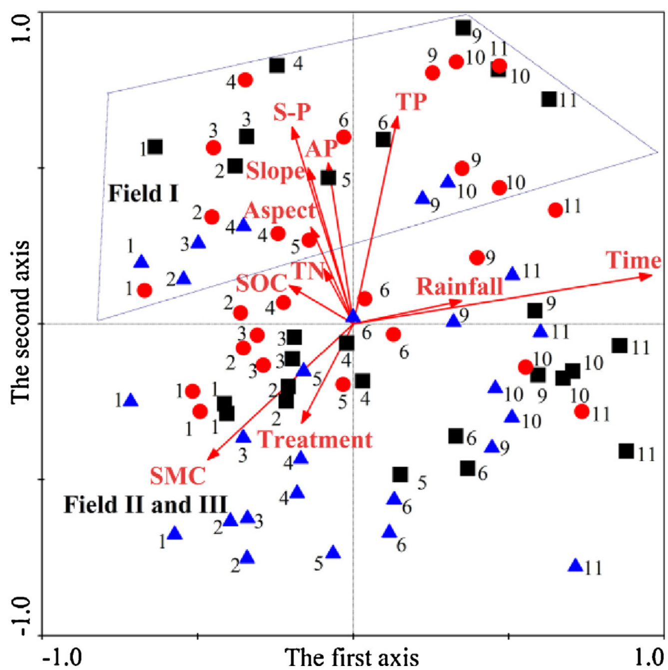

Fig. 1. Ordination diagram showing the results of CCA of plant communities and environmental variables. ■, plant communities of natural revegetation; ●, plant communities of abandoned field introduction of *M. sativa*; ▲, plant communities of abandoned field introduction of *M. suaveolens*. The arabic numbers (1–11) refer to successional time, and arrows represent environmental variables. Time, duration of experiment; Precipitation, yearly precipitation; TN, soil total N; SOC, soil organic C; TP, soil total P; AP, soil available P; SMC, soil moisture content of 0–500 cm; Slope, slope angle; Aspect, slope aspect; S-P, slope position. For Fields I–III see Table 1.

Plant communities showed an obvious separation associated with environmental factors (Figs. 1 and 2). Plant communities were clearly separated by duration of experiment along the first axis

Table 3
Results of canonical correspondence analysis of species and environmental variables during succession with different restoration treatments on the Loess Plateau.

Measures	Axes			
	1	2	3	4
Eigenvalues	0.476	0.126	0.106	0.085
Species–environment correlations	0.921	0.819	0.738	0.664
Cumulative percentage variance of species data	17.9	22.7	26.7	29.9
Cumulative percentage variance of species–environment relation	48.7	61.6	72.5	81.2

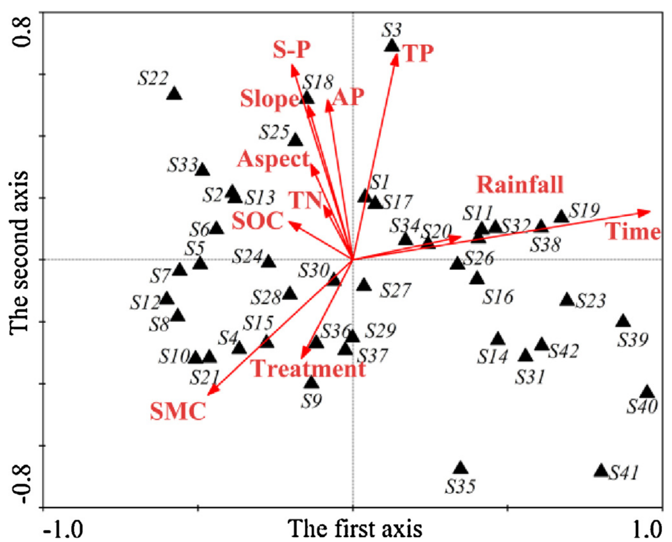

Fig. 2. CCA two-dimensional ordination diagram of the first two axes showing the distribution of 42 species (triangles) and environmental variables (vectors) (see Fig. 1). ▲ (S1–S42) represent plant species (see Appendix B).

from left to right (Fig. 1). The communities in Field I were distributed in the upper part of axis 2, which was associated with topography (slope position, angle, aspect) and soil nutrition (soil organic C, total N and total P) (Fig. 1). During the first three years after seeding, the characteristic species were annual species such as *Viola verecumda*,*Setaria viridis*, *Convolvulus arvensis*, *Plumbagella micrantha*, *Sonchus oleraceus* and *Lepidium apetalum* (Fig. 2). The communities in Fields II and III were distributed at the bottom of the bipplot, and were associated with soil moisture content and restoration treatment (Fig. 1). During the first three years after seeding, the characteristic species in these plots were annual species, such as *Chenopodium glaucum*, *Polygonum nepalense* and *Galium aparine*. Between four and six years after seeding, perennial species such as *M. suaveolens*, *Achnatherum inebrians* and *Medicago falcata* become dominant, while *Oxytropis ochrocephala*, *Artemisia frigida* and *Taraxacum mongolicum* were the characteristic species dominating these communities after nine years.

