Soil-plant characteristics in an age sequence of *coronilla varia* L. plantations along embankments

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Abstract

Objectives: *Coronilla varia* L., a leguminous herb, is widely used in vegetation restoration programs on road embankments to enhance soil nutrients. Our hypothesis is that, under identical climatic conditions, plant and soil properties are determined by the slope aspect and stand age of legume plantations.

Methods: We collected soil samples and investigated plant diversity in an age sequence of 0-, 4-, 10- and 20-year-old *C. varia* L. plantations and natural grasslands.

Results: Stand age, rather than slope aspect, was found to be the main factor influencing the soil and plant feedback on the embankments. Planting *C. varia* L. on the embankments could enhance soil nutrients and improve the soil quality to the level of a natural grassland after 20 years of plantation. The plant diversity and species number were steady after *C. varia* L. had been established for 10 years.

Conclusions: Planting *C. varia* L. on embankments is an effective method for enhancing soil nutrients and maintaining ecosystem stability in the Guanzhong Basin, China.

Keywords: Revegetation, grassland, roadside, plant-soil interface

1. Introduction

Road construction is a major factor in global land-use change, and it produces numerous ecological effects. Roads and the areas adjacent to road construction zones cover 15–20% of American land surfaces (Forman, 2000), and to accomplish road construction, heavy equipment, such as bulldozers, excavators, and dump trucks, is used to excavate buried stream channels and reshape disturbed hill slopes (Madej *et al.*, 2012). Road construction exposes a substantial amount of bare land, and it impacts the physical and ecological properties of the landscape by changing the

dynamics of plant and animal populations, altering the flow of materials, introducing exotic species, and changing the amount of available resources, such as light, water and nutrients (Angold, 1997; Coffin, 2007). The road-effect zone is highly asymmetrical because of the directional flow of materials and the spatial patterns of the different sides of a road, resulting in complex boundaries (Forman and Deblinger, 2000).

The revegetation of embankments is an effective method for maintaining road stability and controlling

erosion (Grant *et al.*, 2011), and road slopes are usually planted with legumes to improve soil nutrient content because of the N-fixing capability and high yield of this plant family (Jáuregui *et al.*, 2013; Yuan *et al.*, 2015). Different features of road development have different negative consequences for the environment (Liu *et al.*, 2008), and slope aspect is a primary factor affecting plant composition and soil properties (Warren and Robert, 2010). Several studies have concluded that the variation in soil and plant properties between two contrasting slope is the result of differences in the amount of incident solar radiation, light intensity, soil and air temperature, humidity, soil moisture, and duration of growing periods (Maren *et al.*, 2015). Recent studies have investigated soil and community properties between north and south aspects, but their results have been controversial (Sternberg and Shoshany, 2001; Bochet and Garc-Fayos, 2004; Warren and Robert, 2010; Maren *et al.*, 2015; Yuan *et al.*, 2015). The link between species traits and soil processes provides a strong argument for considering the potential impact of this relationship on soil and plant restoration (Callaham *et al.*, 2008; Eviner and Hawkes, 2008; Yuan *et al.*, 2015). Numerous studies of roadsides have indicated a relationship between the spread of non-native plant species and soil nutrient levels, and have shown that the disruption of the chemical environment along roads affects plant growth, species diversity and composition, especially in nutrient-poor ecosystems (Cape *et al.*, 2004; Forman, 2000; Heneghan *et al.*, 2008; García-Palacios *et al.*, 2011). Plant-soil interactions are important for understanding the role of biotic control in the functioning of roadside ecosystem, but little is known about these links in the context of ecosystem restoration and succession (Merino *et al.*, 2015; García-Palacios *et al.*, 2011). Changes in plant community composition along a successional gradient exert the strongest influence

on erosion control, soil carbon storage and nitrogen accumulation (Jimenez *et al.*, 2011; García-Palacios *et al.*, 2011), but the mechanisms responsible for community succession following the introduction of legumes on road slopes are largely unknown. Therefore, slope aspect and the duration of restoration on embankments have been primarily considered in the context of their direct effects on the feedback between plants and soil. Our hypothesis is that, in the absence of pressure by large herbivores and under identical climatic conditions, plant diversity and soil properties are determined by the slope aspect (sunny aspect, shady aspect or no slope) and the age of the legume stand. Our goals are to assess the effects of different stand ages and slope aspects on the soil physical-chemical properties and plant diversity of embankments and propose an interaction function between the soil and vegetation.

