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Changes in soil properties with vegetation types in highland grassland of the Loess Plateau, China

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The response of soil properties to vegetation types is still not well understood and the relationship between vegetation types and soil properties has not been quantified in highland grasslands. A field experiment was conducted in highland grassland of the Loess Plateau in China to study the distribution of soil properties under different vegetation. 22 plant communities totaling 17 species that belong to 8 families were selected and root zone soil samples were collected to measure soil properties. The ability of vegetation to influence soil properties was vegetation type and soil property dependent. Generally, cation exchange capacity, soil organic carbon, labile organic carbon, total nitrogen, alkaline phosphatase, and invertase showed similar distribution trends with vegetation types and were higher in soils under *Lilaceae*, *Leguminosae*, *Gramineae*, *Compositae*, *Solanaceae* and *Chenopodiaceae* than those under *Labiatae* and *Rosaceae*. Also, total phosphorus, inorganic, and available phosphorus were higher in soils under *Lilaceae*, *Leguminosae*, *Solanaceae* and *Chenopodiaceae* than under *Gramineae*, *Labiatae* and *Rosaceae*. Catalase activity was not significantly influenced by vegetation type. Statistical analysis suggested that soil organic carbon has significant direct and indirect influences on soil properties and that the combination of soil organic carbon, total phosphorus, and alkaline phosphatase could be used to represent physico-chemical, nutritional and biological properties under different vegetation. Our results highlighted the role of soil organic carbon in the relationship between vegetation and soil properties and indicated the potential of *Leguminosae* and *Lilaceae* to improve soil properties and of *Labiatae* and *Rosaceae* to degrade soil properties in highland grassland of the Loess Plateau.

Key words: Soil enzymes, nutrients, organic carbon, vegetation types, root zone soils.

INTRODUCTION

Vegetation distribution and development is largely dependent on soil conditions (De Deyn et al., 2004; Kardol et al., 2006) and vegetation types were shown to act as useful proxy indicators of soil condition (Coulson et al., 2003). Nutrient limitation occurring in soils is one of the most important factors affecting the structure of plant communities (Grime et al., 1997). On the other hand, changes in vegetation can cause shifts in soil properties (Wardle, 2006) because individual plants concentrate biomass in soils beneath their canopies and modify biogeochemical processes occurring in soils (Burke et al., 1989; Schlesinger et al., 1990), which has attracted attention from scientists in various fields.

The influence of plants on soils is mainly ascribed to the returning of organic materials from plants to the soil, which can eventually significantly affect the physico-chemical, nutritional, and biological properties of soils (Díaz et al., 2004). Plants differ in their capacity to influence soil organic matter, soil nutrient availability and the composition of soil microbial communities, which is essential to understand how plants affect soil properties

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(Bezemer et al., 2006). The changes of vegetation can greatly affect aboveground ecosystem function, in particular plant productivity (Tilman et al., 1996; Hector et al., 1999; Spehn et al., 2000), which will ultimately alter litter decomposition and nutrient cycling and thus soil nutrient conditions and other related properties (Loreau et al., 2001; Lata et al., 2004). It is recognized that plant production, and therefore the quantity of nutrients entering the soil, promotes subsets of the soil biota, particularly those that are regulated primarily by nutrient availability (Mikola and Setälä, 1998). Vegetation can alter biogeochemistry through variation in the quantity and chemistry of their litter, and associated impacts on the soil heterotrophic community (Miki and Kondoh, 2002; Reich et al., 2005; Ross et al., 2006). These differences are directly linked to the specific character of the plant species and soil nutrient conditions. Vinton and Burke (1997) showed that distinctions among different vegetations with respect to litter quality can have remarkable influence on grassland organic matter and soil nutrients.