The CCA analysis revealed several loose groups of correlated explanatory variables (Fig. 2). Duration of experiment was closely correlated with soil total P ($r = 0.272$, $p = 0.012$) and moisture content ($r = -0.586$, $p < 0.001$). Soil organic C was strongly positively correlated with soil total N ($r = 0.638$, $p < 0.001$). Soil total P was strongly positively correlated with soil available P ($r = 0.249$, $p = 0.028$). Soil moisture content was negatively correlated with soil total P ($r = -0.311$, $p = 0.006$) and available P ($r = -0.231$, $p = 0.042$).

Duration of experiment, slope position, restoration treatment, soil moisture content, precipitation, and slope/aspect accounted for 86% (calculated by the sum of six factors divided by the total sum of eigenvalues for all the environmental factors) of the total variance explained by environmental factors (Table 4). The conditional effects also indicated that the contributions of the remaining variables were not significant, explaining only 14% of the total variance in our data (Table 4).

Species richness was lower in the fields where *Medicago* was introduced (Fig. 3a–c). The number of species increased with time in all the fields, regardless of the treatment considered ($r > 0.5$, $p < 0.05$; Fig. 3a–c). Richness was higher in natural revegetation than in *Medicago* treatment in years five–six (Field I), four–six (Field II) and three–six (Field III) (Fig. 3a–c). Richness in *Melilotus* treatment exceeded that in natural revegetation in at least one year in the latter period (9–11 years) in each field. A similar response was observed with the Shannon–Wiener diversity index in Field I ($r > 0.6$, $p < 0.05$; Fig. 3d). In Field I, this variable was significantly higher in *Medicago* treatment than *Melilotus* treatment in four–six years. In Fields II and III, diversity was significantly higher in *Medicago* treatment than in natural revegetation in six–eleven years (Fig. 3e, f).

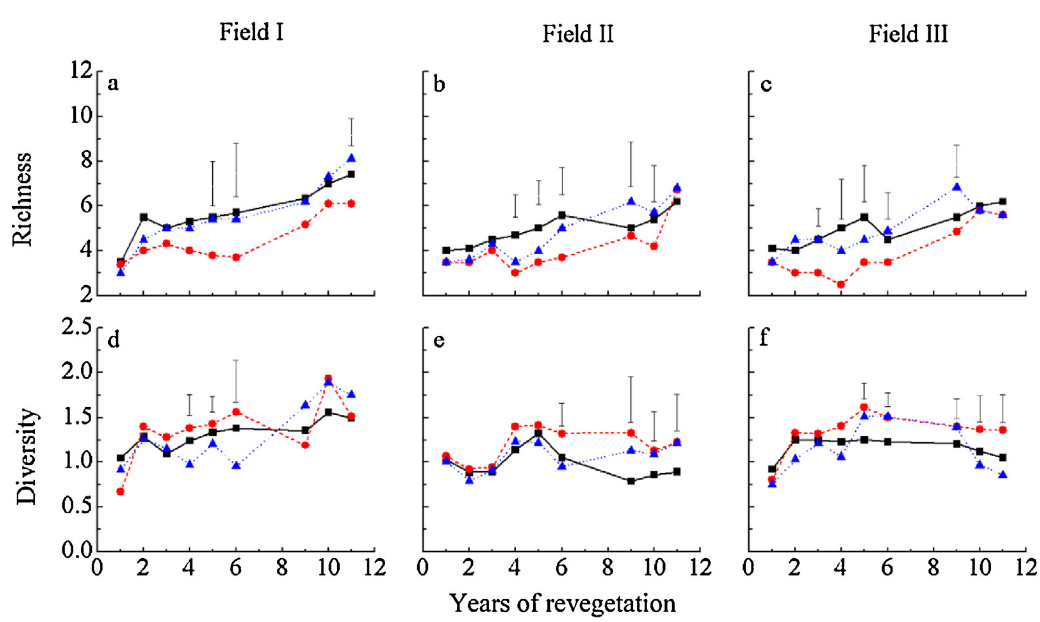

Fig. 3. Variations of species richness (a–c) and Shannon–Wiener diversity index (d–f) with duration of experiment. Bars are *LSD* at $P \leq 0.05$. ■, natural succession; ●, abandoned field introduction of *M. sativa*; ▲, abandoned field introduction of *M. suaveolens*. For Fields I–III see Table 1.

Table 4
Marginal (one variable at a time) and conditional effects (forward selection of variables) obtained from the summary of forward selection for vegetation data explained by the environmental variables in a canonical correspondence analysis. Time, duration of experiment; Precipitation, yearly precipitation; TN, total soil N; SOC, soil organic C; TP, total P; AP, available P; SMC, soil moisture content of 0–500 cm; Slope, slope angle; Aspect, slope aspect; S-P, slope position.

