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Full Length Research Paper

Landform affects on profile distribution of soil properties in black locust (*Robinia pseudoacacia*) land in loessial gully region of the Chinese Loess Plateau and its implications for vegetation restoration

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Black locust (*Robinia pseudoacacia*) has been widely planted in the Chinese Loess Plateau and other parts of the world for soil and water conservation as a greening important forest species. The response of soil properties to black locust varies with landforms. This study was conducted to understand the effects of landforms on profile distribution of soil properties in black locust land in the loessial gully region of the Loess Plateau. Soil samples were collected in sloping land and gully bottom where black locust has planted for 21 years. For the collected soils, physicochemical, nutritional and enzymatic properties were determined. The results showed that 21 years' growth of black locust increased organic matter and nitrogen stocks by 24.65 and 0.66 t hm^{-2}, but decreased soil P stocks by 2.41 t hm^{-2} in 0 - 80 cm soil depth. Gully bottom soils were higher in organic matter, cation exchange capacity (CEC), total nitrogen and phosphorus, available potassium, alkaline phosphatase and invertase, while sloping land soils were higher in pH, nitrate, ammonium and Olsen P. Principle component analysis showed that the first principle component of soil properties can represent major variation of most properties and can reflect the effects of landform on distribution of soil properties in black locust land. These results indicate that the improvement of soil properties by black locust was more obvious in gully bottom than in sloping land and different management measures should be taken according to landforms, reflecting closed mutual interactions between soils and vegetation.

Key words: Black locust, landform, soil properties, forest species selection, vegetation restoration, Loess Plateau.

INTRODUCTION

Landform is one of the 5 fundamental elements of the soil-forming factor theory (Amundsen et al., 1994) and is central to the catena concept for soil development (Hook and Burke, 2000), which is characterized by leaching and redistribution of elements and soil material along landscape. Landform exerts significant effect on soil biological and chemical processes through its influence on soil moisture conditions and flow patterns, solar radiation and temperature regime, plant structure and erosion and sediment redistribution. In the past several decades, many researchers have related the soil properties with landform (Shao et al., 2007, 2008; Zhao et al., 2008). Brubaker et al. (1993) observed increases of sand and silt, organic matter, pH, $CaCO_3$, Ca and Mg, and base saturation but decreases in clay, cation exchange capacity and available K in low position in Nebraska, USA. McKenzie and Ryan (1999) observed terrain, together with climate and parent

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material, to explain as much as 78% of total phosphorus variation and 54% of total Carbon variation in a catchment in southeastern Australia. Chen et al. (1997) found aspect and slope to be controlling factors for soil pH in a mountainous area of eastern Taiwan. Johnson et al. (2000) found that landforms were able to explain 4 - 25% of the variation of soil chemical parameters in the Catskill watershed in New York, USA. Additionally, strong relationships between landforms and soil properties were also observed in young boreal forest soils (Fisher and Binkley, 2000), loess-mantled upland landscape in Missouri (Young and Hammer, 2000) and in northern part of Jordan (Ziadat, 2005), respectively. However, the landform-soil property relationship often changes with plant introduction.

The introduction of black locust (*Robinia pseudoacacia*) to the Loess Plateau dates back to the middle 20th century when the Chinese government launched large-scale tree planting campaigns to reforest denuded mountains in the Loess Plateau. Black locust was considered a promising tree for reforestation due to its fast growth and ability to fix atmospheric nitrogen and has become the pioneer tree in the Loess Plateau. Since the 1950's, the black locust plantation has exceeded 70,000 hm^2 (Guo et al., 2005), which has posed important role in soil and water conservation and environmental protection in the Loess Plateau. Addition to the significant effects on vegetation restoration and soil and water conservation, black locust can greatly improve soil properties. The greatest improvement of soil properties is increasing soil nitrogen levels since the tree is an N fixing legume (Boring and Swank, 1984; Liu and Deng, 1991; Olesniewicz and Thomas, 1999). It has been estimated that black locust can add up to 75 kg N hm^{-2} yr^{-1} in soils (Boring and Swank, 1984). Rice et al. (2004) found that black locust can supplement soil N pools, increase N return in litter fall, and enhance soil N mineralization rates when it growths in nutrient poor ecosystems. Tateno et al. (2007) and Uselman et al. (1999) found the increase of soil N is not only a result of release from decaying N rich black locust leaves and roots, but also from root exudates containing from 1 to 2% of the recently fixed N. Besides to increasing soil N, black locust can enlarge soil available P pools (Gillespie and Pope, 1990) and increase topsoil base saturation which improves cation nutrient availability (Garman and Merkle, 1938; Smith, 1942). Ussiri et al. (2006) reported that black locust can effectively improve soil structure, enhance soil quality, increase root biomass and soil organic C sequestration in reclaimed mine soils of Ohio. The great changes of soil physicochemical, nutritional and biological properties by black locust was also observed in the Loess Plateau of China (Xu and Liu, 2004; Xue et al., 2007; Lewu and Afolayan, 2009).