Plants differ markedly in the belowground communities that they support, and this has important functional consequences (Hunt et al., 1988; Ayres et al., 2006). Soils under different plants frequently support vastly different levels of diversity of various groups of soil organisms, such as endomycorrhizal fungi (Johnson et al., 2003) and saprophytic microbes (Wardle et al., 2003). This effect often occurs in the rhizosphere where soil is several millimeters away from root surface. Grinsted et al. (1982) and Hedley et al. (1982a, b, c) reported the changes in soil physico-chemical, nutritional and biological properties in the rhizosphere induced by rape (*Brassica napus var. emerald*) seedlings. The results from Bergsma-Vlami (2005) showed that vegetation has a significant influence on the dynamics, composition and activity of specific indigenous microorganisms in the rhizosphere. More also, Grayston et al. (1998) and Bardgett et al. (1999) observed that microbial communities, nutrient recycling and nitrogen availability to the plant markedly differ in soils planted with different plants. They explained these differences largely in terms of variations in exudation patterns and plant nutrient acquisition strategies. Although the roots are the predominant factors governing soil properties in the rhizosphere, litterfall and its decomposition play an important role in relationships between plant and soils including the rhizosphere and non rhizosphere (Miki and Kondoh, 2002; Reich et al., 2005).

For a long time, the rhizosphere has been the major site where plant-soil relationships were studied. Many researchers have shown that plant growth can affect soil properties both in rhizosphere and non-rhizosphere soil (Waisel et al., 2002; Séguin et al., 2004; Subke et al., 2004). However, the influence of plants on the rhizosphere is mainly caused by root activities, and simply focusing on changes of soil properties in the rhizosphere cannot completely reveal the effects of plants on soil properties in the bulk soil, especially in highland grasslands where the aboveground plant cover is often discontinuous. Additionally, even if soil properties in the rhizosphere markedly vary with plants and can sensitively indicate the effects of plants on soil properties, it is quite difficult and impossible to partition the rhizosphere from bulk soils in field conditions. Hence, viewing the root zone (soils under the plant canopy) as the research object will be very convenient and applicable in field investigations and have more ecological significance in understanding plant and soil relationship.

Although plant-induced differences in soil properties have been described in diverse ecosystems (Boettcher and Kalisz, 1990; Janssens et al., 1998; Schlesinger and Pilmanis, 1998), the response of soil properties to plant changes remains a controversial issue (Chapman et al., 2006), which is essential in grassland ecological function and biogeochemistry and in response to global climate change (Bai et al., 2004, 2008). Among the soil properties, soil pH and cation exchange capacity, which control the transformation of nutrients and their availability to plants and microorganisms, are the most important properties and often used as soil quality indexes. Soil organic carbon, nitrogen and phosphorous are important properties determining soil fertility and quality, and can be viewed as the basis of soil productivity. Moreover, soil enzymes (intracellular and extracellular) are the mediators and catalysts of biochemical processes essential to soil functions, including nutrient cycling and decomposition of organic matter in soils and their activities are thus strongly dependent on soil environments and biological conditions. In this study, we investigated such soil properties under different vegetation in highland grassland of the China Loess Plateau. Our objectives were to understand how plants affect root zone soil properties and to indicate the relationships between plant and soil properties in highland grassland.

MATERIALS AND METHODS

Study area

The experiment was conducted in Wangdougou watershed in Changwu County, Shaanxi Province, China (35°12′ - 35°16′N, 107°40′ - 107°42′E). The watershed is a field station of the Chinese Ecology Research Net (CERN). The Wangdougou watershed lies in the typical gully region of the Loess Plateau, with an altitude ranging from 800 to 1200 m and covers an area of 8.5 km^2. The study area is characterized by a warm-temperate zone subhumid continental climate. Based on the climate data from 1984 to 2005, the average annual temperature of this site was 9.1°C. The >0°C accumulative temperature was 3866°C, >10°C accumulative temperature was 3029°C and free frost period was 171 days. The average annual precipitation was approximately 584 mm. The rainfall was mainly concentrated from June to September and varied greatly from year to year within a year. All soils were yellow cultivated loessial soil, corresponding to a Calcaric Regosol according to the FAO/UNESCO classification system (FAO/UNESCO, 1988).