Variable	Marginal effects	Conditional effects		
	Eigenvalue	Eigenvalue	*F*	*p*
Time	0.445	0.445	15.277	0.002
S-P	0.086	0.105	3.734	0.002
Treatment	0.085	0.085	3.093	0.002
SMC	0.163	0.085	3.201	0.004
Rainfall	0.118	0.070	2.680	0.002
Slop/aspect	0.086	0.057	2.233	0.004
TN	0.048	0.041	1.614	0.056
TP	0.083	0.036	1.427	0.092
AP	0.063	0.037	0.464	0.104
SOC	0.061	0.020	1.032	0.156

4. Discussion

Despite being a topic heavily studied over the past decades, the relative importance of the factors affecting temporal changes in the structure and composition of vegetation is still being discussed (Grime, 2001; Kardol et al., 2006). On the Loess Plateau, returning degraded farmlands to grasslands has been a widely implemented policy since 1999 (Chen et al., 2007). Legume species such as *M. sativa* and *M. suaveolens* have been used in this process because of their rapid growth and the protection of the soil surface they provide (She et al., 2009). However, we do not know well how environmental factors drive the succession of plant communities after the introduction of legumes in this area. In this study, we described the successional direction of species and communities in the fields after the introduction of legumes, and found that successional time, slope position, restoration treatment, soil moisture content, precipitation, and slope/aspect were the most relevant environmental factors influencing this succession. Our findings help to understand the mechanisms driving plant community succession on the Loess Plateau, and can be used to improve restoration activities carried out as part of the Chinese "Grain for Green" project.

We found that the composition of the sampled communities varied greatly among treatments with duration of experiment (Figs. 1 and 2). The introduction of legumes (i.e. treatment) had significant effects on the succession of the plant community (Table 3) and on both species richness and diversity (Fig. 3). These results are consistent with previous studies showing that the introduction of legumes changed the initial stage of vegetation development on abandoned arable areas (Li et al., 2007; Van der Putten et al., 2000). Suppression of early colonizing plant species by the introduction of other species was presumed to be one of the primary mechanisms driving secondary succession in old-field plant communities (De Deyn et al., 2003; Van der Putten et al., 2000). However, plant species suppression and the establishment of late-successional species varied with the performance of the introduced species (Li et al., 2007). *Medicago sativa* is a perennial species that typically has high cover and biomass, and can grow on the Loess Plateau for more than ten years (Jia et al., 2009). *Melilotus suaveolens*, an annual or biennial herb, dies and is replaced by perennial native species after several years. These differences in the demographic characteristics of these species could have different effects on late-successional species (Fig. 2), resulting in the changes of plant community structure (Fig. 3) and the course of succession (Fig. 1) reported here.

Results from the constrained ordination revealed that duration of experiment was the most important factor in determining community structure during the restoration process (Table 3). This result is in agreement with previous studies, both from the Loess Plateau (Jiao et al., 2008; Zhang and Dong, 2010) and from other semi-arid ecosystems (Lesschen et al., 2008; Martínez et al., 2001; Munson and Lauenroth, 2011). Lesschen et al. (2008) suggest that recovery of vegetation and changes in soil properties after land abandonment are slow, and take at least 40 years in a semi-arid environment in southeast Spain. The change of community structure in vegetation restoration of the semi-arid Loess Plateau is also slow and requires time for development (Zhang, 2005). Precipitation in the semi-arid Loess Plateau is very limited, and it is the main source of water to support vegetation in this area (Li et al., 2003). Annual precipitation had significant effects on community structure in our study (Table 3), which was consistent with the results of Munson and Lauenroth (2011). Low precipitation and high potential evapotranspiration are considered as the main limitations to the establishment and growth of seeded species in semi-arid regions (Munson and Lauenroth, 2011). Legume species such as *Medicago* have high water consumption and evapotranspiration rates (Crawford and Macfarlane, 1995; Scott and Sudemyer, 1993), and their growth is influenced by precipitation (Jia et al., 2009; Li and Huang, 2008). Thus, inter-annual variability in rainfall may influence the interaction of introduced legume species and naturally occurring late-successional species, and thus vegetation development during the early stages of secondary succession.

Topography plays a major role in the redistribution of water, sediments and nutrients within slopes, thereby indirectly impacting plant distribution (Fu et al., 2004; Moeslund et al., 2013; Økland et al., 2008). It is known that aspect and slope position affect factors such as soil chemistry, litter quality, and nutrient cycling (Bennie et al., 2006; Sariyildiz et al., 2005). We found that aspect and slope position had significant effects on species succession (Table 3). The three fields we selected in this study have different topographical characteristics (Table 1), which may differentially influence soil water storage and nutrient cycling. Generally, soils had more nutrients in north-facing slopes than in south-facing slopes because of increased organic matter decomposition and the accumulation of more organic carbon and total N in the former (Rezaei and Gilkes, 2005). Thus, our results suggest that topographic variables and soil properties interact with each other and act on vegetation simultaneously in plant communities throughout secondary succession on the Loess Plateau, as found in other areas (e.g. Bennie et al., 2006; Eiserhardt et al., 2011; Moeslund et al., 2013; Økland et al., 2008).