Although many researches have been conducted to study the effects of black locust on soil properties, the improvement of black locust on soil properties is largely dependent on landforms and most current researches did not consider the effects of landforms. The Chinese Loess Plateau is characterized by complex landforms where black locust is mainly planted in gully bottom and sloping land. The planting of black locust in the Loess Plateau is particularly important in improving regional ecological environment in northwest China. However, the improvement of soil properties by black locust at specific landform is still not well understood. Therefore, the objective of this study was to understand the effects of sloping land and gully bottom on soil properties after 21 years' planting of black locust, providing scientific basis for vegetation restoration.

MATERIALS AND METHODS

Study area

The experiment was conducted in Wangdougou watershed at Changwu county, Shaanxi province, China (35°12′ - 35°16′N, 107°40′ - 107°42′E). The watershed is a filed station of Chinese ecology research net (CERN). It lies in the typical loessial gully region of the Loess Plateau with an altitude of 800 – 1200 m and covers an area of 850 hm^2. The study area is characterized by a warm-temperate sub humid continental climate. Based on the climate data over the period 1984 to 2005, the average annual temperature is 9.1°C. The >0°C accumulative temperature is 3866°C, >10°C accumulative temperature is 3029°C and free frost period is 171 days. The average annual precipitation is 584 mm. The rainfall is mainly concentrated from June to September and varies greatly from year to year and within year. The soil in the area is fine silt in texture and derives from loess. Soil is a Calcarid Regosol (FAO/ISRIC/ISSS, 1998).

Soil sampling and chemical analysis

We set our investigation in a black locust land in the Wangdonggou watershed. The black locust was planted in 1984. Before 1984, the land was bare slope and gully bottom. The organic matter, total N, and Olsen P contents in soils were presented in Table 1. In August of 2005, a 30 m wide × 100 m long transect plot in the gully bottom and an adjacent 40 m wide × 100 m long transect plot in the north-west facing slope (the gradient is 25°C) were selected. Sampling plots were selected according to the method described by Liechty et al. (2005). The growth of black locust in sloping land and gully bottom was described in Table 2. In sampling transect for gully bottom, three 20 - 25 m diameter subplots were established. In sampling transect for sloping land, four 20 - 25 m diameter subplots were established. The subplots did not intersect.

In each subplot, a composite soil sample was collected from 5 evenly spaced locations. Soil samples were collected in 0 - 80 cm depth at intervals of 20 cm with a 5 cm diameter tube auger. Large pieces of undecomposed organic matter were removed, and the moist field soils were then brought to laboratory, air dried and ground to pass through 1 and 0.25 mm nylon screens prior to laboratory analysis.

Soil pH, cation exchange capacity (CEC), organic matter, total N, total and Olsen P were analyzed according to standard methods described by Page et al. (1982). Soil pH was determined using an electrode pH meter in a 1:2 soil:water suspension. Cation exchange capacity was determined by replacement of exchangeable cations by ammonium acetate. Soil organic matter was determined using the Walkley-Black method. Total N was measured using the Kjeldahl method. Total P was determined calorimetrically after wet digestion

Table 1. Nutritional property of soils in the study sites in 1984 and 2005.

Year	Soil depth (cm)	Bulk density (gcm^{-3})	Organic matter ($g\ kg^{-1}$)	Total N ($g\ kg^{-1}$)	Total P ($g\ kg^{-1}$)	Olsen P ($mg\ kg^{-1}$)
1984	0 - 20	1.41	7.40	0.52	0.81	3.80
	20 - 40	1.30	3.73	0.43	0.76	3.80
	40 - 60	1.31	3.05	0.30	0.72	1.30
	60 - 80	1.35	3.77	0.28	0.69	1.30
2005	0 - 20	1.21	11.61	0.71	0.58	4.26
	20 - 40	1.22	7.83	0.52	0.57	3.90
	40 - 60	1.27	5.66	0.39	0.54	4.91
	60 - 80	1.30	4.54	0.31	0.55	3.93

Table 2. Growth of black locust at different landforms.