Table 1. Basic condition of the plant communities in the experiment.

Family	Species number	Plant species	Aboveground biomass (kg m^{-2})	Tissue concentration (g kg^{-1})	
				N	P
Gramineae	1	*Crypsis aculeata Ait.*	0.17	8.3	3.9
	1	*P.flaccidum Griseb.*	0.15	8.3	2.9
	1	*Eulaliopsis brinata (Retz.) C. E. Hubb.*	0.18	7.7	3.2
	1	*A.cristatam L.Gaertn*	0.19	9.2	3.7
	1	*Phragmites communis Trin.*	0.22	6.9	3.6
	2	*Crypsis aculeata Ait.* *Eulaliopsis brinata (Retz.) C. E. Hubb.*	0.16	13.4	4.0
	2	*P.flaccidum Griseb.* *Crypsis aculeata Ait.*	0.23	12.6	3.7
	2	*Crypsis aculeata Ait.* *S.viridis (L) Beauv.*	0.22	14.4	3.7
	3	*Eulaliopsis brinata (Retz.) C. E. Hubb.* *A.cristatam L.Gaertn* *P.flaccidum Griseb.*	0.24	13.4	4.3
	3	*S.viridis (L) Beauv.* *Eulaliopsis brinata (Retz.) C. E. Hubb.* *A.cristatam L.Gaertn*	0.19	14.1	4.5
Compositae	1	*A. hedinii Osteuf.*	0.46	6.6	3.7
	1	*A. capillaris Thunb.*	0.34	8.6	3.3
	1	*Silybum marianum.*	0.37	7.2	3.3
	1	*Sonchus arvensis L.*	0.26	9.2	4.1
Leguminosae	1	*Lens esculenta Moench.*	0.26	19.1	5.0
	1	*G. soja Sieb. Et Zucc.*	0.29	19.8	5.8
	1	*T. repens L.*	0.30	16.2	5.0
Solanaceae	1	*Solanum nigrum L.*	0.20	11.4	3.6
Chenopodiaceae	1	*Ch. Glaucum L.*	0.24	12.2	3.8
Lilaceae	1	*H. minor Mill.*	0.17	12.0	3.8
Rosaceae	1	*Duchesnea filipendula (Hemsl.) Pritzel*	0.09	4.2	3.0
Labiatae	1	*Coronilla varia L.*	0.16	3.2	2.9

Experiment design and soil sampling

We selected 22 neighboring sites for field investigation. The 22 sites are all located on gentle southern slopes with a gradient of 1.5 - 2°. The soils were not fertilized and the plants were not mowed. Other environmental factors such as relief, soil type, grazing and soil erosion similar and differences in soil properties were attributed to vegetation types.

There were a total of 17 dominant plant species that belonged to 8 families growing in the selected investigation sites. The number of plant species in each site varied from three to seven, but we only listed the dominant plant species in Table 1. There were ten sites with dominant plants belonging to *Gramineae*, four sites to *Compositae* and three sites to *Leguminosae*. *Solanaceae*, *Chenopodiaceae*, *Lilaceae*, *Rosaceae* and *Labiatae* dominated in one site each. For each site, five plots (0.8 m × 0.8 m) were selected and plants were cut at ground level. The cut material included living biomass and standing dead material. The plant samples were dried at 70°C for 24 h and weighed. Aboveground biomass was determined as the sum of the standing biomass at the cuts (Table 1). Five soil cores (5 cm diameter) were sampled (0 to 15 cm depth) in each plot and mixed to obtain a composite soil sample for laboratory analysis. Soil was collected under the plant canopies to represent root zone soil samples.