Plant distribution at small spatial scales is strongly affected by soil properties (Cramer et al., 2008; Standish et al., 2007). Soil moisture content had significant effects on vegetation dynamics in this study (Table 3), which is consistent with previous studies (Jiao et al., 2008; Moeslund et al., 2013). Soil moisture affects a number of factors important for plant growth beyond the availability of water (Moeslund et al., 2013). For example, soil moisture has been demonstrated to affect the amount of nitrogen available to plants through its impact on mineralization rates (Giesler et al., 1998; Loiseau et al., 2005). The introduction of legumes can also greatly affect soil moisture dynamics in these areas (Zeng et al., 2008). For example, alfalfa has high photosynthetic and transpiration rates but low water use efficiency (Saeed and Ei-Nadi, 1997; Xu et al., 2007), and has been found to cause soil desiccation (up to 5 m depth) four years after its introduction (Jia et al., 2006; Li and Huang, 2008). In this study, we found that soil moisture content was negatively associated with succession time of *Medicago* communities (Fig. 1), suggesting that the introduction of this species may have reduced soil moisture. Although soil water deficit resulted from long-term growing of *Medicago*, it can be restored gradually by planting low water demand crops (Wang et al., 2008). On the other hand, *Medicago* can maintain high biomass and vegetation cover in the long-term on the Loess Plateau (Guan et al., 2012; Deng et al., 2014; Jiang et al., 2007), which is very important for controlling soil erosion and maintaining soil fertility. Previous studies show that arable lands converted into grasslands can change soil properties (e.g. soil C and N) (Bonet 2004; Ruprecht, 2006; Lesschen et al., 2008), and this change can feed back to plant community succession (Connell and Slatyer, 1977; Breemen and Finze, 1998; Deng et al., 2014). In this study, soil chemistry properties (organic C, total N, total P and available P) played a small role relative to topographic factors (slope and aspect/position), soil moisture (soil water and precipitation) and restoration (treatment and time), which is not consistent with previous studies (Goodland and Pollard, 1973; Jiao et al., 2008; Liu et al., 2012). In arid and semi-arid regions, precipitation and soil moisture were the main factors limiting vegetation establishment and growth (Chen et al., 2007; Flanagan and Johnson, 2005; Moeslund et al., 2013). In addition, topographic factors (such as slope and aspect) strongly influence the distribution and storage of precipitation and soil moisture, and the accumulation and export of soil nutrients (Zuo et al., 2008; Liu et al., 2012). Therefore, despite the significant changes of soil chemistry properties after *Medicago* and *Melilotus* introduction over 11 years, soil chemistry effect on plants establishment and species replacement throughout succession may still be limited.

5. Conclusions

This study outlined environmental factors affecting vegetation properties during old-field succession after the introduction of *Medicago* and *Melilotus* on the semi-arid Loess Plateau of China. These introduced species differentially affected the establishment of late-successional species, and modified the successional trajectories of the studied plant communities. Duration of experiment, slope position, soil moisture content, precipitation, and slope/aspect were the key factors influencing these trajectories. Our study has implications for studies of secondary succession and the topographic and climatic impacts on vegetation change in recovered ecosystems of the semi-arid Loess Plateau. Our results emphasize the importance of plant–topography–climate interactions in defining the structure and composition of plant communities during secondary succession.

Acknowledgments

This research was supported by the Fundamental Research Funds for the Central Universities (lzujbky-2012-k02, 860974), “111” Program (B0751) and Innovative Team Program of Ministry of Education. We thank Professor Fernando T. Maestre for his suggestions and comments on this paper.

Appendix A.

Yearly precipitation from 2003–2013 at the experiment site of Yuzhong County, Gansu, China. Dotted line refers to yearly average precipitation in 2002–2013.

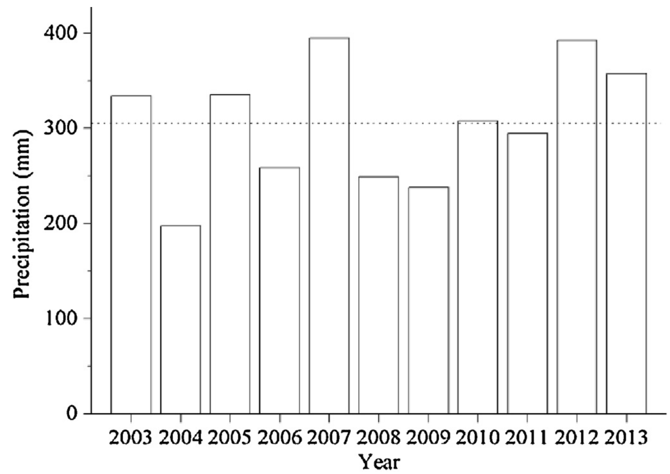

Fig. A 1. Yearly precipitation from 2003-2013 at the experiment site.

Appendix B.

Information on taxonomy, life form and functional group of the 42 species present in the vegetation restoration process on the abandoned fields after legume species introduction (*Medicago sativa* L. and *Melilotus suaveolens* L.). Taxonomy follows Wu et al., (1994–2013).

Information on taxonomy, life form and functional group of the 42 species present in this study.

