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Effects of legume species introduction on vegetation and soil nutrient development on abandoned croplands in a semi-arid environment on the Loess Plateau, China

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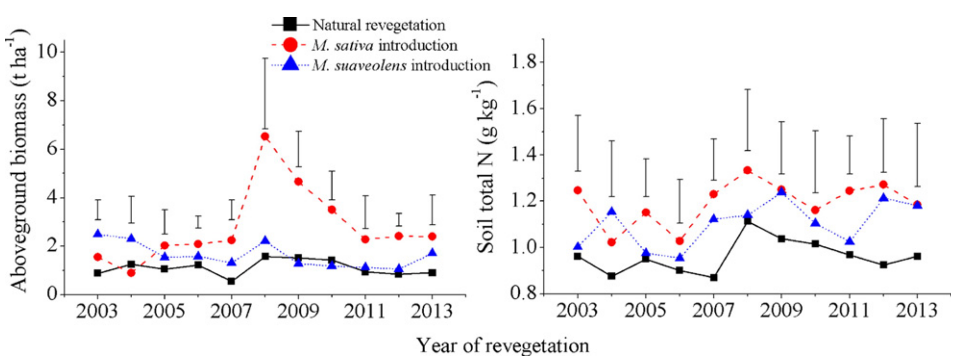
HIGHLIGHTS

- *Medicago sativa* introduction increased biomass, cover and soil nitrogen content.
- *Melilotus suaveolens* introduction were not effective approaches for revegetation.
- *Medicago sativa* can be the preferred species for revegetation on the Loess Plateau.
- P fertilizers should be applied for effective management of revegetation fields.

GRAPHICAL ABSTRACT



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ABSTRACT

Revegetation facilitated by legume species introduction has been used for soil erosion control on the Loess Plateau, China. However, it is still unclear how vegetation and soil resources develop during this restoration process, especially over the longer term. In this study, we investigated the changes of plant aboveground biomass, vegetation cover, species richness and density of all individuals, and soil total nitrogen, mineral nitrogen, total phosphorus and available phosphorus over 11 years from 2003 to 2013 in three treatments (natural revegetation, *Medicago sativa* L. introduction and *Melilotus suaveolens* L. introduction) on the semi-arid Loess Plateau. *Medicago* significantly increased aboveground biomass and vegetation cover, and soil total nitrogen and mineral nitrogen contents. The *Medicago* treatment had lower species richness and density of all individuals, lower soil moisture in the deep soil (i.e., 1.4–5 m), and lower soil available phosphorus. *Melilotus* introduction significantly increased aboveground biomass in only the first two years, and it was not an effective approach to improve vegetation biomass and cover, and soil nutrients, especially in later stages of revegetation. Overall, our study suggests that *M. sativa* can be the preferred plant species for revegetation of degraded ecosystems on the Loess Plateau, although phosphorus fertilizer should be applied for the sustainability of the revegetation.

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1. Introduction

Soil erosion is a global problem and has resulted in the loss of soil fertility and ecosystem productivity, thus increasing poverty, human migration and other social problems (Adeel, 2005). The Loess Plateau is located in the upper and middle courses of the Yellow River in China, and is known as a hotspot for drought and soil erosion (Chen et al., 2007; Turner et al., 2011). The soil itself is highly erodible by wind and water especially because of cropping practices (e.g., tillage) which have lowered soil organic matter levels and led to poor soil structure (Yang and Shao, 2000). Vegetation cover and biomass in this region is extremely low due to very limited rainfall, high evaporation rates and severe human disturbance such as overgrazing and intensive cultivation, thereby providing even less protection against soil erosion (Chen et al., 2007; Wang et al., 2011). Recognizing the severity of this erosion problem, the Chinese government proposed the 'Grain for Green Project' in western China in 1999 to convert low-yielding farmlands back into forests and pastures with the objectives of reducing soil erosion and improving environmental quality (Chen et al., 2007).

Species introduction is an effective approach to accelerate the revegetation for the 'Grain for Green Project'. Some legume species have been used for revegetation on the Loess Plateau (Wang et al., 2015) because of their high yield, fixation of nitrogen and adaptability to the semi-arid environmental conditions. Studies have shown that legume species introduction can significantly increase vegetation cover and biomass and improve ecosystem services such as protection of the soil surface and carbon sequestration (An et al., 2013; Li et al., 2006). The presence of vegetation intercepts rainfall, reduces surface runoff, reduces surface shear stress (Li et al., 2007) and thus significantly prevents soil erosion (Brandt, 1988; Woo and Luk, 1990). The biomass of legumes can be used to develop the livestock industry and to improve the income of local farmers, thus contributing to regional socioeconomic development (Fu et al., 2010a; Li et al., 2003). Therefore, how to increase vegetation cover and biomass of degraded ecosystems and maintain them in a sustainable way has been one of the central issues of restoration ecology.

Alfalfa (*Medicago sativa* L.), a perennial legume species, has become one of the most important agricultural forage species in the world (Russelle, 2001; Ventroni et al., 2010). It has the greatest feed protein per unit area among the forage and grain legumes (Erice et al., 2010) and was introduced into China from Iran (Persia) more than 2000 years ago. In recent decades, it has been widely planted on the Loess Plateau to increase livestock production and address the government environmental objective of preventing soil erosion (Li and Huang, 2008). *Melilotus suaveolens* L., a biennial legume species, is also a high-quality forage species and has also been widely used in the revegetation process on the Loess Plateau. Some studies suggest that vegetation cover and biomass can be improved temporarily and plant species composition is significantly influenced after *M. sativa* and *M. suaveolens* introduction on the Loess Plateau (Li et al., 2006). However, it is unclear how vegetation and soil nutrients develop over the longer term after *M. sativa* and *M. suaveolens* introduction on abandoned fields.

In the soil-vegetation system, complex feedback mechanisms regulate soil formation, plant community development, and erosion-sedimentation processes (Kirkby et al., 1998; Puigdefabregas et al., 1999). Revegetation may cause an accumulation of organic matter and may change nutrient and moisture contents in the soil (Eaton et al., 2008). Some studies however suggest that legume species (e.g., *M. sativa*) are plants with high water and phosphorus (P) demand and that their introduction can significantly influence soil water dynamics and organic carbon, nitrogen (N) and P in soils (Jiang et al., 2006). These altered soil physical and chemical properties can then in turn influence the production of biomass and ecosystem functioning (Breemen and Finze, 1998; Connell and Slatyer, 1977; De Deyn et al., 2003). Soil moisture (Chen et al., 2007) and available P (Jiao et al., 2008) are the main limiting factors affecting vegetation establishment and growth on the Loess Plateau. Elucidating the dynamics of soil water and nutrients in the revegetation process may therefore have important implications for the sustainable management of land resources on the Loess Plateau and similar regions (Jia et al., 2012; Yang et al., 2014).

To understand whether legume species introduction could support a sustainable revegetation (i.e., high vegetation coverage, biomass, and soil nutrients over the long term), a reasonable approach is to investigate how vegetation, soil moisture and nutrients develop. To this end, we performed a study of introducing *M. sativa* and *M. suaveolens* to abandoned farmlands on the semi-arid Loess Plateau in April 2003 and assessed their effects on vegetation, soil moisture and nutrients over the following 11 years. The objectives of this study were to evaluate the effects of three revegetation methods (i.e., natural revegetation, *M. sativa* planting and *M. suaveolens* planting) on (i) plant aboveground biomass, cover, density of all individuals, species richness, and the aboveground biomass, cover, and individual densities of functional groups, (ii) soil water storage and dynamics, and (iii) soil total N (TN), mineral N, total P (TP) and available P (AP). The ultimate goal is to provide the basis for improved management decisions for the revegetation on the Loess Plateau.