Laboratory analysis

Plant samples were ground and passed through a 0.5 mm sieve for the analysis of nitrogen and phosphorus concentration. Nitrogen concentration in plant tissue was determined by micro-Kjeldahl digestion procedure (Page et al., 1982). Phosphorus concentration was determined by digesting in sulfuric acid and peroxide (Murphy and Riley, 1962) (Table 1). Soil samples were air dried at room temperature, lightly crushed with a pestle in a ceramic mortar, and passed through a 1 mm and 0.25 mm sieve for analysis.

Soil pH, cation exchange capacity (CEC), organic carbon (SOC), total nitrogen (N_t), total and available phosphorus (P_t and P_a) 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. The CEC was determined by replacement of exchangeable cations by ammonium acetate. The

Table 2. Distribution of soil properties and soil organic carbon as affected by different vegetations.

Vegetation	pH	CEC ($cmolkg^{-1}$)	SOC (gkg^{-1})	LOC g (kg^{-1})	MLOC (gkg^{-1})	HLOC (gkg^{-1})	F_{LOC} (%)	F_{MLOC} (%)	F_{HLOC} (%)
Chenopodiaceae	8.46 ^{a}	14.73^{bcd}	7.60^{ab}	1.83^{ab}	1.08^{ab}	0.58^{b}	24.1	14.3	7.6
Compositae	8.09 ^{a}	16.85^{bc}	8.87^{ab}	2.28^{a}	1.49^{a}	0.79^{a}	25.7	16.8	8.9
Gramineae	8.03 ^{a}	16.50^{abc}	8.70^{ab}	2.35^{a}	1.41^{a}	0.71^{a}	27.0	16.2	8.2
Labiatae	8.32 ^{a}	13.59^{cd}	4.65^{b}	1.12^{b}	0.37^{c}	0.22^{c}	24.0	8.1	4.8
Leguminosae	8.12 ^{a}	17.61^{a}	8.92^{a}	2.35^{a}	1.38^{a}	0.72^{a}	26.3	15.5	8.0
Lilaceae	8.20 ^{a}	17.25^{ab}	8.17^{ab}	1.83^{ab}	1.19^{ab}	0.65^{b}	22.4	14.5	8.0
Rosaceae	8.24 ^{a}	11.76^{d}	5.11^{b}	1.68^{b}	0.75^{b}	0.49^{bc}	32.8	14.7	9.6
Solanaceae	8.29 ^{a}	14.73^{bcd}	7.76^{ab}	1.84^{ab}	1.29^{a}	0.69^{b}	23.7	16.6	8.9

CEC, cation exchange capacity; SOC, soil organic carbon; LOC, labile organic carbon; MLOC, medium labile organic carbon; HLOC, high labile organic carbon; F_{LOC}, fraction of LOC to SOC; F_{MLOC}, fraction of MLOC to SOC; F_{HLOC}, fraction of HLOC to SOC. Means in the same column with different letters are significantly different at $p<0.05$ level.

SOC was determined using the Walkley–Black method. The N_t was measured using the Kjeldahl method. The P_t was determined colorimetrically after wet digestion with sulfuric acid and perchloric acid. The P_a was determined by the Olsen method. Organic phosphorus (P_o) was determined by the Saunders and Williams (1955) ignition procedure. Inorganic phosphorus (P_i) was determined according the procedure proposed by Jiang and Gu (1989). Ammonium N (N_a) and nitrate N (N_n) were analyzed by Lachat Flow Analyzer (AutoAnalyzer3-AA3, Seal Analytical, Mequon, WI) after extraction by potassium chloride (Kachurina et al., 2000). Labile organic carbon concentration was determined at three dilutions, 33.3, 167 and 333 mmol L^{-1}, of potassium permanganate (Blair et al., 1995). The fractions determined are referred to as highly labile organic carbon (HLOC), medium labile organic carbon (MLOC) and labile organic carbon (LOC). Furthermore, the activities of alkaline phosphatase (A.phos) and invertase (Invert) were measured with the methods described by Zhou and Zhang (1980). Soil catalase activity (Cat) was measured using the 0.1mol L^{-1} potassium permanganate titration method (Johnson and Temple, 1964).