	Species	Family	Life form	Functional group
S1	*Medicago sativa* L.	Leguminosae	Perennial	Legume
S2	*Viola verecumda* A.Gray	Violaceae	Annual	Forb
S3	*Potentilla bifurca* L.	Rosaceae	Perennial	Forb
S4	*Salsola collina* Pall.	Chenopodiaceae	Annual	Forb
S5	*Setaria viridis* (L.) Beauv.	Gramineae	Annual	Forb
S6	*Convolvulus arvensis* L.	Convolvulaceae	Annual	Forb
S7	*Corispermum declinatum* Steph. ex Stev.	Chenopodiaceae	Annual	Forb
S8	*Chenopodium glaucum* L.	Chenopodiaceae	Annual	Forb
S9	*Melilotus suaveolens* L.	Leguminosae	Biennial	Legume
S10	*Elsholtzia ciliata* (Thunb.) Hyland.	Labiatae	Annual	Forb
S11	*Heteropappus altaicus* (Willd.) Novop	Compositae	Perennial	Forb
S12	*Polygonum nepalense* Meisn.	Polygonaceae	Perennial	Forb
S13	*Malcolmia africana* (L.) R. Br.	Brassicaceae	Annual	Forb
S14	*Stipa grandis* P. Smirn.	Gramineae	Perennial	Grass
S15	*Phlomis umbrosa* Turcz.	Labiatae	Perennial	Forb
S16	*Oxytropis ochrocephala* Bunge	Leguminosae	Perennial	Legume
S17	*Pedicularis kansuensis* Maxim.	Scrophuhrhceae	Perennial	Forb
S18	*Sonchus oleraceus* L.	Compositae	Annual	Forb
S19	*Saussurea pulchella* Fisch. ex DC.	Compositae	Perennial	Forb
S20	*Poa annua* L.	Gramineae	Perennial	Grass
S21	*Galium aparine* L. var. tenerum Gren.et (Godr.) Rebb.	Rubiaceae	Annual	Forb
S22	*Plumbagella micrantha* (Ledeb.) Spach	Plumbaginaceae	Annual	Forb
S23	*Agropyron cristatum* (Linn.) Gaertn.	Gramineae	Perennial	Grass
S24	*Lappula echinata* Gilib.	Boraginaceae	Annual	Forb
S25	*Lepidium apetalum* Willd.	Cruciferae	Annual	Forb

(*Continued*)

	Species	Family	Life form	Functional group
S26	*Artemisia frigida* Willd.	Compositae	Perennial	Forb
S27	*Plantago depressa* Willd.	Plantaginaceae	Biennial	Forb
S28	*Cirsium setosum* (Willd.) MB.	Compositae	Perennial	Forb
S29	*Achnatheruminebrians* (Hance) Keng	Gramineae	Perennial	Grass
S30	*Aster tataricus* L. f.	Compositae	Perennial	Forb
S31	*Astragalus polycladus* Bur. et Franch.	Leguminosae	Perennial	Legume
S32	*Leymus racemosus* (Lam.) Tzvcel.	Gramineae	Perennial	Grass
S33	*Potentilla acaulis*L.	Rosaceae	Perennial	Forb
S34	*Torularia humilis* (C.A.Meyer) O.E. Schulz.	Cruciferae	Perennial	Forb
S35	*Elymus dahuricus* Turcz.	Gramineae	Perennial	Grass
S36	*Cornulaca alaschanica* Tsien et G. L. Chu	Chenopodiaceae	Annual	Forb
S37	*Medicago falcata* L.	Leguminosae	Biennial	Legume
S38	*Taraxacum mongolicum* Hand. Mazz.	Compositae	Perennial	Forb
S39	*Potentilla potaninii* Wolf	Rosaceae	Perennial	Forb
S40	*Potentilla fragarioides* L.	Rosaceae	Perennial	Forb
S41	*Heteropappusaltaicus* (Willd.) Novopokr.	Compositae	Perennial	Forb
S42	*Vicia sepium* L.	Leguminosae	Perennial	Legume