2. Materials and methods

2.1. Study area

The 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. This region is characterized by a moderate temperate semiarid climate with highly fluctuating rainfall and mean annual precipitation of 305 mm, with approximately 60% occurring from June–September. Average annual open-pan evaporation is about 1300 mm. The soil is Heima (Calcic Kastanozems, FAO Taxonomy), with a field water holding capacity of 22.9% by weight and a permanent wilting point of 4.5% by weight (Shi et al., 2003). The growing season of vegetation in this area is from April to October. The agriculture in this area is typical rain-fed farming with main crops of spring wheat (*Triticum aestivum*), flax (*Linum usitatissimum*), pea (*Pisum sativum*) and potato (*Solanum tuberosum*).

2.2. Experimental settings and design

Three fields were selected from croplands in April 2003, where serious soil erosion had occurred (Guo et al., 2010). All of the three fields were on hillslopes. One is north-east facing with a slope of 10–14°, and the other two are south-east facing with slopes of 12–16° and 4–8°, respectively. Each field was abandoned and divided into three plots (35 m × 40 m per plot, next to each other and at the same elevation), and the three plots received one of three treatments randomly: (i) natural revegetation, (ii) seeded with the perennial legume species alfalfa (*M. sativa* L.) at a density of 22.5 kg ha^{-1}, and (iii) seeded with the biennial legume species sweetclover (*M. suaveolens* L.) at a density of 11.3 kg ha^{-1}. The planting densities used in this study were the optimum densities for these two legume species and were recommended by the local agricultural technical personnel with a purpose of obtaining high yields. All of the fields had been used as croplands to grow spring wheat for several decades before April 2003. Averages of soil organic carbon, TN, TP and AP content before legume species introduction in these three fields were 8.32 g kg^{-1}, 0.89 g kg^{-1}, 0.71 g kg^{-1} and 19.85 mg kg^{-1}, respectively, and no significant differences were found among fields. Treatments were established without grazing (fencing), tillage, fertilization, harvesting or any other management after April 2003.

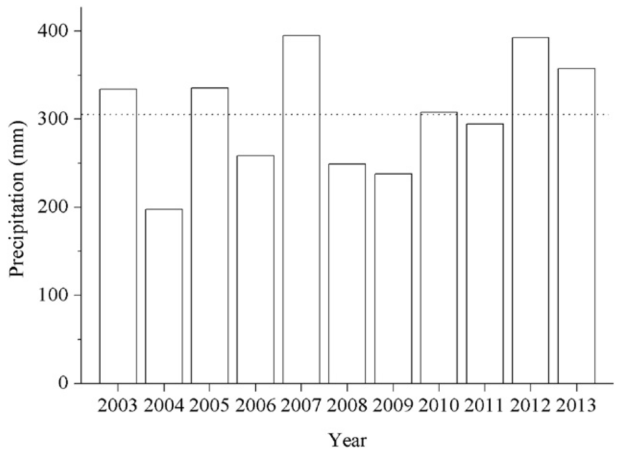

Fig. 1. Yearly precipitation in 2003–2013 at the experiment site of Yuzhong County, Gansu, China. Dotted line refers to yearly average precipitation in 2003–2013. Data are from the automatic weather station of Ecological Research Station of Lanzhou University in the Yuzhong County.

2.3. Vegetation sampling

Ten sampling quadrats ($1\ m \times 1\ m$) were randomly placed in each field at the beginning of August each year (2003–2013). To avoid edge effects of plant communities, all quadrats were at least 3 m from the field boundaries. In each quadrat, the number of species and the number of individuals of each species were counted. Total aboveground biomass was assessed as the weight of all plant species after cutting all plants at the soil surface and drying to constant weight at 80 °C for 48 h. We calculated plant density of each species using the individual number of each species per m^2. The estimates of total aboveground biomass, density, and richness are based on data from 2003 to 2013. During 2011–2013, we did more detailed vegetation surveys in each quadrat in which canopy cover (%), aboveground biomass and density of each species were also estimated, and the species were divided into three functional groups: legumes, grasses and other forbs (hereafter simply 'forbs') and with three life forms: annual, biennial and perennial.

2.4. Soil sampling

Three replicated soil cores (8 cm diameter × 20 cm depth) were randomly collected in each plot after removing plant residues at the end of the growing season in October each year (2003–2013). Each soil sample was air-dried for the estimation of soil parameters. AP was extracted by the Olsen method (Olsen et al., 1954). TP was determined by the molybdate colorimetric method after perchloric acid digestion and ascorbic acid reduction (O'Halloran and Cade-Menun, 2006). Soil organic C was determined by the Walkley–Black method (Nelson and Sommers, 1982). TN was determined by using the K_2SO_4–$CuSO_4$–Se distillation method (Bremner and Mulvaney, 1982). Soil mineral nitrogen was determined with a Smartchem Discrete Auto Analyzer. At each sampling time, the ratio of soil organic carbon to TN (C/N) and the ratio of soil organic carbon to AP (C/P) were calculated. Soil water content was determined gravimetrically to a depth of 500 cm in increments of 20 cm for three cores per plot in October for all sampling years.

2.5. Statistical analyses

A linear mixed model was used in the analysis of aboveground biomass, cover, density of all individuals, and richness; aboveground biomass, cover, and individual densities of functional groups;