Landform	Stand density tree (hm^{-2})	Diameter breast height (cm)	Height (m)	Biomass ($t\ hm^{-2}$)
Gully bottom	1924	10.0	12.0	79.09
Sloping land	2250	7.0	9.5	55.66
F	3.64	18.12	8.00	17.61
P	0.129	0.013	0.047	0.014

with sulfuric acid and perchloric acid. Olsen P was determined by the Olsen method. Ammonium and nitrate were analyzed by Lachat flow analyzer (AutoAnalyzer3-AA3, Seal Analytical, Mequon, WI) after extracted by potassium chloride (Kachurina et al., 2000). Available K in soils was extracted with 1 mol l^{-1} neutral ammonium acetate and measured by atomic absorption spectrometry (SpectrAA-220 Zeeman, Varian Inc., Palo Alto, CA). Alkaline phos-phatase and invertase activities were measured by the procedure described by Zhou and Zhang (1980).

Statistical analysis

Correlation, variance and principal component analysis were conducted using SAS software (SAS Institute, 1999). Correlation analysis was performed to reveal the relationships among different soil properties, variance analysis was performed to test difference of soil properties as affected by landform and soil depth, principal component analysis was performed to simplify the interpretation of soil property dataset and to reflect overall effects of landforms on soil property.

RESULTS AND DISCUSSION

Changes of soil properties by black locust

21 years' growth of black locust has greatly improved soil properties in the study site (Table 1). Although bulk density changed slightly with soil depth, it has been decreased significantly in 0 - 80 cm soil depth by black locust. The decrease of bulk density was 0.2 gcm^{-3} in 0 - 20 cm depth, which is greater than the decrease in deep soils (20 - 80 cm) where the bulk density decreased by 0.04 to 0.08 g cm^{-3}. This agrees with the finding of Ussiri et al. (2006) that conversion of pasture to black locust significantly decreased the bulk density of the top 10 cm.

Organic matter and total N were significantly increased in soils after 21 years' growth of black locust. The increase of organic matter is due to the long term accumulation and decomposition of organic material in soils, while that of total N is due to the N fixation by black locust and also to the returning of plant N with the fall of litters. Organic matter was increased by 56.9, 109.9, 85.6 and 20.4% in 0 - 20, 20 - 40, 40 - 60 and 60 - 80 cm soil depths, while total N was increased by 36.5, 20.9, 30.0 and 10.7% in corresponding depths, respectively. Accordingly, the organic matter and N stocks have been enlarged by 7.23, 9.41, 6.39, 1.63 t hm^{-2} and 0.25, 0.15, 0.20, 0.05 t hm^{-2} in 0 - 20, 20 - 40, 40 - 60 and 60 - 80 cm soil depths and 24.65 and 0.66 t hm^{-2} in 0 - 80 cm soil depth. These results are consistent with findings that black locust can greatly increase soil C and N pool (Boring and Swank, 1984; Rice et al., 2004; Ussiri et al., 2006).

Unlike organic matter and total N, total P showed a significant reduction in 0 - 80 cm soils after 21 years plantation of black locust. The decrease of total P can be attributed to the plant uptake of soil P and the transferring of P from soil pool to plant pool. Generally, legumes require more P than other plants for root development and energy driven processes because it enhances the symbiotic N fixation process in legume plants (Al-Niemi et al., 1997; Gillespie and Pope, 1990; Marschner, 1995; Vanlauwe et al., 2000). Therefore, more soil P was utilized during black locust growth and transported into above ground plant P pool, resulting in the decrease of soil total P. The largest decrease of total P occurred in 0 - 20 cm soil depth which contained 28.4% less P than that before black locust was planted. Total P contents were 25.0, 25.0 and 20.3% lower in the 20 - 40, 40 - 60 and 60 - 80 cm soil depths compared to the soils in 1984. Accordingly, P stocks have been minished by 0.88, 0.59, 0.51, 0.43 t hm^{-2} in 0 - 20, 20 - 40, 40 - 60 and 60 - 80 cm soil depths and 2.41 t hm^{-2} in 0 - 80 cm soil depth. The uptake intensity of soil P was determined by black locust's fine root distribution in soil profiles. In the Loess Plateau, the surface area, length and volume of black locust's fine root present the maximum in 0 - 20 cm soils and decreased with soil depth (Cheng et al., 2006). This explains our observation that decrease of total P declined with soil depth and further hints that the uptake intensity of P by black locust declined with soil depth.