2. Materials and Methods

The field study was conducted along the sides of a district highway between the regions of Xi'an and Niubei (33°19'–35°12'N–106°37'–110°14'E) of central Shaanxi Province, China (Figure 1). This area lies to the west of the Guanzhong Basin and rises from 376 to 506 m above sea level. The region has a continental climate with an annual rainfall of 550–650 mm, and the mean temperature is 24.5 to 26.7°C and -2 to -1°C in summer and winter, respectively. The soil is derived from loess parent materials and is classified as an Earth-cumuli-Orthic Anthrosol (Sun *et al.*, 2013). The district highway from Xi'an to Niubei consists of three highways: the highway around Xi'an, the highway from Xi'an to Baoji, and the highway from Baoji to Niubei, and these three highways were built in different years. The highways around Xi'an, from Xi'an to Baoji and from Baoji to Niubei were built in 2003, 1993 and 2009, respectively, and the

revegetation projects of the embankments of the three highways included legume stands of 10 years (S10), 20 years (S20), and 4 years (S4) of age. After removing all of the herbs, the embankments of all

three high ways were planted with *Coronilla varia* L by seeding, and the addition of a 30 cm layer of topsoil was used to encourage the establishment of plant cover on the study road slopes.

Figure 1. Location of the five treatments in an age sequence of 0- (CK), 4- (S4), 10- (S10) and 20- (S20) year-old *Coronilla varia* L. plantations and natural grasslands (NA) from study highways in the Guanzhong Plain, China, as well as, the sampling sites along the embankments.

Figure 2. Mean soil water content (b) and bulk density (a) in the 0-10 cm and 10-20 cm soil layers in an age sequence of 0- (S0), 4- (S4), 10- (S10), and 20-year-old (S20) *Coronilla varia* L. plantations and natural grassland (NA). Error bars indicate the standard error of the mean, and bars with different letters above them are significantly different at $P < 0.05$. Significant differences between the different soil depths are indicated by symbols: *: $P < 0.05$; ns: not significant different.

2.1. Experimental design and sampling

A common method to study vegetation restoration is to monitor plants and soils under similar climatic conditions and follow the sequence of vegetation development. The 'space-for-time' substitution makes the critical assumption that each site in the sequence differs only in age and that both the abiotic and biotic components of each site have experienced the same history (Wang *et al.*, 2015). In this study, we selected the three highways with revegetation stands of different ages: S4, S10 and S20, and we also selected areas containing bare land with newly built topsoil (CK) and natural grassland (NA) near the studied highways as controls. The distances between the CK, NA and the selected highways were no greater than 1 km. Therefore, there were five treatments in this study, and in August 2013, nine sites were established along the embankments in each of the five treatments: three sites with a sunny slope, three sites with a shady slope and three sites with no slope. The sites with the same slope aspect were separated by 5 km. At each site, we established a 50 m line transect along the road in the middle of the embankments, and five quadrats (1×1 m) were separated by 10 m on each transect. In total, we surveyed forty-five quadrats in each treatment.

2.2. Soil sampling and analysis

We selected 135 soil sampling quadrats along the three highways (S20, S10 and S4), and 90 quadrats in the CK and NA at topsoil depths of 0-10 cm and 10-20 cm. Soil bulk density (BD), porosity and soil water content (SWC) were measured from soil cores (volume, 100 cm³) from both topsoil layers using the volumetric ring method. Soil samples were collected from five points in the quadrats of each plot, and the samples from the same layers were mixed together to produce one sample per

plot. All of the soil samples were air-dried and then passed through a 0.14 mm sieve for further analysis. Soil organic matter (SOC), available phosphorus (AP), ammonia nitrogen (AN) and nitrate nitrogen (NN) were analyzed following the methods recommended by the Agricultural Chemistry Specialty Council of the Soil Science Society of China (Council, 1983). Total Nitrogen (TN) was measured with the Kjeldahl method using a distilling unit (Tecator, Höganäs, Sweden), and total soil phosphorus (TP) was determined by perchloric acid digestion (Olsen SR, 1982).