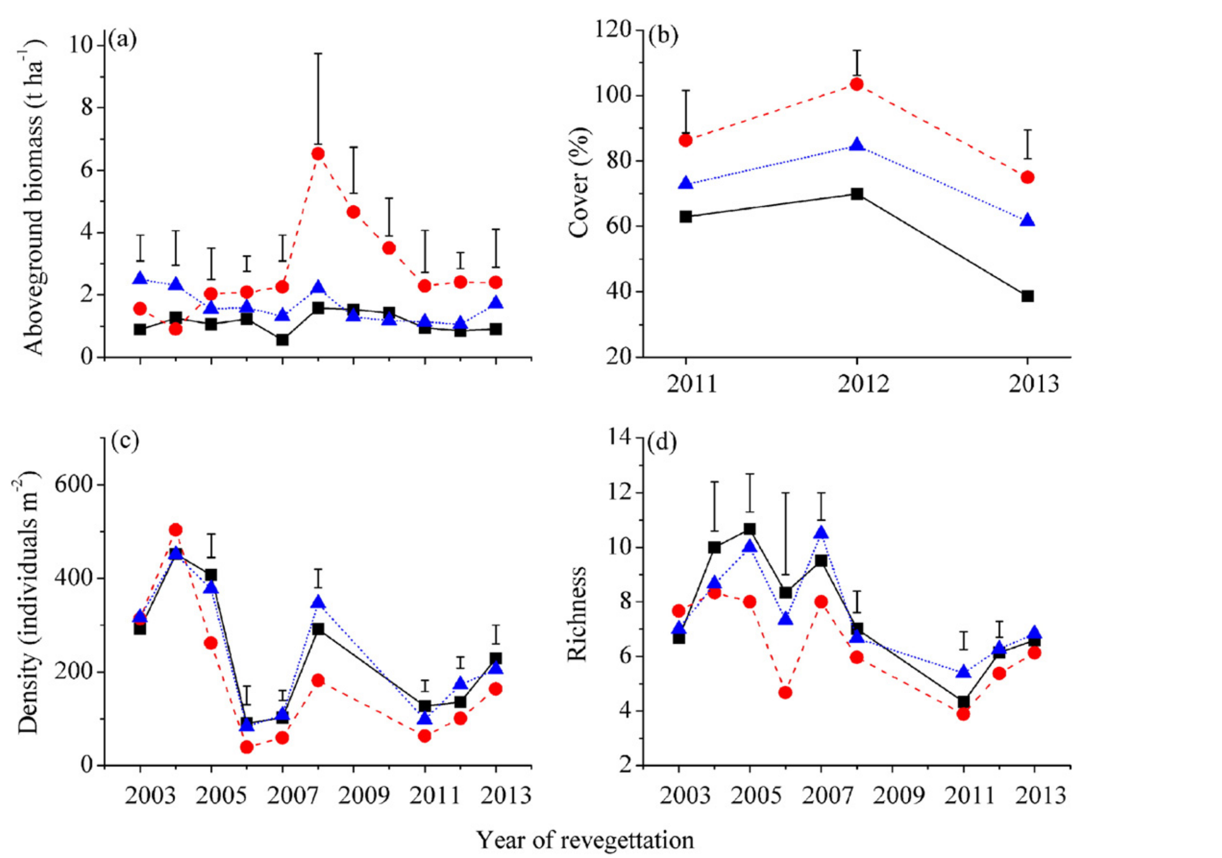

Fig. 2. Variations of total aboveground biomass (t ha^{-1}) (a), total cover (%) (b), density (individuals m^{-2}) (c) and species richness (d) in the three treatments with duration of experiment. Bars are the LSD at $P = 0.05$. ■, natural revegetation; ●, abandon fields planted with *Medicago sativa*; ▲, abandon fields planted with *Melilotus suaveolens*. Note that total cover (%) is reported for 2011–2013 while other variables are reported for 2003–2013.

aboveground biomass, cover, and individual densities of life forms; and soil properties (soil moisture content, TN, mineral N, C/N, TP, AP and C/P) in each year. The field effect was treated as a random factor while the main effect of regeneration treatment was treated as a fixed factor. Multiple comparisons further discussed in the text were made using the method of least significant differences (LSD) at the significance level of 0.05. The analyses were carried out using GenStat 17th Edition (VSN Int., 2014).

3. Results

3.1. Precipitation

Inter-annual variability in precipitation was high in the study. Annual precipitation ranged from 197 mm in 2004 to 394 mm in 2007 (Fig. 1). In 2003, 2005, 2007, 2012 and 2013, the annual precipitations were 12%, 12.5%, 33%, 22% and 18% greater than the average value (305 mm) over 11 years from 2003 to 2013, respectively; in 2004, 2006, 2008 and 2009, annual precipitation was lower than the average value.

3.2. Plant community

3.2.1. Aboveground biomass, cover, density and richness

Aboveground biomass was greatest in the *Melilotus* treatment in the first two years after revegetation, and afterwards it was greatest in the *Medicago* treatment (Fig. 2a). The maximum aboveground biomass of 6.5 t ha^{-1} appeared in the *Medicago* treatment in the sixth year. Vegetation cover was greater in the *Medicago* treatment than the other two treatments in the 9th–11th years (from 2011 to 2013) (Fig. 2b), the only years for which vegetation cover was measured. Density of individual plants had no significant difference among the three treatments in the first two years, and afterwards it was significantly lower in the *Medicago* treatment than the other two treatments (Fig. 2c). Species richness exhibited the same patterns as density in the 1st–10th years, but there were no significant differences among treatments in the 11th year (Fig. 2d).

3.2.2. Functional groups and life forms

In the 9th–11th years of revegetation, density and cover, but not aboveground biomass of both forbs and grasses were significantly lower in the *Medicago* treatment than the other two treatments (Fig. 3a, c, d, f, g, i). The density, cover and aboveground biomass of legumes were greater in the *Medicago* treatment than the other two treatments (Fig. 3b, e, h). *Medicago* had significantly greater proportions of density, cover and aboveground biomass than either grass or other forbs (Fig. 4). The plant community in each treatment was dominated by perennials in 2011–2013 as seen from the significantly higher density, cover and aboveground biomass of perennials than annuals and biennials (Fig. 5). Densities of annual, biennial and perennial species were significantly lower in the *Medicago* treatment, while vegetation cover and aboveground biomass of perennials were significantly higher in the *Medicago* treatment than the other two treatments.

3.3. Soil water storage and dynamics

Soil water content (%) in the top 1.4 m of the soil within each treatment had high inter-annual variability. After revegetation for ten years, soil water contents at 1.4–5 m in the natural revegetation and *Melilotus* treatments were still higher than the permanent wilting point of 4.5% (Fig. 6a, c). In contrast, soil water content at 1.4–5 m significantly declined in the *Medicago* treatment in the fourth year and was close to the permanent wilting point in the 11th year (Fig. 6b).

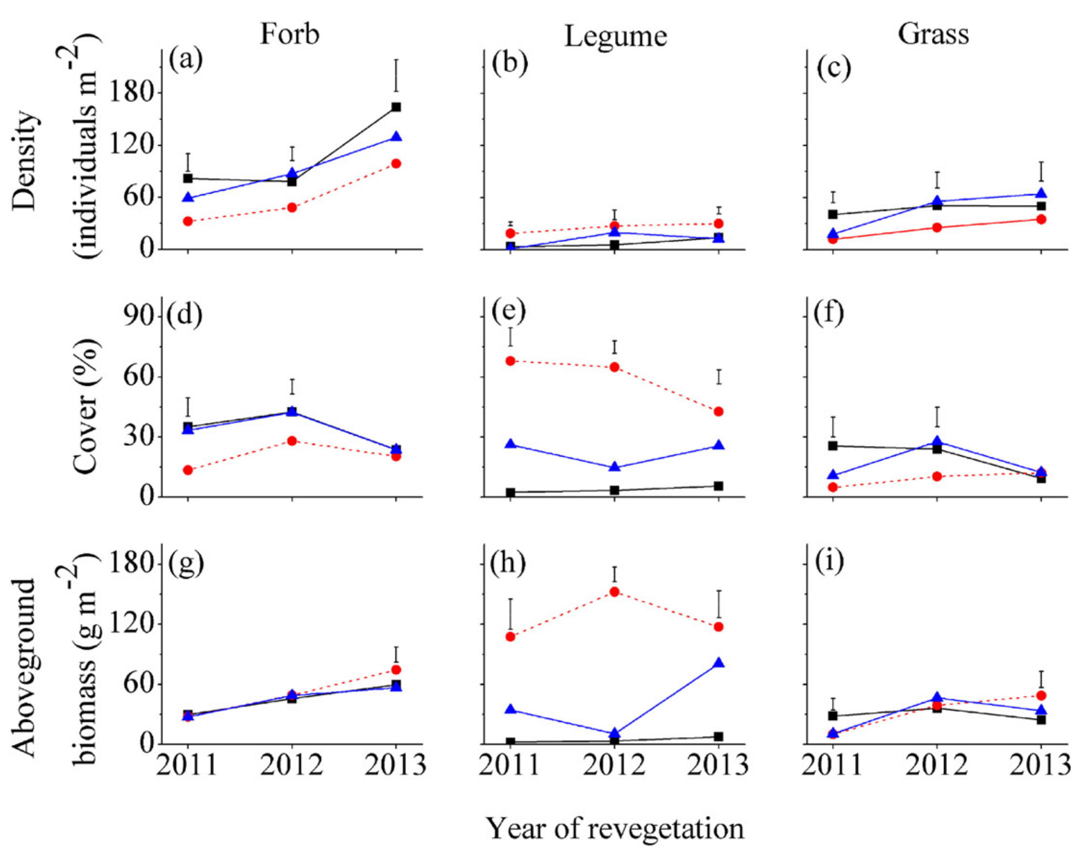

Fig. 3. Changes of density (individuals m^{-2}) (a, b, c), cover (%) (d, e, f) and aboveground biomass (g m^{-2}) (g, h, i) at the functional group level in the three treatments in 2011–2013. Bars are the LSD at $P = 0.05$. ■, natural revegetation; ●, abandon fields planted with *Medicago sativa*; ▲, abandon fields planted with *Melilotus suaveolens*.