References

Aarrestad, P.A., Masunga, G.S., Hytteborn, H., Pitlagano, M.L., Marokane, W., Skarpe, C., 2011. Influence of soil, tree cover and large herbivores on field layer vegetation along a savanna landscape gradient in northern Botswana. J. Arid Environ. 75, 290–297.
Barberá, G.G., Navarro-Cano, J.A., Castillo, V.M., 2006. Seedling recruitment in a semi-arid steppe: the role of microsite and post-dispersal seed predation. J. Arid Environ. 67, 701–714.
Bennie, J., Hill, M.O., Baxter, R., Huntley, B., 2006. Influence of slope and aspect on long-term vegetation change in British chalk grasslands. J. Ecol. 94, 355–368.
Bezemer, T.M., Lawson, C.S., Hedlund, K., Edwards, A.R., Brook, A.J., Igual, J.M., Mortimer, S.R., Van der Putten, W.H., 2006. Plant species and functional group effects on abiotic and microbial soil properties and plant–soil feedback responses in two grasslands. J. Ecol. 94, 893–904.
Bonet, A., 2004. Secondary succession of semi-arid Mediterranean old-fields in south-eastern Spain: insights for conservation and restoration of degraded lands. J. Arid Environ. 56, 213–233.
Breemen, N.V., Finze, A.C., 1998. Plant–soil interaction: ecological aspects and evolutionary implications. Biogeochemistry 42, 1–19.
Bremner, J.M., Mulvaney, C.S., 1982. Methods of soil analysis. In: Page, A.L., Millar, R. H., Keeney, D.R. (Eds.), Nitrogen-Total., Part 2, Chemical and Microbiological Properties. Madison, Wisconsin, pp. 595–624.
Cao, S.X., 2008. Why large-scale afforestation efforts in China have failed to solve the desertification problem? Environ. Sci. Technol. 42, 1826–1831.
Cao, S.X., 2011. Impact of China's large-scale ecological restoration program on the environment and society in arid and semiarid areas of China: achievements problems, synthesis, and applications. Crit. Rev. Env. Sci. Technol. 41, 317–335.
Cao, S.X., Chen, L., Shankman, D., Wang, C.M., Wang, X.B., Zhang, H., 2011. Excessive reliance on afforestation in China's arid and semi-arid regions: lessons in ecological restoration. Earth-Sci. Rev. 104, 240–245.
Cao, S.X., Chen, L., Yu, X.X., 2009. Impact of China's Grain for Green Project on the landscape of vulnerable arid and semi-arid agricultural regions: a case study in northern Shaanxi Province. J. Appl. Ecol. 46, 536–543.
Chen, L.D., Wei, W., Fu, B.J., Lü, Y.H., 2007. Soil and water conservation on the Loess Plateau in China: review and perspective. Prog. Phys. Geogr. 31, 389–403.
Connell, J.H., Slatyer, R.O., 1977. Mechanisms of succession in natural communities and their role in community stability and organization. Am. Nat. 111, 1119–1144.
Cortina, J., Amat, B., Castillo, V., Fuentes, D., Maestre, F.T., Padilla, F.M., Rojo, L., 2011. The restoration of vegetation cover in the semi-arid Iberian southeast. J. Arid Environ. 75, 1377–1384.
Cramer, V.A., Hobbs, R.J., Standish, R.J., 2008. What's new about old fields? Land abandonment and ecosystem assembly. Trends Ecol. Evol. 23, 104–112.
Crawford, M.C., Macfarlane, M.R., 1995. Lucerne reduces soil moisture and increases livestock production in an area of high groundwater recharge potential. Aust. J. Exp. Agric. 35, 171–180.
De Deyn, G.B., Raaijmakers, C.E., Zoomer, H.R., Berg, M.P., de Ruiter, P.C., Verhoef, H. A., Bezemer, T.M., Van der Putten, W.H., 2003. Soil invertebrate fauna enhances grassland succession and diversity. Nature 422, 711–713.
Deng, L., Wang, K.B., Li, J.P., Shangguan, Z.P., Sweeney, S., 2014. Carbon storage dynamics in alfalfa (*Medicago sativa*) fields in the hilly-gully region of the Loess Plateau, China. Clean – Soil Air Water 42, 1–10.
Eiserhardt, W.L., Svenning, J.C., Kissling, W.D., Balslev, H., 2011. Geographical ecology of the palms (Arecaceae): determinants of diversity and distributions across spatial scales. Ann. Bot. 108, 1391–1416.
Flanagan, L.B., Johnson, B.G., 2005. Interacting effects of temperature: soil moisture and plant biomass production on ecosystem respiration in a northern temperate grassland. Agric. For. Meteorol. 130, 237–253.
Fu, B.J., Liu, S.L., Ma, K.M., Zhu, Y.G., 2004. Relationships between soil characteristics, topography and plant diversity in a heterogeneous deciduous broad-leaved forest near Beijing, China. Plant Soil 261, 47–54.
Giesler, R., Högberg, M., Högberg, P., 1998. Soil chemistry and plants in Fennoscandian boreal forest as exemplified by a local gradient. Ecology 79, 119–137.
Goodland, R., Pollard, R., 1973. The Brazilian cerrado vegetation: a fertility gradient. J. Ecol. 61, 219–224.
Guan, X.K., Zhang, X.H., Turner, N.C., Xu, B.C., Li, F.M., 2012. Two perennial legumes (*Astragalus adsurgens* Pall. and *Lespedeza davurica* S.) adapted to semiarid environments are not as productive as lucerne (*Medicago sativa* L.) but use less water. Grass Forage Sci. 68, 469–478.