Data analysis

To determine the effects of vegetation on soil properties and to identify the relationships among these soil properties, one way variance analysis, correlation analysis, path analysis, principal component analysis and correspondence analysis were conducted using procedures of SAS (SAS Institute, 1999). One way variance analysis was used to test the differences of soil properties with plant families. The correlation analysis was carried out to test the relationships between plant biomass and soil organic carbon and labile organic carbon, and relationships among soil properties. Path analysis was used to partition the effects of soil properties on enzyme activities into direct and indirect influences. Principal component analysis was performed to simplify the interpretation of the effects of vegetation on soil properties. Correspondence analysis was conducted to relate soil properties with vegetation.

RESULTS AND DISCUSSION

Effects on soil pH and CEC

Soil pH in the root zone of *Chenopodiaceae* was highest with a value of 8.46, which was followed by soils under *Labiatae* and *Solanaceae*. *Gramineae* and *Compositae* had the lowest soil pH, which were 8.03 and 8.10, respectively (Table 2). The variation of soil pH values in root zone was about 0.4 units among the different plant genera, which is mainly caused by the changes in soil organic matter and its effects on soil biological processes because the influence of root activity merely occurred in soils around root surface. The accumulation and decomposition of organic material results in the formation of organic and inorganic acids that provide proton to soils and subsequent pH changes (Yan et al., 1996; Naramabuye and Haynes, 2006). Haynes (1983) also suggested that the accumulation of soil organic matter is an important contributing factor to the decline of surface soil pH. Therefore, a soil with high organic matter content will have a low pH value, which was consistent with the negative relationship between pH and organic matter observed in our experiment ($r = -0.583$, $p = 0.0014$).

The highest CEC was found in the root zone of *Leguminosae* and *Gramineae*, while the lowest CEC was examined in the soil under *Labiatae* and *Rosaceae* (Table 2). Generally, soil CEC is determined by soil mineral composition, soil pH, and organic matter fractions (Gillman, 1981; Haynes, 1983; Mahboubi et al., 1993). In this study, the soils and the geographic conditions in each plot were the same and no soil erosion occurred in the plots. Therefore, we assumed that the soil mineral compositions are also the same for each plots and thus we attributed the difference of CEC in root zone soils of various plants to the vegetation induced variations in soil pH and organic matter content. This was supported by the correlation analysis result which showed that CEC was negatively related with soil pH ($r = -0.585$, $p = 0.001$) and positively related with organic matter ($r = 0.925$, $p<0.001$).