Soil water content (mm) in the top 1.4 m of the soil had no significant difference among treatments in each year (Fig. 7a). Soil water content at 1.4–5 m had no significant difference among treatments in the first three years, and afterwards it was significantly lower in the *Medicago* treatment than the other two treatments (Fig. 7b). No significant differences in soil water content at 1.4–5 m were found in the natural revegetation and *Melilotus* treatments in each year (Fig. 7b).

3.4. Soil nutrition

Both soil TN and mineral N were greater in the *Medicago* treatment than the other two treatments during the experimental period, except in the second year after revegetation (Fig. 8a, b). Natural revegetation had lower soil TN and mineral N than the other two treatments in each year (Fig. 8a, b). C/N in the *Medicago* and *Melilotus* treatments were increased at first and subsequently declined with time of revegetation, and it had no significant trend with time in natural revegetation. C/N had no significant difference among treatments in the first two years, it was lower in natural revegetation in the 3rd to 5th years, and afterwards it was lower in the *Medicago* treatment (Fig. 8c). Soil TP was not significantly different among treatments in each year; it showed a declining trend in the first and second years, and afterwards a slight increase with time in all treatments (Fig. 8d). Available P was lower in *Medicago* and *Melilotus* treatments than natural revegetation in the first four years after revegetation, and afterwards it was lower in the *Medicago* treatment (Fig. 8e). C/P ratios in each treatment were greater than 1000 in each year, and they were greatest in the *Medicago* treatment and lowest in natural revegetation in each year (Fig. 8f).

4. Discussion

Conversion of arable lands into grasslands can increase vegetation cover and reduce soil erosion (Lesschen et al., 2008; Ruprecht, 2006). In this study, *Medicago* introduction significantly increased aboveground biomass and vegetation cover in the long term (Fig. 2a, b), which is consistent with some previous studies (Guan et al., 2013; Munson and Lauenroth, 2012). Li et al. (2006) also observed increase of aboveground biomass and vegetation cover after *Medicago* introduction on abandoned fields, but their experiment only lasted for three years. The higher aboveground biomass in the *Medicago* treatment can be used to support animal husbandry, thereby increasing the income of local farmers, reducing their excessive land reclamation and indirectly improving the ecological environment of this semi-arid loess region (Li et al., 2003). In addition, vegetation cover has important influences on soil erosion and soil productive capacity (Brandt, 1988; Primentel et al., 1995). Regardless of the fact that greater aboveground biomass

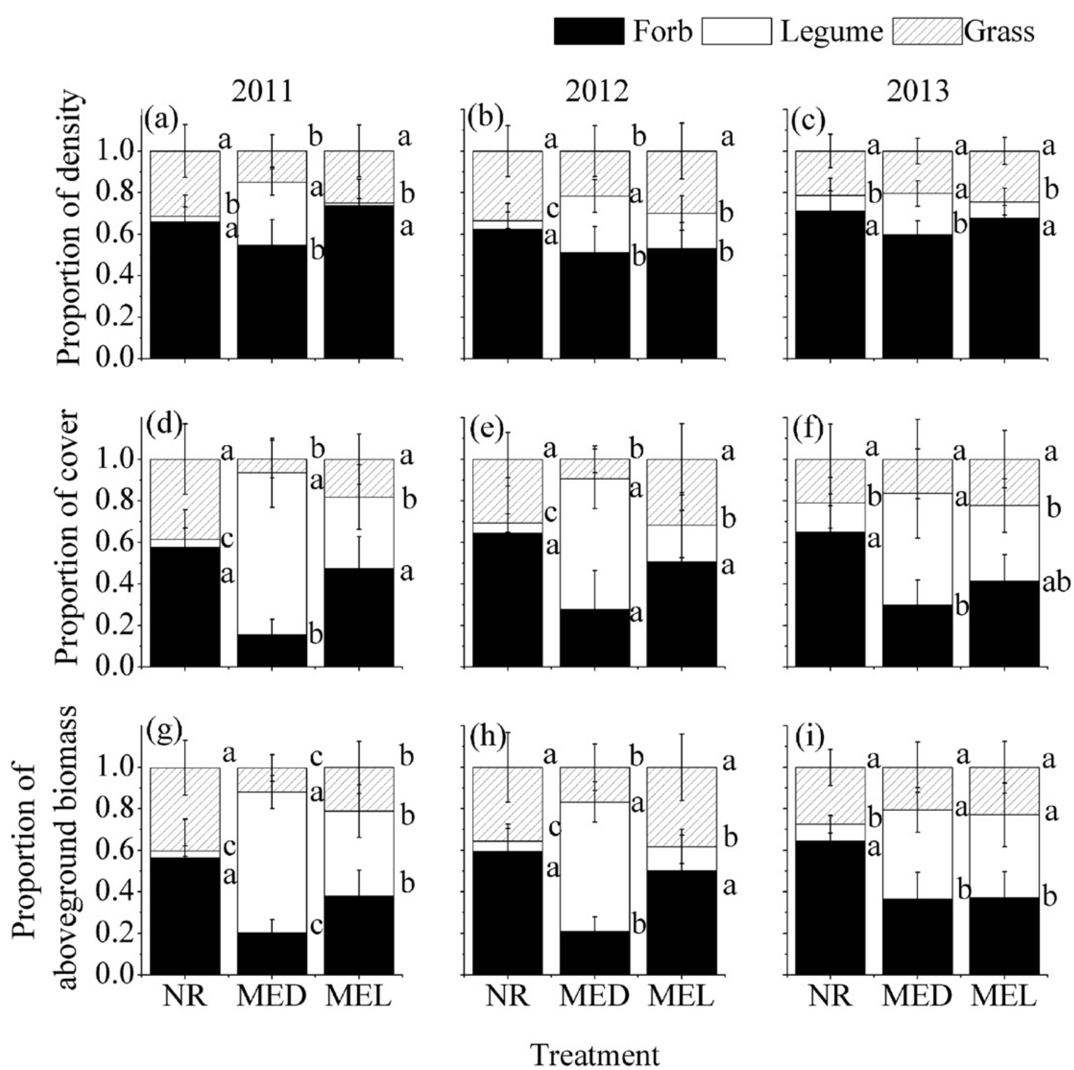

Fig. 4. Proportions of density (a, b, c), cover (d, e, f) and aboveground biomass (g, h, i) at the functional group level in the three treatments in 2011–2013. Different lower letter indicates significant difference among treatments in a year at $P = 0.05$. NR, natural revegetation; MED, abandon fields planted with *Medicago sativa*; MEL, abandon fields planted with *Melilotus suaveolens*.