Grime, J.P., 2001. Plant functional types, communities and ecosystems. Ecol.: Achiev. Challenge 161–181.
Hobbs, R.J., Arico, S., Aronson, J., Baron, J.S., Bridgewater, P., Cramer, V.A., Epstein, P. R., Ewel, J.J., Klink, C.A., Lugo, A.E., Norton, D., Ojima, D., Richardson, D.M., Sanderson, E.W., Valladares, F., Vilà, M., Zamora, R., Zobel, M., 2006. Novel ecosystems: theoretical and management aspects of the new ecological world order. Global Ecol. Biogeogr. 15, 1–7.
Jia, Y., Li, F.M., Wang, X.L., Yang, S.M., 2006. Soil water and alfalfa yields as affected by alternating ridges and furrows in rainfall harvest in a semiarid environment. Field Crop. Res. 97, 167–175.
Jia, Y., Li, F.M., Zhang, Z.H., Wang, X.L., Guo, R.Y., Siddique, K.H.M., 2009. Productivity and water use of alfalfa and subsequent crops in the semiarid Loess Plateau with different stand ages of alfalfa and crop sequences. Field Crop. Res. 114, 58–65.
Jiang, J.P., Xiong, Y.C., Jia, Y., Li, F.M., Xu, J.Z., Jiang, H.M., 2007. Soil quality dynamics under successional alfalfa field in the semi-arid Loess Plateau of Northwestern China. Arid Land Res. Manage. 21, 287–303.
Jiang, W.Y., Cheng, Y.F., Yang, X.X., Yang, S.L., 2013. Chinese Loess Plateau vegetation since the Last Glacial Maximum and its implications for vegetation restoration. J. Appl. Ecol. 50, 440–448.
Jiao, J.Y., Tzanopoulos, J., Xofis, P., Mitchley, J., 2008. Factors affecting distribution of vegetation types on abandoned cropland in the hilly-gullied Loess Plateau region of China. Pedosphere 18, 24–33.
Fan, J., Gao, Y., Wang, Q.J., Sukhdev, S.M., Li, Y.Y., 2014. Mulching effects on water storage in soil and its depletion by alfalfa in the Loess Plateau of northwestern China. Agric. Water Manage. 138, 10–16.
Kardol, P., Bezemer, T.M., van der Putten, W.H., 2006. Temporal variation in plant–soil feedback controls succession. Ecol. Lett. 9, 1080–1088.
Lengyel, S., Varga, K., Kosztyi, B., Lontay, L., Déri, E., Török, P., Tóthmérész, B., 2012. Grassland restoration to conserve landscape-level biodiversity: a synthesis of early results from a large-scale project. Appl. Veg. Sci. doi:http://dx.doi.org/10.1111/j.1654-109X.;1; 2011.01179.x.
Lesschen, J.P., Cammeraat, L.H., Kooijman, A.M., van Wesemael, B., 2008. Development of spatial heterogeneity in vegetation and soil properties after land abandonment in a semi-arid ecosystem. J. Arid Environ. 72, 2082–2092.
Li, F.M., Xu, J.Z., Sun, G.J., 2003. Restoration of degraded ecosystems and development of water-harvesting ecological agriculture in the semi-arid Loess Plateau of China. Acta Ecol. Sin. 23, 1901–1909 [in Chinese].
Li, J.H., Fang, X.W., Jia, J.J., Wang, G., 2007. Effect of legume species introduction to early abandoned field on vegetation development. Plant Ecol. 191, 1–9.
Li, Y.H., Huang, M.B., 2008. Pasture yield and soil water depletion of continuous growing alfalfa in the Loess Plateau of China. Agric. Ecosyst. Environ. 124, 24–32.
Liu, T.S., 1985. Loess and the Environment. China Ocean Press, Beijing.
Liu, X.P., Zhang, W.J., Yang, F., Zhou, X., Liu, Z.J., Qu, F., Lian, S.Q., Wang, C.L., Tang, X.G., 2012. Changes in vegetation–environment relationships over long-term natural restoration process in Middle Taihang Mountain of North China. Ecol. Eng. 49, 193–200.
Loiseau, P., Louault, F., Roux, X.L., Bardy, M., 2005. Does extensification of rich grasslands alter the C and N cycles, directly or via species composition? Basic Appl. Ecol. 6, 275–287.
Martínez, M.L., Vázquez, G., Sánchez Colón, S., 2001. Spatial and temporal variability during primary succession on tropical coastal sand dunes. J. Veg. Sci. 12, 361–372.
Maestre, F.T., Bowker, M.A., Puche, M.D., Belén Hinojosa, M., Martínez, I., García-Palacios, P., Castillo, A.P., Soliveres, S., Luzuriaga, A.L., Sánchez, A.M., Carreira, J. A., Gallardo, A., Escudero, A., 2009. Shrub encroachment can reverse desertification in semi-arid Mediterranean grasslands. Ecol. Lett. 12, 930–941.
Maestre, F.T., Cortina, J., 2004. Are *Pinus halepensis* plantations useful as a restoration tool in semiarid Mediterranean areas? For. Ecol. Manage. 198, 303–317.
Moeslund, J.E., Arge, L., Bøcher, P.K., Dalgaard, T., Ejrnæs, R., Odgaard, M.V., Svenning, J.C., 2013. Topographically controlled soil moisture drives plant diversity patterns within grasslands. Biodivers. Conserv. 22, 2151–2166.
Munson, S.M., Lauenroth, W.K., 2011. Plant community recovery following restoration in semiarid grasslands. Restor. Ecol. 20, 656–663.