2.3. Plant properties

In each quadrat, we determined the species number (*S*) and the number of individuals of each species. The Shannon-Wiener diversity index (*H*) and Menhinick index (*Me*) values of the S4, S10, S20 and NA treatments were calculated as follows:

Shannon-Wiener diversity index (*H*),

$$H = -\sum_{i=1}^S (P_i \ln P_i)$$

Menhinick index (*Me*),

$$Me = S / \sqrt{N},$$

Where *H* is the Shannon-Wiener diversity index; *P_i* is the ratio of the individual number of species, *I*, in the sample plot; *S* is the total species number of the grassland community; and *N* is the total number of each individual species.

2.4. Data analysis

All of the data were expressed as the mean ± the standard error (SE) of the three sites. The *H*, *Me*, *S*, plant cover and SWC, BD, SOC, TN, TP, AP, AN and NN data were

analyzed by two-way analysis of variance (ANOVA) to determine the main effects and interactions of the different restoration ages (CK, S4, S10, S20 and NA) and aspects at $P < 0.05$. One-way ANOVA followed by a least significant difference (LSD) test ($P < 0.05$) was used to examine the effects of restoration ages on the soil and plant properties, and paired sample t-tests were used to analyze the effects of soil depth on the soil properties. Pearson correlation analysis was performed the relationship between the soil chemical-physical properties and plant characteristics. All of the statistical analyses were conducted with the statistical software program SPSS 11.5 for Windows (Chicago, Illinois, USA).

3. Results

3.1. Response of soil and plant properties

The ANOVAs indicated that there were significant impacts ($P < 0.05$) of restoration age on the soil and plant properties, but no effect of slope aspect ($P > 0.05$). In addition, there were no significant effects ($P > 0.05$) of stand age $\times$ slope aspect interaction on the soil properties and plant diversity (Table 1). These analyses indicated that the responses of the soil and plant properties were dependent on restoration age and not on slope aspect.

Table 1. Effects of stand age (Age) and slope aspect (Asp) on the Shannon-Wiener index (H), Menhinick index (Me), species number (S), plant cover, soil water content (SWC), soil bulk density (BD), soil organic carbon (SOC), total nitrogen (TN), total phosphorus (TP), available phosphorus (AP), ammonium nitrogen (AN), and nitrate nitrogen (NN).

Factors	Age			Asp			Age*As p		
	df	F	P	df	F	P	df	F	P
H	3	3.381	0.023	2	1.579	0.227	6	1.194	0.343
Me	3	4.418	0.013	2	0.863	0.434	6	1.129	0.376
S	3	11.174	<0.001	2	2.598	0.095	6	1.731	0.157
Cover	3	7.122	0.001	2	3.089	0.065	6	3.952	0.007
SWC	4	6.680	0.001	2	0.465	0.633	8	0.381	0.923
BD	4	4.212	0.008	2	0.494	0.615	8	0.893	0.535
SOC	4	9.914	<0.001	2	2.411	0.107	8	0.59	0.778
TN	4	10.235	<0.001	2	2.111	0.139	8	0.509	0.840
TP	4	5.718	0.002	2	0.733	0.489	8	0.219	0.985
AP	4	4.963	0.003	2	0.610	0.550	8	0.909	0.522
AN	4	2.413	0.071	2	2.957	0.067	8	0.189	0.989
NN	4	5.243	0.003	2	0.845	0.440	8	1.262	0.300

The analysis of soil physical properties revealed clear trends in BD and SWC along the plantations temporal gradient (Figure 2). It the 0-10 cm layer, BD in the CK, S4, S10, S20 and NA were 1.38, 1.36, 1.25, 1.25, and 1.26 g cm⁻³, respectively, and BD decreased significantly as the standage increased. The SWC was lowest in S4, and no significant differences were found among the CK, S10, S20 and NA treatments. The results indicated that after 20-years restoration, the soil physical properties of the embankments were similar to those of natural grassland.

The establishment and development of *C.varia* L. resulted in enriched SOC, TN, NN, AN, and TP in the highway embankments and decreased AP (P<0.05) (Figure 3). The SOC at the soil depth of 0–10 cm increased from S4 (5.66 g kg⁻¹) to S20 (25.45 g kg⁻¹), and SOC in the S20 treatment was similar to that in NA. In the 10-20 cm layer, SOC increased from

4.94 g kg⁻¹ in S4 to 13.73 g kg⁻¹ in S20 (Figure 3a). Compared to CK, TN in S20 increased 2.6-fold in the 0-10 cm layer and 1.8-fold in the 10–20 cm layer (Figure 3b). After *C.varia* L. had been established for 20 years, the levels of SOC, TN, TP and NN were significantly higher than those in the S4 and CK treatments. In contrast, AP decreased gradually and became nearly constant after *C.varia* L. stood for 10 years (Figure 3d).