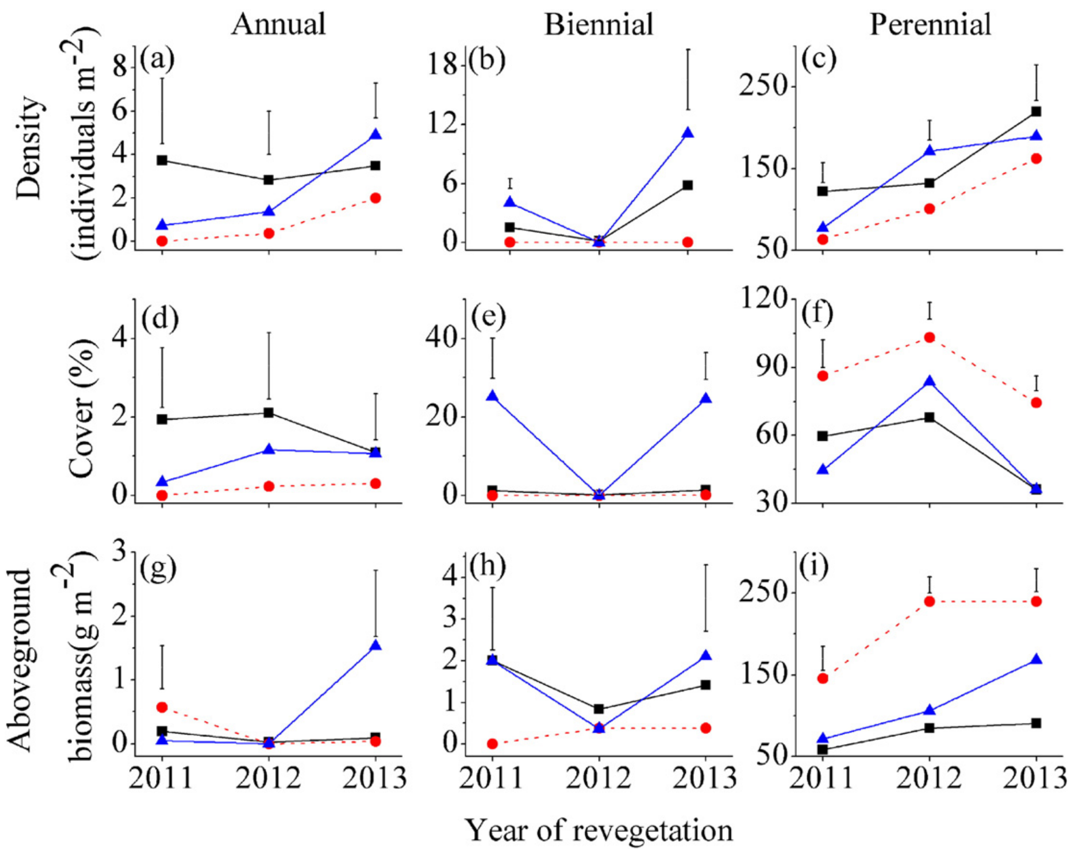

Fig. 5. Changes of density (individuals m^{-2}) (a, b, c), cover (%) (d, e, f) and aboveground biomass ($g\ m^{-2}$) (g, h, i) at the life history level in the three treatments in 2011–2013. Bars are the LSD at $P = 0.05$. ■, natural revegetation; ●, abandon fields planted with *Medicago sativa*; ▲, abandon fields planted with *Melilotus suaveolens*.

in the *Melilotus* treatment was found in the first two years after revegetation, it declined rapidly and was not significantly different from natural revegetation between years 3 and 11 (Fig. 2a). *Melilotus* is a biennial forage species and can be replaced by highly competitive native plant species over time. The low aboveground biomass and vegetation cover in natural revegetation and the *Melilotus* treatment suggest that they are less effective in improving vegetation conditions and preventing soil erosion in the semi-arid region of the Loess Plateau.

Some previous studies suggest that seeding perennial species can significantly change species richness and reduce the number of natural colonizers (Van der Putten et al., 2000; Li et al., 2008). In this study, species richness and density of all individuals were significantly lower in the *Medicago* treatment than the other two treatments (*Melilotus* treatment and natural revegetation) (Fig. 2c, d). These results are consistent with other studies (Christian and Wilson, 1999; Collins et al., 1998). For instance, Christian and Wilson (1999) found that fields with introduced

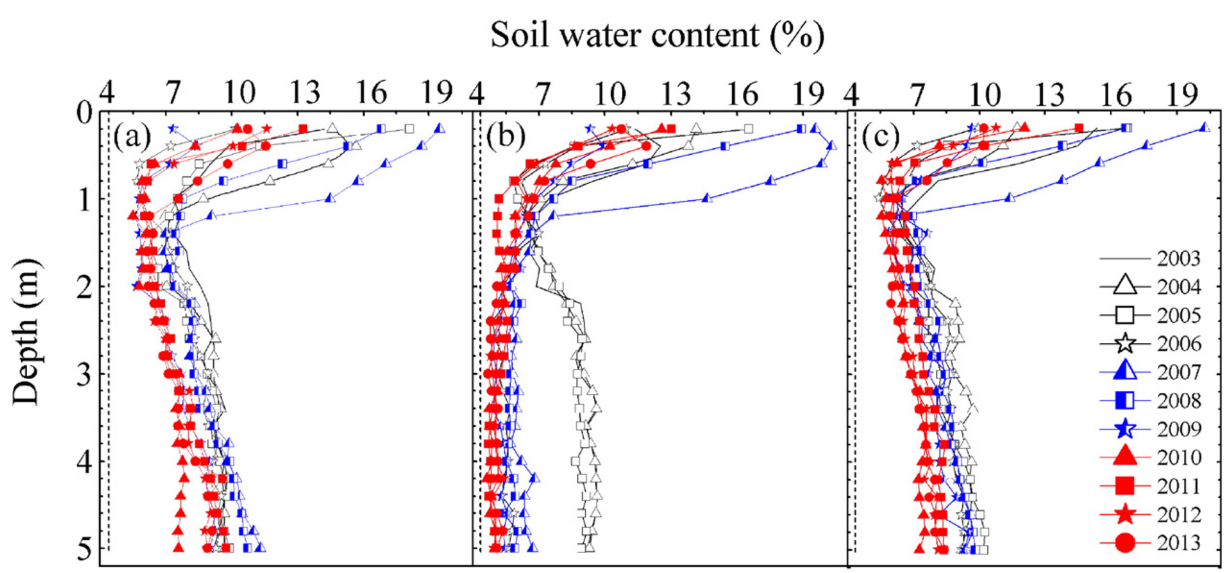

Fig. 6. Profile of soil moisture in the upper 0–5 m layer at increments of 0.2 m in the three treatments from 2003 to 3013. (a) nature revegetation; (b) abandon fields planted with *Medicago sativa*, and (c) abandon fields planted with *Melilotus suaveolens*. The dotted line denotes permanent wilting coefficient (4.5%).