Opposite to total P, Olsen P in soils was increased greatly after 21 years' growth of black locust, which was consistent with the findings reported by Nuruzzaman et al. (2005) and Vanlauwe et al. (2000) that legume plant can improve P availability in soils. The Olsen P content was increased by 326 and 290% in 0 - 20 and 20 - 40 cm depths, and by 391 and 293% in 40 - 60 and 60 - 80 cm depths, respectively. The increase of Olsen P was more obvious in 40 - 80 cm soil depth than in 0 - 40 cm soil depth. This was due to the intensive uptake of Olsen P by black locust roots in 0 - 40 cm depth.

Landform effects on profile distribution of soil properties in black locust land

In the study area, precipitation is the only source of soil water. Landform governs the redistribution of precipitation in land surface and controls mass movement in soil profiles. Generally, water from precipitation readily flow from sloping land into gully bottom, resulting in high water content in gully soils and low water content in sloping land soils. The growth of black locust in the 2 landforms is therefore significantly affected (Table 2), which would cause great difference in biological cycling of materials and thus in soil properties.

Physicochemical properties

Different soil properties presented different profile distribution pattern in soils of black locust land in the study area (Table 3). Bulk density and soil pH values increased with soil depth, while cation exchange capacity and organic matter decreased with soil depth. Bulk density increased from 1.21 gcm^{-3} in 0 - 20 cm soil depth to 1.30 gcm^{-3} in 60 - 80 cm soil depth. However, profile distribution of pH, CEC and organic matter are interrelated. In forest land, litters mainly distribute in surface soils and greatly increase organic matter in this layer soils after decomposition. Additionally, organic materials accumulated in surface soils will leach into deeper soils and increase organic matter in subsurface soils. Averagely, organic matters in 0 - 20 and 20 - 40 cm soils were 2.56 and 1.72 times of that in 60 - 80 cm soils, respectively. The accumulation and decomposition of organic materials can release amount of organic and inorganic acids into soils, resulting in the reduction of soil pH. Therefore, pH values showed an opposite profile distribution pattern to that of organic matter. This was consistent with the negatively relationship between pH and organic matter observed in this study ($r = -0.553$, $p < 0.05$). The profile distribution of CEC in black locust land was characterized by a decreasing trend with soil depth. Cation exchange capacity was negatively related with soil pH ($r = -0.699$, $p < 0.01$) and positively related with organic matter ($r = 0.595$, $p < 0.05$), suggesting that CEC was largely con- trolled by pH and organic matter in this study. The profile allocation of pH, CEC and organic matter observed in this study were closely agreed with other results (Annan-Afful et al., 2005; Hussain et al., 1999; Jozefaciuk et al., 2006).

Organic matter, pH and CEC were significantly affected by landforms and soil depth, while bulk density was not affected by them. In 0 - 80 cm soil depth, gully bottom was higher in organic matter and CEC but lower in pH value compared with sloping land. Soils in gully bottom content 3.55, 2.91, 2.68, 1.31 gkg^{-1} more organic matter and is 2.51, 1.95, 1.03, 0.98 cmol kg^{-1} higher in CEC than sloping land, but is 0.17, 0.11,0.16, 0.11 lower in pH values than sloping land in 0 - 20, 20 - 40, 40 - 60 and 60 - 80 cm soil depths, respectively. In gully bottom, organic matter and CEC were 7.67 gkg^{-1} and 3.60 cmolkg^{-1} higher in surface soils (0 - 20 cm) than in deep soils (60 - 80 cm). In sloping land, they were 5.43 and 1.89 cmol kg^{-1} higher in surface soils than in deep soils, respectively. Meanwhile, pH values were 0.1 and 0.04 pH units lower in surface soils than in deep soils in gully bottom and sloping land, respectively. This implies that changes of physicochemical properties by black locust were greater in gully bottom than in sloping land.