Plant cover increased significantly from S4 to S20 (P<0.05), but *H*, *S* and *Me* decreased significantly (P<0.05, Table 2). After four years of plantation with *C. varia* L., the greatest *S* value was 13.33, and there were approximately 12 other species. Compared with the S4 treatment, the number of additional species in S10 was approximately 5, and no change occurred in the 10 subsequent years, indicating that the ecosystem began to stabilize after 10 years of restoration with *C. varia* L.

Table 2. Cover, species number (*S*), Shannon-Wiener index (*H*), and Menhinick index (*Me*) in an age sequence of 4- (S4), 10- (S10), and 20-year-old (S20) *Coronilla varia* L. plantations and natural grassland (NA). The different letters indicate significant differences at P<0.05.

Type	Main species	Cover (%)	<i>S</i>	<i>H</i>	<i>Me</i>
S4	<i>Coronillavaria</i> , <i>Setariavin</i> <i>disBeauv.</i>	77±6b	13.33±1.28a	1.39±0.15ab	0.23±0.08ab
S10	<i>Coronillavaria</i> , <i>Cyperusr</i> <i>otundus</i> ,	92±3ab	6.56±0.77b	1.12±0.11b	0.19±0.06b
S20	<i>Coronillavaria</i> , <i>Echinoc</i> <i>hloa crus-galliBeauv.</i>	98±1a	6.67±0.73b	1.13±0.15b	0.21±0.07b
NA	<i>Acalyphaaustralis</i> , <i>Imper</i> <i>atacylindricaBeauv.</i> <i>Dendranthemaindicum</i>	76±11b	15.56±2.58a	1.72±0.18a	0.96±0.32a

Figure 3. Soil organic carbon (SOC), total nitrogen (TN), total phosphorus (TP), available phosphorus (AP), ammonium nitrogen (AN) and nitrate nitrogen (NN) in 0-10 cm (black bars) and 10-20 cm (gray bars) soil layers. Significant differences among the five treatments with different stand ages are labeled with different lower case letters ($P < 0.05$). Significant differences between the different soil depths are indicated by symbols: **: $P < 0.1$; *: $P < 0.05$; ns: not significantly different.

3.2. Plant-soil interaction

A correlation analysis of the soil parameters of the 0–10 cm layer with stand age, plant cover and diversity showed that the soil physicochemical properties were strongly interrelated, and plant diversity was also positively interrelated. However, the relationship between the soil and plant properties was not significant. The results showed that *H*, *Me*, *S*, SOC, TN, TP, AN, and NN were positively related with stand age, but slope aspect and AP were not significantly related to any of the other factors. Furthermore, BD was significantly negatively correlated with SOC, TN, TP, AN, and NN.

4. Discussion

In contrast to our expectations, there are on significant differences in the soil and plant properties between the north-facing and south-facing slopes and these results are not consistent with most of the findings from previous research or with the general pattern usually reported for soil properties. Typically, soils have been found to be more fertile on north-facing slopes (Maren *et al.*, 2015). So, previous studies have concluded that slope aspect is an important driver of soil and plant processes because the different aspects have different SWC, nutrient and light values (Sternberg and Shoshany, 2001; Yuan *et al.*, 2015). Soil water availability has been recognized as a key factor affecting the cover and biomass of road slope vegetation, and it is assumed to be the decisive factor contributing to the composition, structure and density of plant communities in areas with less than 600 mm of precipitation annually (Feng, *et al.*, 2012). The SWC between the shady and sunny aspects was not significantly different in our study ($F=0.465$, $P=0.63$), and this may have occurred because the road surfaces could catch rainfall and supply an

additional water to the adjacent road slope (Feng *et al.*, 2012). Thus, slope aspect was not a dominant factor influencing soil and plant characteristics during embankment restoration.