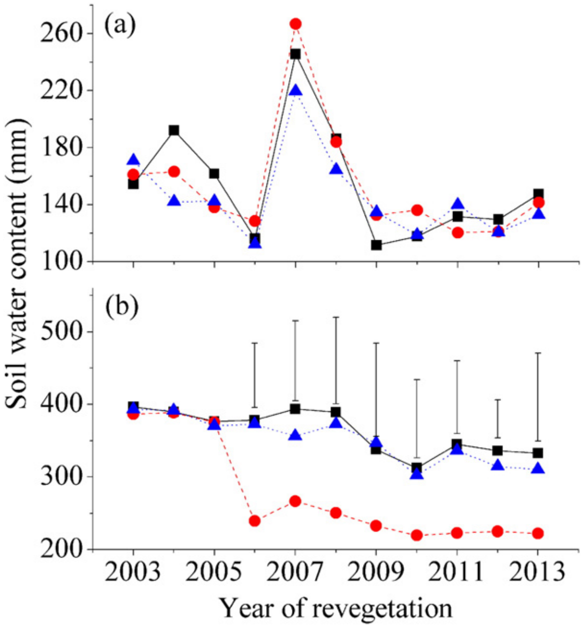

Fig. 7. Soil water content (mm) in (a) the upper 1.4 m and (b) the 1.4–5 m of soil in the three treatments from 2003 to 2013. Bars are the LSD at $P = 0.05$. ■, nature revegetation; ●, abandon fields planted with *Medicago sativa*; ▲, abandon fields planted with *Melilotus suaveolens*.

perennial grasses had lower species richness and diversity than those of natural succession in the northern mixed prairie in Canada. Suppression of early colonizing plant species was presumed to be one of the primary mechanisms driving secondary succession in old-field plant communities (Van der Putten et al., 2000). However, inhibition of later-successional species depended on the performance of the species introduced. The differences in life histories of *Medicago* and *Melilotus* may exert different influences on species composition during succession (Li et al., 2008). Early stages of plant community development in restored fields maintained a high coexistence of different plant functional types (Munson and Lauenroth, 2012). Overall, perennial legume introduction may have competitively suppressed other functional types, which resulted in low species density, vegetation cover and biomass of forbs and grasses in *Medicago* fields.

In semi-arid regions, soil moisture is the main factor limiting vegetation establishment and growth (Munson and Lauenroth, 2012; Yang et al., 2014). In this study, soil moisture in natural revegetation and *Melilotus* treatments showed similar patterns of minimal water deficit in the deep soil of 1.4–5 m (Fig. 6a, c). This could be explained by the fact that the roots of the species in these two treatments are mainly distributed in the soil layer of 0–2 m, and their total aboveground biomass and vegetation cover were low, thereby reducing transpiration and water uptake by roots. This pattern is in contrast to the *Medicago* treatment in which soil moisture of 1.4–5 m dramatically decreased over time and even decreased to the permanent wilting coefficient (Fig. 6b). Vegetation cover and aboveground biomass in the *Medicago* treatment in all experimental years were high, and *Medicago* likely had high photosynthetic and transpiration rates but low water use efficiency (Saeed and Ei-Nadi, 1997; Xu et al., 2006). Additionally, its roots are deep (greater than 5 m) and thus can take up water from deep soil (Dunin et al., 2001; Li and Huang, 2008). The excessive depletion of deep soil moisture by the root system of *Medicago* and long-term insufficient rainfall infiltration may ultimately lead to a lower soil moisture in the deep soil in *Medicago* fields than natural revegetation and *Melilotus* fields. Although soil water deficit in deep soil resulted from long-term growth of *Medicago*, it can be gradually restored by planting crops for four years after the *Medicago* field has been plowed (Wang et al., 2008). Moreover, a relatively consistent soil moisture in the shallow soil (i.e., 0–1.4 m) where most of the roots of many species are present indicates that establishment and growth of later-succesional species may not be influenced by the soil desiccation in the deep soil. Therefore, we suggest that the deep soil desiccation in *Medicago* fields may not be severe enough to limit revegetation.

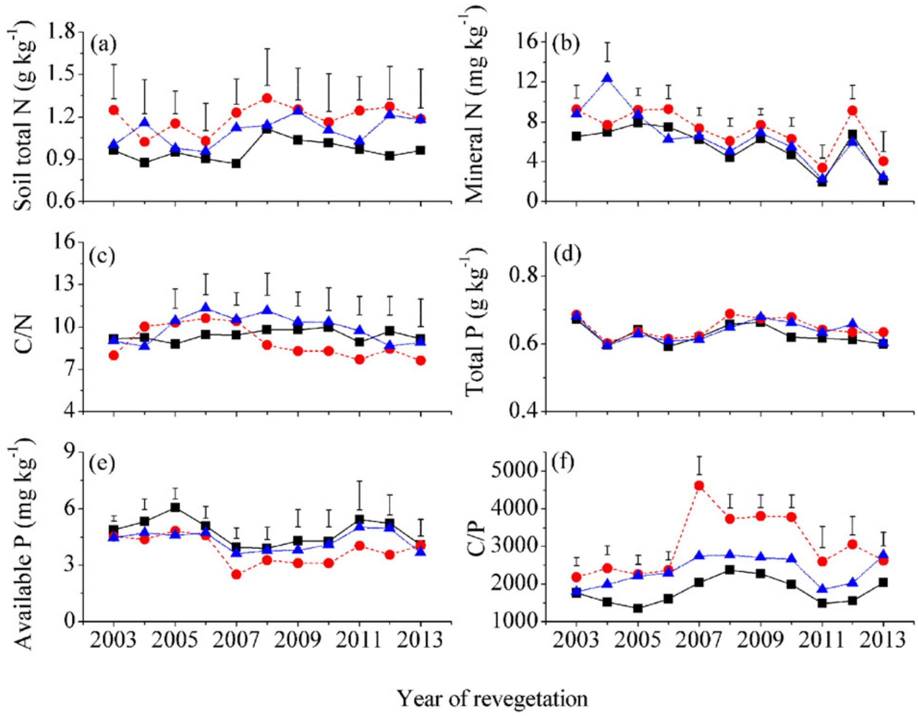

Fig. 8. Variation in (a) total soil N, (b) soil mineral N, (c) the ratio of soil organic C to total soil N (C/N), (d) soil total P (TP), (e) available P and (f) soil organic C to available P (C/P) in the soil depth of 0–20 cm with duration of experiment. Bars are the LSD at $P = 0.05$. ■, natural revegetation; ●, abandon fields planted with *Medicago sativa*; ▲, abandon fields planted with *Melilotus suaveolens*.

Revegetation can greatly influence the soil N cycle on the semi-arid Loess Plateau (An et al., 2013). Our results suggest that *Medicago* fields had greater soil total N and mineral N contents than *Melilotus* and natural revegetation fields (Fig. 8a–c), which is consistent with some previous studies (Guo et al., 2010; Li et al., 2008). *Medicago* has a strong ability to symbiotically fix large amounts of atmospheric N and thus can act as an important N sink. For example, estimates of annual N_2 fixation by alfalfa range from 70 to 400 kg N ha^{-1} (Peterson and Russelle, 1991). *Medicago* fields had greater density, vegetation cover and biomass of legumes than the other two treatments after revegetation for ten years (Figs. 3, 4). The N fixed by *Medicago* can be used by alfalfa itself, and it can also ultimately move to the soil and be used by other plants. In addition, the changes in grasses and forbs may have strong effects on soil N dynamics (Fornara and Tilman, 2008; Knops and Tilman, 2000). It has been shown that C_3 grasses and forbs decreased the rates of accumulation of N in the soil on a Minnesota sand plain of the U.S. (Knops and Tilman, 2000). *Medicago* fields had significantly lower total density, and density and cover of forbs and grasses after revegetation for ten years. These results indicate that N fixed by legumes in *Medicago* fields may not be used by other plants and/or was less effectively used by other plants, with a lower plant density of forbs and grasses, thus contributing to N accumulation in the soil. The greater biomass and vegetation cover in *Medicago* fields can effectively reduce soil erosion, which may reduce the loss of soil N through runoff and transport of sediments (Fu et al., 2010b; Jia et al., 2012).