Nutritional properties

Since closely linked with organic matter, total N in soils presented a similar profile distribution pattern with organic matter (Table 3). It decreased gradually with soil depth and was 0.18, 0.17, 0.19, 0.09 g kg^{-1} higher in gully bottom than in sloping land soils in 0 - 20, 20 - 40, 40 - 60 and 60 - 80 m soil depths, respectively. Nitrate and ammonium are plant available nitrogen in soils and can be absorbed by plants. Soil conditions in gully bottom accelerate the uptake of nitrate and ammonium by plant and speed up the depletion of them in soils. As a result, the amount of nitrate and ammonium remained in soils were lower in gully bottom than in sloping land (Table 3).

Table 3. Profile distribution of soil properties as affected by landform.

Landform	Soil depth(c)	Bulk density (g cm^{-3})	pH	CEC (cmol kg^{1})	OM (g kg^{-1})	Total N (g kg^{-1})	Nitrate (mg kg^{1})	AM (mg kg^{1})	Total P (g kg^{-1})	Olsen P (mg kg^{-1})	AK (mg kg^{-1})	A. phos. µg glu g^{-1}h^{-1}	Invertase µg ph(OH) g^{-1}h^{-1}
Gully bottom	0 - 20	1.22 ab	8.22 d	20.09 a	12.64 a	0.76 a	2.72 ab	5.68 ab	0.63 a	3.53 a	165.91 a	178.47 a	1612.81 a
	20 - 40	1.22 ab	8.27 cd	18.00 ab	8.96 bc	0.59 ab	2.49 abc	5.07 ab	0.59 ab	3.30 a	115.44 a	93.20 b	736.25 b
	40 - 60	1.27 ab	8.28 bc	16.49 b	6.81 cd	0.47bcd	1.30 bc	4.88 b	0.57 bc	3.40 a	125.63 a	45.45 bc	303.44 cd
	60 - 80	1.28 ab	8.32 bc	16.49 b	4.97 de	0.34 de	1.26 c	4.40 b	0.57abc	2.65 a	90.85 a	23.25 c	245.63 cd
Sloping land	0 - 20	1.21 b	8.39 ab	17.58 ab	9.09 b	0.58 ab	3.54 a	6.64 a	0.57 abc	4.73 a	134.36 a	94.79 b	410.00 bc
	20 - 40	1.23 ab	8.38 ab	16.05 b	6.05 de	0.42cde	2.50 abc	6.18 ab	0.56 abc	4.40 a	105.76 a	21.30 c	51.88 d
	40 - 60	1.27 ab	8.44 a	15.46 b	4.13 de	0.28 e	2.33 abc	5.51 ab	0.55 bc	4.50 a	96.24 a	5.40 c	33.75 d
	60 - 80	1.33 a	8.43 a	15.51 b	3.66 e	0.25 e	1.69 bc	5.08 ab	0.53 c	4.58 a	93.90 a	2.31 c	44.38 d
F values													
Landform		0.25	61.46	4.7	14.54	11.03	4.68	5.23	4.81	1.89	1.74	10.35	42.23
Soil depth		2.83	3.96	3.74	24.92	17.48	5.4	2.38	3.91	0.79	2.07	15.27	23.8
Landform*Soil depth		0.35	0.45	0.17	0.3	0.28	0.28	0.22	0.56	0.8	0.19	0.62	6.1
P values													
Landform		0.6213	<0.001	0.0419	0.0010	0.0032	0.0421	0.0327	0.0397	0.1841	0.2019	0.0041	<0.0001
Soil depth		0.0631	0.0220	0.0269	<0.0001	<0.001	0.0065	0.0980	0.0230	0.5109	0.1354	<0.0001	<0.0001
Landform*Soil depth		0.7916	0.7181	0.9168	0.8238	0.8361	0.8419	0.8825	0.6445	0.5094	0.9018	0.6120	0.0038

Note: CEC, cation exchange capacity; OM, organic matter; AM, ammonium; AK, available potassium; A.phos, alkaline phosphatase.

On the other hand, nitrate is apt to leach from surface soils into deep soils and may loss from the 0 - 80 cm soils when soil water is enough high. This gives another expla- nation for the difference of nitrate between gully bottom and sloping land.