Previous studies have also shown that the amelioration of soil physical and chemical properties is strongly related to the age of the vegetation stand (Li *et al.*, 2007; Zhu *et al.*, 2010; Wang *et al.*, 2015). *C.varia* L., which can fix nitrogen with its roots, significantly enriched SOC, TN, NN, AN, and TP in this study. Additionally, vegetation cover has significant effects on soil properties, primarily through the input of organic matter to the soil via the carbon and energy supplied from root exudates and plant remains (Rutigliano *et al.*, 2004). On the other hand, *C. varia* L. can maintain high biomass and vegetation cover over the long-term on the roadslope, which is very important for controlling soil erosion and maintaining soil fertility (Yuan *et al.*, 2015). Accelerating the recovery and promotion of SOC is a fundamental and effective method for stabilizing soil structure (Gregorich *et al.*, 2003) and in this study, SOC is positively related to TN, NN, AN, and TP (Table 3), which emphasize the central role of SOC in determining soil quality (Adak *et al.*, 2014; Gregorich *et al.* 2003). In addition, the reduction of soil BD indicated that the soil structure had been improved (Zhu *et al.*, 2010). Therefore, restoration with *C.varia* L. can enhance soil quality over time, and return it to the level of natural grassland after 20 years.

As expected, the results of this study indicated that the responses of plant properties were dependent on stand age. We found that plant diversity and richness varied greatly among treatments with stand age, but there was no consistent relationship between plant diversity and richness ($P<0.05$, Table 3). The plant cover in the S4 treatment was lower than that of S10 and S20, but the *S* value was greater than that of S10 and S20. Due to the lower plant cover in S4, there were

additional resources and light available to facilitate the growth of other species (Hautier *et al.*, 2009), but the suppression of plant species and the establishment of late-successional species decreased with stand age

as competition for light and nutrient increased. Plant diversity and species number stabilized after *C.varia* L. had been established for 10 years.

Table 3. Pearson correlation coefficients among stand age, slope aspect (Asp), Shannon-Wiener index (*H*), Menhinick index (*Me*), species number (*S*), plant cover, soil water content (SWC), bulk density (BD), soil organic carbon (SOC), total nitrogen (TN), total phosphorus (TP), available phosphorus (AP), ammonium nitrogen (AN) and nitrate nitrogen (NN).

	Age	Asp	<i>H</i>	<i>Me</i>	<i>S</i>	Cover	SWC	BD	SOC	TN	TP	AP	AN
<i>H</i>	0.355 *	-0.253											
<i>Me</i>	0.392 *	-0.22	0.719* *										
<i>S</i>	0.332 *	-0.236	0.664* *	0.976 **									
Cover	-0.122	0.22	0.577* *	0.628 **	0.579 **								
SWC	0.194	0.122	-0.268	0.486 **	0.553 **	0.362* **							
BD	0.378 *	-0.091	0.068	0.049	0.128	-0.087	-0.276						
SOC	0.607 **	-0.132	0.017	0.022	-0.035	0.053	0.575 **	0.441 **					
TN	0.663 **	-0.162	0.217	0.257	0.204	-0.106	0.431 **	0.465 **	0.946 **				
TP	0.474 **	0.012	-0.105	-0.24	-0.272	0.352* **	0.656 **	0.317 *	0.870 **	0.767 **			
AP	-0.269	-0.048	0.026	0.012	0.086	-0.287	-0.133	0.217	-0.222	-0.183	-0.179		
AN	0.401 **	-0.253	0.205	0.25	0.188	-0.077	0.104	0.446 **	0.437 **	0.528 **	0.226	-0.320	
NN	0.533 **	-0.116	0.143	0.239	0.184	-0.208	0.223	0.452 **	0.775 **	0.793 **	0.531 **	-0.176	0.406 **

*Correlation is significant at the 0.05 level (2-tailed).

**Correlation is significant at the 0.01 level (2-tailed).

5. Conclusion

We use the 'space-for-time' substitution to test whether plant and soil properties are determined by the slope aspect and stand age of legume plantations on embankments under identical climatic conditions. As expected, stand age was the main factor influencing the soil and plant feedback, but slope aspect had no effect on plant diversity in this study given the same soil water content. Planting *C. varia* L. on the embankments could enhance soil nutrients and improve soil quality to the level of natural grassland after 20 years of plantation. *C. varia* L. showed strong competitiveness and was a suitable species for embankments revegetation in the study region.

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