The ratio of soil organic C to total soil N (C/N) plays an important role in determining the ability of soil microorganisms to assimilate and mineralize N (Jia et al., 2006b). If soil C/N ratio is less than 15, the effective nitrogen content provided in the mineralization process will exceed the demand of microorganisms, thus increasing the N available for plants (Chen, 1990; Huang, 2000). In this study, C/N ratios in *Medicago* and *Melilotus* treatments significantly increased with time over the first five years (Fig. 8c), but C/N ratios were still less than 15. In addition, the C/N ratio significantly declined in the *Medicago* and *Melilotus* treatments after revegetation for six years, and it was lower in the *Medicago* treatment. Overall, these results indicate that *Medicago* and *Melilotus* treatments (particularly *Medicago* treatment) increased N availability for plants across the experiment period of 11 years (particularly after year six). Combined with high vegetation coverage and biomass, this is beneficial for a sustainable revegetation for soil erosion control. These results are consistent with other studies that indicate that legume forage can effectively improve soil N content (Saikh et al., 1998; Jiang et al., 2006; Yimer et al., 2007; Guo et al., 2010).

Past studies have largely ignored the role of another main limiting factor, P, in affecting vegetation establishment and growth on the Loess Plateau (Jiao et al., 2008). In this study, soil total P content (about 0.6–0.7 g kg^{-1}) in each treatment is sufficient for plant growth (Fu et al., 2010b; Jia et al., 2007). However, only a small part of the total phosphorus can be transformed into available P. Total P showed no significant differences among treatments in all years, but available P declined significantly with time in the *Medicago* treatment in this study (Fig. 8d, e). After agricultural abandonment, soil available P may decrease greatly due to the cessation of phosphate fertilizer application and its immobilization in living plant biomass (Jia et al., 2006b; Jiang et al., 2006). It is also possible that the vegetation in the *Medicago* treatment consumes much available P (Jia et al., 2006a). In fact, some studies showed that soil available P will be acquired by microorganisms when C/P ratios are greater than 300 (Jiang et al., 2006). In this study, C/P was greater than 300 in all treatments (Fig. 8f), suggesting that soil microorganisms were competing with plant species for soil available P and thus were leading to the further decrease of available P (Jia et al., 2006a). Thus, for effective management of revegetation fields, P fertilizers and other strategies that can improve the transformation from total P to available P should be implemented.

5. Conclusions

In this study, we seeded legume species *M. sativa* and *M. suaveolens* to investigate their effects on the dynamics of plant communities, soil moisture and nutrient status in abandoned croplands on the semi-arid Loess Plateau. During 1–11 years after revegetation, *M. sativa*, but not *M. suaveolens* and natural revegetation, was effective in increasing vegetation cover and aboveground biomass as well as soil N content, which is beneficial for the revegetation process and ecosystem improvement. We concluded that *M. sativa* can be the preferred plant species for revegetation of degraded ecosystems on the Loess Plateau.

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Appendix A

Important value (IV) and the information on taxonomy, life form and functional group of the 23 species that appeared in the 11th year revegetation fields on the Loess Plateau. IV was calculated as: IV = RA + RB + RC, where RA is the relative abundance, RB is the relative aboveground biomass and RC the relative cover of the species. RA, RB and RC were all represented as percent values. NR, natural revegetation; MED, abandon fields planted with *Medicago sativa*; MEL, abandon fields planted with *Melilotus suaveolens*.

Species	Treatment			Family	Life form	Functional group
	NR	MED	MEL			
Artemisia frigida Willd.	54.0	25.7	40.2	Compositae	Perennial	Forb
Heteropappus altaicus (Willd.) Novop	3.8	11.9	3.5	Compositae	Perennial	Forb
Agropyron craistatum (Linn.) Gaertn.	10.4	4.8	12.4	Gramineae	Perennial	Grass
Stipa grandis P. Smirn.	10.8	10.7	9.4	Gramineae	Perennial	Grass
Leymus racemosus (Lam.) Tzvcel.	0.3	3.5	0.1	Gramineae	Perennial	Grass
Astragalus polycladus Bur. et Franch.	1.6	0	0.4	Leguminosae	Perennial	Legume
Sonchus oleraceus L.	2.3	0.1	0.2	Compositae	Annual	Forb
Viola verecunda A. Gray	4.3	0.5	0.1	Violaceae	Annual	Forb
Medicago sativa L.	0	38.6	0	Leguminosae	Perennial	Legume
Potentilla potaninii Wolf	0.2	0	0	Rosaceae	Perennial	Forb
Oxytropis ochrocephala Bunge	4.5	0.1	1.0	Leguminosae	Perennial	Legume
Potentilla fragarioides L.	0.4	0	0	Rosaceae	Perennial	Forb
Saussurea pulchella Fisch. ex DC.	0.2	1.7	0.2	Compositae	Perennial	Forb
Torularia humilis (C.A.M.) O.E. Schulz.	0.1	1.3	0.8	Cruciferae	Perennial	Forb
Poa annua L.	1.7	0.1	1.3	Gramineae	Perennial	Grass
Setaria viridis (L.) Beauv.	0.1	0.6	1.6	Gramineae	Annual	Forb
Salsola collina Pall.	0	0.04	0.1	Chenopodiaceae	Annual	Forb
Heteropappus	0	0	0.9	Compositae	Perennial	Forb

(continued on next page)

(*continued*)

Species	Treatment			Family	Life form	Functional group
	NR	MED	MEL			
altaicus (Willd.) Novopokr.						
Vicia sepium L.	0.1	0	12.4	Leguminosae	Perennial	Legume
Melilotus suaveolens L.	0.1	0	13.6	Leguminosae	Biennial	Legume
Taraxacum mongolicum Hand.-Mazz.	1.3	0	0.1	Compositae	Perennial	Forb
Medicago falcata L.	1.4	0.1	0.7	Leguminosae	Biennial	Legume
Convolvulus arvensis L.	0	0	0.9	Convolvulaceae	Annual	Forb

References

Adeel, Z., 2005. Ecosystems & Human Well-Being: Desertification Synthesis. World Resources Institute, Washington.

An, S.S., Cheng, Y., Huang, Y.M., Liu, D., 2013. Effects of revegetation on soil microbial biomass, enzyme activities, and nutrient cycling on the Loess Plateau in China. Restor. Ecol. 21, 600–607.

Brandt, C.J., 1988. The transformation of rainfall energy by a tropical rain forest canopy in relation to soil erosion. J. Biogeogr. 15, 41–48.

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., Keneey, D.R. (Eds.), Nitrogen-total, Part 2, Chemical and Microbiological Properties, pp. 595–624 (Wisconsin: Madison).

Chen, W.X., 1990. Soil Science and Environmental Microbiology. Beijing Agriculture University Press, Beijing, China (in Chinese).

Chen, L.D., Wei, W., Fu, B.J., Lǔ, Y.H., 2007. Soil and water conservation on the Loess Plateau in China: review and perspective. Prog. Phys. Geogr. 31, 389–403.

Christian, J.M., Wilson, S.D., 1999. Long-term ecosystem impacts of an introduced grass in the northern Great Plains. Ecology 80, 2397–2407.

Collins, S.L., Knapp, A.K., Briggs, J.M., Blair, J.M., Steinauer, E.M., 1998. Modulation of diversity by grazing and mowing in native tallgrass prairie. Science 280, 745–747.

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.

De Deyn, G.B., Raaijmakers, C.E., Zoomer, H.R., Berg, M.P., de Ruiter, P.C., Verhoef, H.A., et al., 2003. Soil invertebrate fauna enhances grassland succession and diversity. Nature 422, 711–713.

Dunin, F.X., Smith, C.J., Zegelin, S.J., Leuning, R., Denmead, O.T., Poss, R., 2001. Water balance changes in a crop rotation involving Lucerne. Aust. J. Agric. Res. 52, 247–261.

Eaton, J.M., McGoff, N.M., Byrne, K.A., Leahy, P., Kiely, G., 2008. Land cover change and soil organic carbon stocks in the Republic of Ireland 1851–2000. Clim. Chang. 91, 317–334.