Effects on soil organic carbon

The contents of SOC and the three labile organic carbon

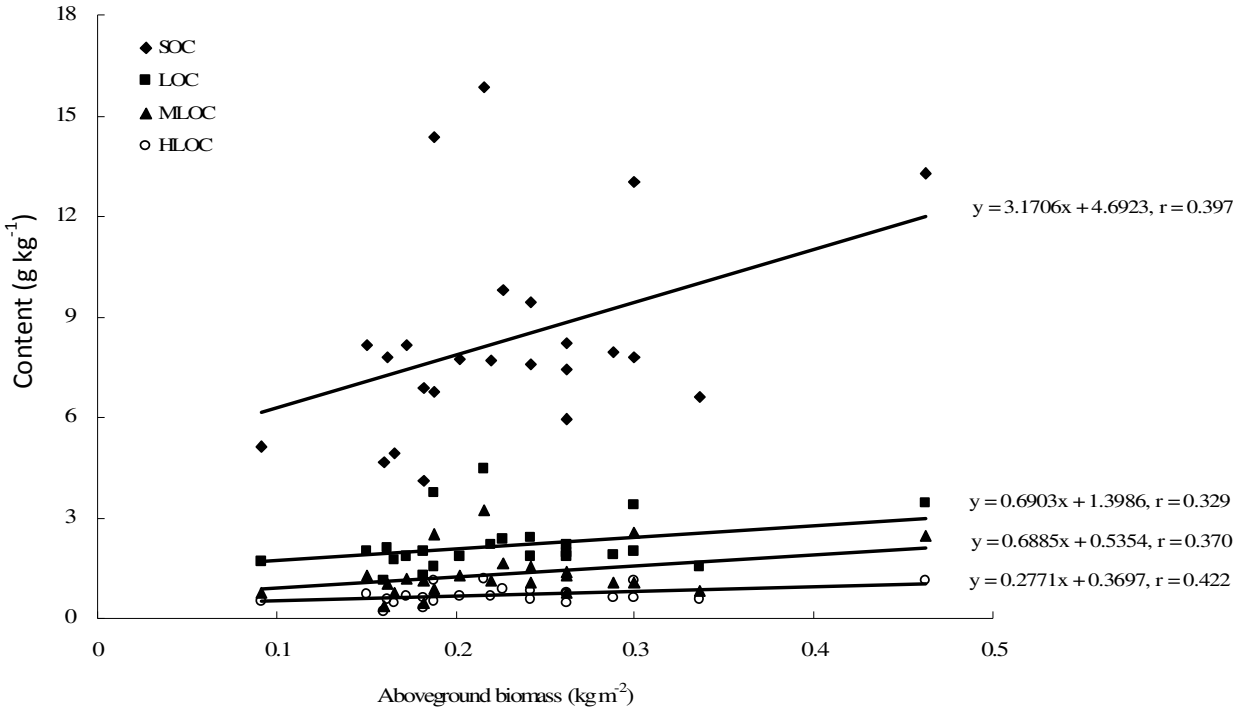

Figure 1. Relationship between aboveground biomass and soil organic carbon (SOC), labile organic carbon (LOC), medium organic carbon (MLOC) and highly labile organic carbon (HLOC). $r_{0.05}$ = 0.388.

forms (LOC, MLOC and HLOC) in root zone soils significantly differ among plants (Table 2). *Labiatae* and *Rosaceae* had the lowest SOC in soils, while *Leguminosae, Gramineae* and *Compositae* had the highest SOC in soils. The SOC in root zone under other plants was quite high with the content around 8 g kg^{-1}. The contents of the three labile organic carbons in root zone soils shared the same trend with SOC. However, the proportion of LOC, MLOC and HLOC to SOC were quite different from the concentrations of LOC, MLOC and HLOC. The proportion of LOC to SOC was somewhat opposite to the proportion of MLOC to SOC. The differences in the proportions of LOC, MLOC and HLOC to SOC indicate the differences in the nature and transformations of carbon in soil organic carbon pool with different vegetation.

No organic fertilizers and animal excreta were added in our selected plots, hence the changes in soil organic carbon are attributed to the returning of plant residue and the decomposition of such residues, which are closely linked to the plants grown in the soil and to the litter quality (Vinton and Burke, 1997; Loreau et al., 2001; Subke et al., 2004). *Labiatae* and *Rosaceae*, like *Coronilla varia L.* and *Duchesnea filipendula (Hemsl.) Pritzel*, are all vivacious plants and have little above ground biomass. The amount of litter returned to soils is less compared with other plants in our experiment. In addition, the decomposition of *Labiatae* and *Rosaceae* litters was difficult due to their low nitrogen content (Table 1) because tissue N is the limiting factor for the litter decomposition (Hartemink and O'Sullivan, 2001; Hall and Matson, 2003). As a result, SOC and labile carbon in root zone soils of *Labiatae* and *Rosaceae* were lowest among the studied plants. Other plants had considerable biomass and returned more litter to soils and consequently, much organic materials were accumulated in root zone soils and SOC and labile carbons were enhanced. Owing to the higher tissue N content, the litter of *Leguminosae* was easy to decompose in soils, which resulted in the highest SOC in root zone soils. The effects of vegetation on SOC are also indirectly supported by the relationships between above ground biomass and SOC, LOC, MLOC, HLOC (Figure 1), which shows a general trend that SOC, LOC, MLOC and HLOC increase as aboveground biomass increases.