Total P was significantly higher in gully bottom than in sloping land and decreased with soil depth in both land forms. The difference of total P between 0 - 20 cm soils and 60 - 80 cm soils was 0.06 gkg^{-1} in gully bottom and 0.04 gkg^{-1} in sloping land, respectively. Although black locust enhanced reduction of soil total P, the landform's effects on total P was not in contradiction to black locust's effect. The growth of black locust was better in gully bottom than in sloping land (Table 2), which would lead to the more decrease of total P in gully bottom. However, P is apt to loss with runoff and transport from sloping land into gully bottom (Shigaki et al., 2006), which would increase total P in gully bottom and partly counteract the great decline of total P by black locust's uptake. Olsen P was 1.20, 1.10, 1.10, 1.93 mg kg^{-1} lower in gully bottom than in sloping land. The lower content of Olsen P in gully bottom is attributed to the intensive plant uptake of soil P because Olsen P is plant available phosphorus in soils. Although total P was higher in gully bottom, the release of available P from mineral forms is very slow and is not readily occurred in natural soils (Yang et al., 2005; Allen and Mallarino, 2006). Therefore, total P and Olsen P was not correlated in this study (r = -0.134, p = 0.506) and the influence of landforms on total P and Olsen P was different.

Plant available K declined with soil depth in black locust land soils (Table 3). On the one hand, plant uptake of available K in deep soils lowered available K in these depths, meanwhile the accumulation of organic materials in surface soils released K into soils and increased their amount in available form. On the other hand, available K is positively related with CEC ($r = 0.570$, $p < 0.01$) and negatively related with soil pH ($r = -0.427$, $p < 0.05$). Therefore, profile distribution of available K was similar to CEC but opposite to pH. Although available K was higher in gully bottom than in sloping land soils, the difference was not significant. This observation implies that available K is not significantly affected by landform in black locust land. This can be ascribed to following 2 reasons. The first reason is that available K in the study area is high and can meet the requirement by plant growth (Li, 2004), which makes available K response slowly to plant uptake. The second reason is that K can easily transfer from non-available forms into available forms and can supplement the depletion of available K caused by plant uptake. This transformation supplements the available K pool and alleviates the influence of plant uptake on available K at different landforms.

Enzymatic properties

Soil enzyme is highly related with soil biological properties and is often used to reflect biological properties (Cavigelli et al., 2005; Zhou et al., 2008; Shao et al., 2008; Jadia et al., 2009). Activities of alkaline phosphatase and invertase in black locust land decreased markedly with soil depth. This might be attributed to the enzyme properties. Alkaline phosphatase and invertase are hydrolase in soils and are mainly extracellular, their activities endure despite the lysis of the cells. Additionally, these enzymes are released by microorganisms in response to their substrates. When organic matter and total N is increased, the activity of these enzymes is also increased. Profile distribution of alkaline phosphatase and invertase was therefore influenced by organic matter and total N in soils. In this experiment, alkaline phosphatase and invertase shared the similar profile distribution pattern with that of organic matter and total N and present very significant relationships with them (Figure 1). The activities of both enzymes were all higher in gully bottom than in sloping land (Table 3). The activities of alkaline phosphatase in gully bottom were 1.9, 4.4, 8.4 and 10.0 times of that in sloping land in 0 - 20, 20 - 40, 40 - 60 and 60 - 80 cm soil depths, respectively. Meanwhile the activities of invertase in gully bottom were 3.9, 14.2, 9.0, and 5.5 times of that in sloping land in 0-20, 20-40, 40-60, and 60-80 cm soil depths, respectively. These results imply that the effects of black locust on soil alkaline phosphatase and invertase were more obvious in gully bottom than in sloping land.

Overall reflection of soil properties as affected by landforms

Soil properties include physicochemical, nutritional and biological properties. Each property responds specifically to landforms. Therefore, principal component analysis was performed to simplify the interpretation of soil property dataset and to reflect overall effects of landform on soil property. Table 4 shows the eigenvectors of the final 4 principal components. The first principal component was composed of organic matter, total N, ammonium, alkaline phosphatase and invertase. The second principal component was composed of pH, CEC and total P. The third principal component was composed of Olsen P and available K. The fourth principal component was composed of bulk density and nitrate. The 4 principal components together explained 85% of total variance and the first principal component contributed most to the total variance, indicating that the first principal component can be classified as a factor to represent the major variation of most properties. Therefore, we illustrate differences of soil properties between gully bottom and sloping land soils by calculating first component score through following formula:

$$FPC = \sum E_i P_i$$

where FPC is the score of the first principal component, E_i is the eigenvectors of the properties composed in first component, P_i is the standardized values or contents of these properties. Because the unit of each property is different, here we use standardized values or contents of properties to calculate FPC so as to eliminate unit's influence.