Erice, G., Louahlia, S., Irigoyen, J.J., Sanchez-Diaz, M., Avice, J.C., 2010. Biomass partitioning, morphology and water status of four alfalfa genotypes submitted to progressive drought and subsequent recovery. J. Plant Physiol. 167, 114–120.

Fornara, D.A., Tilman, D., 2008. Plant functional composition influences rates of soil carbon and nitrogen accumulation. J. Ecol. 96, 314–322.

Fu, B.J., Li, S.G., Yu, X.B., Yang, P., Yu, G.R., Feng, R.G., et al., 2010a. Chinese ecosystem research network: progress and perspectives. Ecol. Complex. 7, 225–233.

Fu, X.L., Shao, M.A., Wei, X.R., Horton, R., 2010b. Soil organic carbon and total nitrogen as affected by vegetation types in northern Loess Plateau of China. Geoderma 155, 31–35.

Guan, X.K., Zhang, X.H., Turner, N.C., Xu, B.C., Li, F.M., 2013. 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.

Guo, Z.B., Yan, G., Zhang, R.H., Li, F.M., Zeng, Z.X., Liu, H., 2010. Improvement of soil physical properties and aggregate-associated C, N, and P after cropland was converted to grassland in semiarid Loess Plateau. Soil Sci. 175, 99–104.

Huang, C.Y., 2000. Soil Science. China Agriculture Press, Beijing China (in Chinese).

Jia, X., Wei, X., Ma, S., Li, X., 2012. Distribution of soil carbon and nitrogen along a revegetational succession on the Loess Plateau of China. Catena 95, 160–168.

Jia, Y., Li, F.M., Wang, X.L., 2006a. Soil quality responses to alfalfa watered with a field micro-catchment technique in the Loess Plateau of China. Field Crop Res. 95, 64–74.

Jia, Y., Li, F.M., Wang, X.L., Xu, J.Z., 2006b. Dynamics of soil organic carbon and soil fertility affected by alfalfa productivity in a semiarid agro-ecosystem. Biogeochemistry 80, 233–243.

Jia, Y., Xu, B.C., Li, F.M., Wang, X.L., 2007. Availability and contributions of soil phosphorus to forage production of seeded alfalfa in semiarid Loess Plateau. Acta Ecol. Sin. 27, 42–47.

Jiang, H.M., Jiang, J.P., Jia, Y., Li, F.M., Xu, J.Z., 2006. Soil carbon pool and effects of soil fertility in seeded alfalfa fields on the semi-arid Loess Plateau in China. Soil Biol. Biochem. 38, 2350–2358.

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.

Kirkby, M.J., Abrahart, R., McMahon, M.D., Shao, J., Thornes, J.B., 1998. MEDALUS soil erosion models for global change. Geomorphology 24, 35–49.

Knops, J., Tilman, D., 2000. Dynamics of soil nitrogen and carbon accumulation for 61 years after agricultural abandonment. Ecology 81, 88–98.

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., Okin, G., Alvarez, L., Epstein, H., 2007. Quantitative effects of vegetation cover on wind erosion and soil nutrient loss in a desert grassland of southern New Mexico, USA. Biogeochemistry 85, 317–332.

Li, J.H., Xu, D.H., Wang, G., 2008. Weed inhibition by sowing legume species in early succession of abandoned fields on Loess Plateau, China. Acta Oecol. 33, 10–14.

Li, J.H., Fang, X.W., Jia, J.J., Wang, G., 2006. Effect of legume species introduction to early abandoned field on vegetation development. Plant Ecol. 191, 1–9.

Li, Y.S., Huang, M.B., 2008. Pasture yield and soil water depletion of continuous growing alfalfa in the r of China. Agric. Ecosyst. Environ. 124, 24–32.

Munson, S.M., Lauenroth, W.K., 2012. 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.), Total Carbon, Organic Carbon and Organic Matter, pp. 539–579 (Wisconsin: Madison) (Part 2).

O'Halloran, I.P., Cade-Menun, B.J., 2006. Total and organic phosphorus. In: Carter, M.R., Gregorich, E.G. (Eds.), Soil Sampling and Methods of Analysis, 2nd ed. Canadian Society of Soil Science/CRC Press, Boca Raton, FL.

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, p. 19.

Peterson, T.A., Russelle, M.P., 1991. Alfalfa and the nitrogen cycle in the Corn Belt. J. Soil Water Conserv. 46, 229–235.

Primentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., McNair, M., et al., 1995. Environmental and economic costs of soil erosion and conservation benefits. Science 267, 1117–1123.

Puigdefabregas, J., Sole, A., Gutierrez, L., del Barrio, G., Boer, M., 1999. Scales and processes of water and sediment redistribution in drylands: results from the Rambla Honda field site in Southeast Spain. Earth-Sci. Rev. 48, 39–70.

Ruprecht, E., 2006. Successfully recovered grassland: a promising example from romanian old-fields. Restor. Ecol. 14, 473–480.

Russelle, M.P., 2001. Alfalfa: after an 8000-year journey, the "Queen of Forages" stands poised to enjoy renewed popularity. Am. Sci. 89, 252–261.

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.

Saikh, H., Varadachari, C., Ghosh, K., 1998. Changes in carbon, nitrogen and phosphorus levels due to deforestation and cultivation: a case study in Simlipal National Park, India. Plant Soil 198, 137–145.

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).

Turner, N.C., Molyneux, N., Yang, S., Xiong, Y.C., Siddique, K.H.M., 2011. Climate change in south-west Australia and north-west China: challenges and opportunities for crop production. Crop Pasture Sci. 62, 445–456.

Van der Putten, W.H., Mortimer, S.R., Hedlund, K., Van Dijk, C., Brown, V.K., Lepš, K., et al., 2000. Plant species diversity as a driver of early succession in abandoned fields: a multi-site approach. Oecologia 124.

Ventroni, L.M., Volenec, J.J., Cangiano, C.A., 2010. Fall dormancy and cutting frequency impact on alfalfa yield and yield components. Field Crop Res. 119, 252–259.

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. Agric. Water Manag. 95, 190–198.

Wang, Y., Fu, B., Lü, Y., Chen, L., 2011. Effects of vegetation restoration on soil organic carbon sequestration at multiple scales in semi-arid Loess Plateau, China. Catena 85, 58–66.

Wang, Y.Q., Shao, M.A., Zhang, C.C., Han, X.W., Mao, T.X., Jia, X.X., 2015. Choosing an optimal land-use pattern for restoring eco-environments in a semiarid region of the Chinese Loess Plateau. Ecol. Eng. 74, 213–222.

Woo, M.K., Luk, S., 1990. Vegetation effects on soil and water losses on weathered granitic hillslopes, south China. Phys. Geogr. 11, 1–16.

Xu, J., Yin, R., Li, Z., Liu, C., 2006. China's ecological rehabilitation: unprecedented efforts, dramatic impacts, and requisite policies. Ecol. Econ. 57, 595–607.

Yang, L., Wei, W., Chen, L., Chen, W., Wang, J., 2014. Response of temporal variation of soil moisture to vegetation restoration in semi-arid Loess Plateau, China. Catena 115, 123–133.

Yang, W.Z., Shao, M.A., 2000. Soil Water Study of Loess Plateau. Science Press, Beijing (in Chinese).

Yimer, F., Ledin, S., Abdelkadir, A., 2007. Changes in soil organic carbon and total nitrogen contents in three adjacent land use types in the Bale Mountains, south-eastern highlands of Ethiopia. For. Ecol. Manag. 242, 337–342.