Effects on soil N

The N_t and N_o in root zone soils varied greatly with plants and shared the same trend (Table 3), which followed the order of *Leguminosae*, *Lilaceae*, *Gramineae* > *Solanaceae*, *Chenopodiaceae*, *Compositae* > *Rosaceae* and *Labiatae*. Such a trend of N_t and N_o with plant genus is similar to that of SOC and labile organic carbons. This similarity could be ascribed to the significant relations and

Table 3. Distribution of nitrogen and phosphorus in soils as affected by different vegetations.

Vegetation	N_t (gkg^{-1})	N_o (gkg^{-1})	N_n (mgkg^{-1})	N_a (mgkg^{-1})	P_t (gkg^{-1})	P_i (mgkg^{-1})	P_o (mgkg^{-1})	P_a (mgkg^{-1})
Chenopodiaceae	0.88^{abc}	0.84^{b}	4.1^{bc}	5.6^{b}	0.75^{abc}	643^{ab}	103^{c}	24^{b}
Compositae	0.85^{abc}	0.82^{b}	5.6^{b}	6.7^{a}	0.71^{abc}	538^{c}	167^{ab}	13^{c}
Gramineae	0.95^{abc}	0.91^{a}	3.9^{bc}	5.9^{b}	0.63^{c}	493^{d}	137^{b}	5^{d}
Labiatae	0.42^{c}	0.40^{d}	3.3^{c}	6.3^{ab}	0.65^{bc}	494^{d}	154^{b}	2^{d}
Leguminosae	1.05 ^{a}	1.01^{a}	9.9^{a}	6.0^{b}	0.85^{a}	637^{b}	208^{a}	30^{a}
Lilaceae	0.98^{ab}	0.94^{a}	2.7^{c}	6.4^{ab}	0.86^{ab}	682^{a}	176^{ab}	22^{b}
Rosaceae	0.62^{bc}	0.60^{c}	1.6^{c}	4.8^{c}	0.66^{bc}	518^{c}	144^{b}	3^{d}
Solanaceae	0.89^{abc}	0.85^{b}	8.5^{a}	5.5^{b}	0.73^{abc}	625^{b}	107^{c}	24^{b}

N_t, total nitrogen; N_o, organic nitrogen; N_n, nitrate nitrogen; N_a, ammonium nitrogen; P_t, total phosphorus; P_i, inorganic phosphorus; P_o, organic phosphorus; P_a, available phosphorus. Means in the same column with different letters are significantly different at $p<0.05$ level.

Table 4. Correlation coefficients among soil nitrogen and tissue N, pH, cation exchange capacity and soil organic carbon.

Parameter	Tissue N	pH	CEC	SOC	LOC	MLOC	HLOC	N_t	N_n	N_a
N_t	0.461*	-0.608***	0.891***	0.969***	0.936***	0.945***	0.944***			
N_n	0.242	-0.073	0.442*	0.411*	0.439*	0.475*	0.449*	0.435*		
N_a	0.290	-0.439*	0.732***	0.719***	0.687***	0.748***	0.694***	0.710***	0.354	
N_o	0.458*	-0.612***	0.887***	0.969***	0.936***	0.944***	0.944***	1.000***	0.422*	0.708***

CEC, cation exchange capacity; SOC, soil organic carbon; LOC, labile organic carbon; MLOC, medium labile organic carbon; HLOC, high labile organic carbon; N_t, total nitrogen; N_o, organic nitrogen; N_n, nitrate nitrogen; N_a, ammonium nitrogen. *** Significant at P<0.001; * significant at 0.05.