Nelson, D.W., Sommers, L.E., 1982. Methods of Soil Analysis. In: Page, A.L., Miller, R. H., Keeney, D.R. (Eds.), Part 2., Total Carbon, Organic Carbon and Organic Matter. Madison, Wisconsin, pp. 539–579.
Normile, D., 2007. Getting at the roots of killer dust storms. Science 317, 314–316.
Økland, R.H., Rydgren, K., Økland, T., 2008. Species richness in boreal swamp forests of SE Norway: the role of surface microtopography. J. Veg. Sci. 19, 67–74.
Olsen, S.R., Cole, C.V., Watanabe, F.S., Dean, L.A., 1954. Estimation of Available Phosphorus in Soils by Extraction with Sodium Bicarbonate. United States Department of Agriculture Circular 939, pp. 19.
Pielou, E.C., 1966. The measurement of diversity in different types of biological collections. J. Theor. Biol. 13, 131–144.
Potthoff, M., Jackson, L.E., Steenwerth, K.L., Ramirez, I., Stromberg, M.R., Rolston, D. E., 2005. Soil biological and chemical properties in restored perennial grassland in California. Restor. Ecol. 13, 61–73.
Rezaei, S.A., Gilkes, R.J., 2005. The effects of landscape attributes and plant community on soil chemical properties in rangelands. Geoderma 125, 167–176.
Römermann, C., Dutoit, T., Poschlod, P., Buisson, E., 2005. Influence of former cultivation on the unique Mediterranean steppe of France and consequences for conservation management. Biol. Conserv. 121, 21–33.
Ruprecht, E., 2006. Successfully recovered grassland: a promising example from romanian old-fields. Restor. Ecol. 14, 473–480.
Saeed, I.A.M., Ei-Nadi, A.H., 1997. Irrigation effects on growth yield, and water use efficiency of alfalfa. Irrig. Sci. 17, 63–68.
Sariyildiz, T., Anderson, J.M., Kucuk, M., 2005. Effects of tree species and topography on soil chemistry litter quality, and decomposition in Northeast Turkey. Soil Biol. Biochem. 37, 1695–1706.
Scott, P.R., Sudemyer, R.A., 1993. Evapotranspiration from agricultural plant communities in the high rainfall zone of the southeast of Western Australia. J. Hydrol. 146, 301–319.
She, D.L., Shao, M.A., Timm, L.C., Reichardt, K., 2009. Temporal changes of an alfalfa succession and related soil physical properties on the Loess Plateau, China. Pesq. Agropec. Bras. 44, 189–196.
Shi, Z.Y., Liu, W.Z., Guo, S.L., Li, F.M., 2003. Moisture properties in soil profiles and their relation to landform at Zhonglianchuan watershed. Agric. Res. Arid Areas 21, 101–104 [in Chinese].
Standish, R.J., Stokes, B.A., Tibbett, M., Hobbs, R.J., 2007. Seedling responses to phosphate addition and inoculation with arbuscular mycorrhizas and the implications for old-field restoration in Western Australia. Environ. Exp. Bot. 61, 58–65.
Suding, K.N., Gross, K.L., Houseman, G.R., 2004. Alternative states and positive feedbacks in restoration ecology. Trends Ecol. Evol. 19, 46–53.
Török, P., Vida, E., Deák, B., Lengyel, S., Tóthmérész, B., 2011. Grassland restoration on former croplands in Europe: an assessment of applicability of techniques and costs. Biol. Conserv. 20, 2311–2332.
ter Braak, C.J.F., Smilauer, P., 2002. CANOCO Reference Manual and User's Guide to Canoco for Windows: Software for Canonical Community Ordination (Version 4.5). Micro-Computer Power. Ithaca, NY, US.
Van der Putten, W.H., Mortimer, S.R., Hedlund, K., Van Dijk, C., Brown, V.K., Lepš, K., Rodriguez-Barrueco, C., Roy, J., Diaz Len, T.A., Gormsen, D., Korthals, G.W., Lavorel, S., Santa Regina, I., Smilauer, P., 2000. Plant species diversity as a driver of early succession in abandoned fields: a multi-site approach. Oecologia 124, 91–99.
Wang, G.Y., Innes, J.L., Lei, J.F., Dai, S.Y., Wu, S.W., 2007. China's forestry reforms. Science 318, 1556–1557.
Wang, X.L., Sun, G.J., Jia, Y., Li, F.M., Xu, J.Z., 2008. Crop yield and soil water restoration on 9-year-old alfalfa pasture in the semiarid Loess Plateau of China. Agr. Water Manage. 95, 190–198.
Wang, Y.F., Fu, B.J., Lü, Y.H., Song, C.J., Luan, Y., 2010. Local-scale spatial variability of soil organic carbon and its stock in the hilly area of the Loess Plateau, China. Quat. Res. 73, 70–76.
Wu, Z.Y., Raven, P.H., Hong, D.Y. (Eds.), 1994–2013. Flora of China. Science Press, Missouri Botanical Garden Press, Beijing, St. Louis.
Xu, B.C., Shan, L., Li, F.M., 2007. Comparison of ecophysiological characteristics of seven plant species in semiarid loess hilly-gully region. Chin. J. Appl. Ecol. 18, 990–996 [in Chinese].
Zeng, Z.X., Liu, X.L., Jia, Y., Li, F.M., 2008. The effect of conversion of cropland to forage legumes on soil quality in a semiarid agroecosystem. J. Sustain. Agric. 32, 335–353.
Zhang, J.D., Qiu, Y., Cai, B.F., Zheng, F.Y., 2000. Succession analysis of plant communities in Yancun low-middle hills of Luliang Mountains. J. Plant Res. Environ. 9, 34–39.
Zhang, J.T., 2005. Succession analysis of plant communities in abandoned croplands in the eastern Loess Plateau of China. J. Arid Environ. 63, 458–474.
Zhang, J.T., Dong, Y.R., 2010. Factors affecting species diversity of plant communities and the restoration process in the loess area of China. Ecol. Eng. 36, 345–350.
Zuo, X.A., Zhao, H.L., Zhao, X.Y., Guo, Y.R., Li, Y.L., Luo, Y.Y., 2008. Plant distributionat the mobile dune scale and its relevance to soil properties and topographic features. Environ. Geol. 54, 1111–1120.