The profile distributions of FPC in gully bottom and sloping land are presented in Figure 2. It clearly showed that FPC decreased greatly with soil depth and was significantly higher in gully bottom than that in sloping land. First component scores in gully bottom soils are 1.6, 2.2, 2.8, and 2.4 times of that in sloping land in 0 - 20, 20 - 40, 40 - 60 and 60 - 80 cm soils, respectively. Combined with the results in section 3.2 we can conclude that the distribution of FPC in soils can well reflect the distribution of soil properties as affected by landform and can be used to indicate changes of soil properties in black locust land.

Implications for black locust forest management

Results from this study demonstrate the potential for black locust to improve soil properties in loessial gully region of the Loess Plateau in both sloping and gully bottom. While the effects of black locust on soil properties varied significantly with landforms. However, it has confirmed that black locust accelerated the consumption of soil water in the Loess Plateau. Wang et al. (2004, 2008) have showed that water deficits in different soil depth (0 - 500 cm) occurred in 20 years black locust stand and the deficit degree was related with plant growth in 6 sites of the Loess Plateau. He et al. (2003) and Chen et al. (2008) have observed that 18 years growth of black locust greatly decreased soil water contents in 0 - 600 cm soils and the decrease was greater in gully bottom than in sloping land. Therefore, the formation of soil water deficits will inhibit plant growth and soil properties will no longer be improved once the growth is restrained, which will result in the degradation of black locust forest. In the study area,

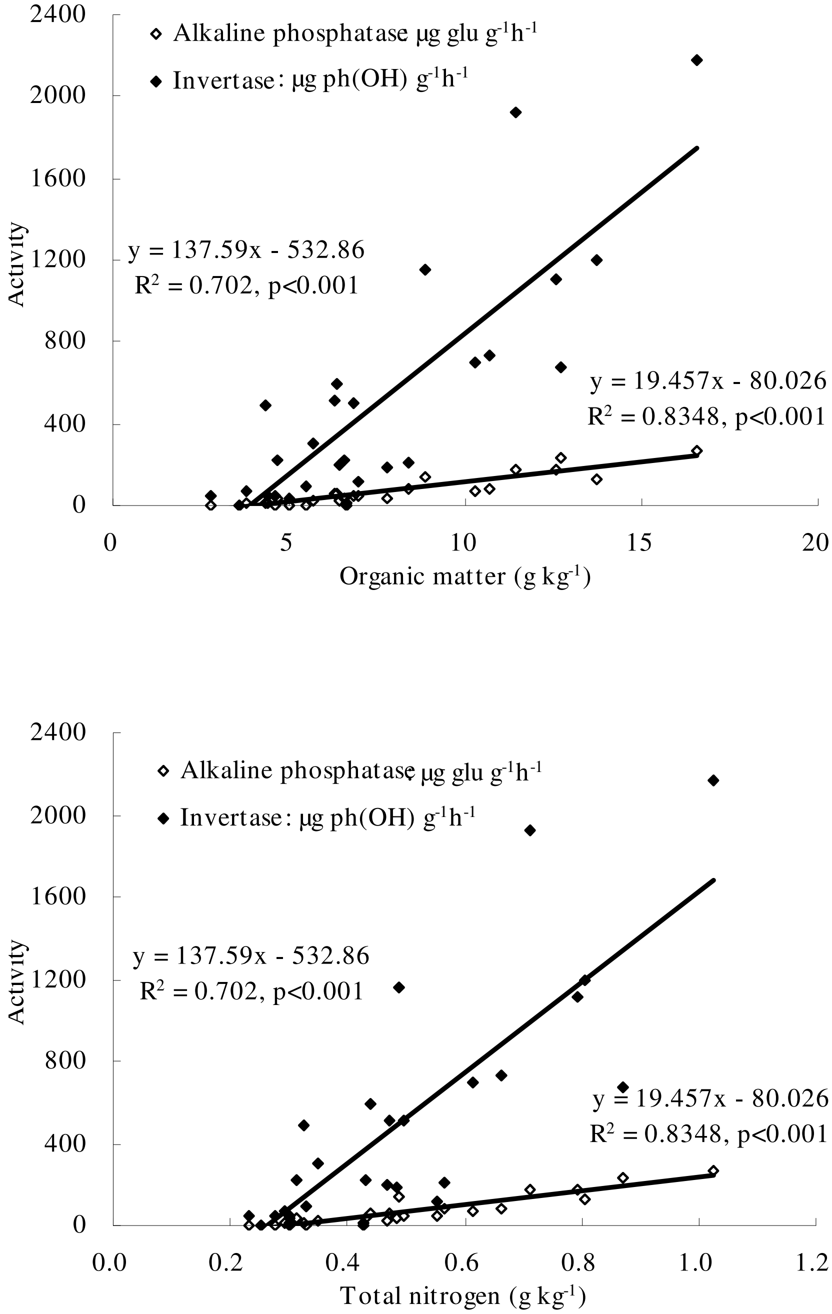

Figure 1. Relationships of alkaline phosphatase and invertase to organic matter and total nitrogen.

irrigation can not be applied and soil water deficit can not be supplemented, therefore, other adjusting measures should be taken in proper growth stage to hold back the exhaust of soil water by black locust so as to maintain improved soil properties and guarantee land productivity. As our results showed, effects of black locust on soil properties changed with landforms, adjusting measures for black locust forest should also be taken according to landforms.

In sloping land, soil water content was always lower than gully bottom and can not meet long-term growth of black locust and soil properties can only be improved in short time scale, black locust should be converted to plants like grasses or some shrubs, which not only consume less soil water, but also maintain soil fertility conditions improved by black locust growth. An alternative approach in sloping land is to reduce plant density when soil water deficit emergence. However, in gully bottom,

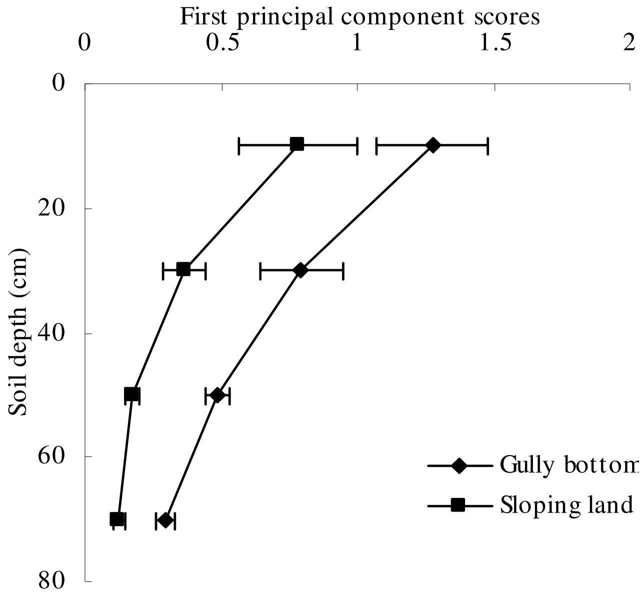

Figure 2. Profile distribution of first principal component scores in sloping and gully bottom black locust land.

soil water condition can not inhibit long-term growth of black locust and soil properties could be improved in a long time scale, therefore, black locust could be planted in long time or in high plant density (Aytekin et al., 2009; Jadia et al., 2009; Lewu and Afolayan, 2009).

Nonetheless, further research should be conducted to reveal changes of soil properties with plantation time of black locust, which will provide evidence for when the regulation should be taken for the black locust forest.

Conclusions

In the loessial gully region of the Loess Plateau, profile distribution pattern of soil properties in black locust land varied with soil properties and landforms. Soil pH values increased with soil depth, while most other properties decreased with soil depth. 21 years' growth of black locust increased soil organic matter, total N and Olsen P, but decreased soil bulk density and total P. Gully bottom soils were higher in organic matter, CEC, total N and P, available K, alkaline phosphatase and invertase, while sloping land soils were higher in pH, nitrate, ammonium and Olsen P. Organic matter, total N, ammonium, alkaline phosphatase and invertase can represent overall distribution of soil properties and can reflect the effects of landform on distribution of soil properties in black locust land. Generally, the improvement of soil properties by black locust was more obvious in gully bottom than in sloping land. However, further growth of black locust might cause negative effects on soil water environment and the improvement of soil properties and thus adjusting measures should be taken according to landforms.

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