interactions among these properties with plant tissue N concentration (Table 5) and to the bio-cycling of N by different plants. In our study, the aboveground biomass was not harvested and removed, that is, the dead plant materials were still retained in the ecosystem. The effects of vegetation on soil N are thus mainly caused by the processes of N bio-cycling and N enriching in root zone soils. Due to the higher N contents in litters and higher SOC in root zone soils, *Leguminosae* had the highest N_t and N_o. Although without the ability to fix atmosphere nitrogen, the large amount of aboveground biomass of *Lilaceae*, *Gramineae*, *Solanaceae*, *Chenopodiaceae* and *Compositae* concentrated lots organic materials in soils and accelerated the bio-cycling of N, which favors the accumulation of deep soil N in surface soils and also enhances the N_t and N_o in the root zone soils. The poor bio-cycling process and the inability to fix atmosphere nitrogen made *Labiatae* and *Rosaceae* have a low N_t and N_o in root zone soils.

As the readily and easily available forms of N in soil for root uptake, the N_n and N_a did not follow similar trends to N_t and N_o with vegetation (Table 3). Although the highest and lowest N_n was also detected in root zone soils of *Leguminosae* and *Rosaceae*, respectively, and N_n was somewhat opposite to total and organic N in root zone soils under other plants. The high N_t and N_o correspond to the low N_t in root zone of *Lilaceae*, *Gramineae*, *Compositae* and *Chenopodiaceae*. Similarly, the low N_t and N_o correspond to the high N_a in root zone of *Labiatae*. The N_a can be adsorbed at cation exchange sites and the amount increases with increasing soil organic carbon and CEC (Mengel and Kirby, 2001). Therefore N_a is closely related with pH, CEC, SOC and labile organic carbons (Table 4). The N_a and N_n in soils depend on the mineralization of organic nitrogen which relates more to soil biological process and soil properties than plant tissue N (Bollag and Stotzky, 2000; Stevenson and Cole, 1999). Therefore, N_a and N_n showed poor relations with tissue N but significant relations with N_o (Table 4). The low soil pH, high CEC and SOC favor the mineralization of organic nitrogen (Bollag and Stotzky, 2000; Stevenson and Cole, 1999) and enhance the accumulation of N_n and N_a in soils. On the other hand, N_n is readily leached and lost from surface layer soils, while N_a is apt to adsorb onto soil components, fix in soil minerals and volatilize in calcareous soils (Mengel and Kirby, 2001). By and large, the contents of N_n and N_a are mainly affected by the aforementioned processes through which the influence of plants is exerted.

Effects on soil P

Except for the soils under *Gramineae* that had a relatively low P content, P shared similar pattern with N in soils under various plants. The similar trend of P to N can also be explained by the bio-cycling process of P. For those plants with large aboveground biomass (*Leguminosae*,

Table 5. Activities of enzymes in soils as affected by different vegetations.

Vegetation	Alkaline phosphatase pH(OH) (μg g^{-1} h^{-1})	Invertase (glu) μg $g^{-1}h^{-1}$)	Catalase ($KMnO_4$) (ml $g^{-1}h^{-1}$)
Chenopodiaceae	140^{c}	1313^{c}	4.38^{a}
Compositae	245^{a}	3123^{a}	4.71^{a}
Gramineae	206^{ab}	2688^{b}	4.75^{a}
Labiatae	43^{d}	388^{d}	4.65^{a}
Leguminosae	209^{ab}	3188^{a}	4.65^{a}
Lilaceae	154^{c}	3350^{a}	4.78^{a}
Rosaceae	118^{cd}	1269^{c}	4.51^{a}
Solanaceae	193^{bc}	2588^{b}	4.63^{a}

Means in the same column with different letters are significantly different at $p<0.05$ level.

Chenopodiaceae and *Solanaceae*), the bio-cycling of P was vigorous and P was enriched in the root zone while for those plants with small aboveground biomass (*Gramineae*, *Rosaceae* and *Labiatae*), the bio-cycling of P was slow and P enrichment in the root zone soils could be neglected. The low soil P in soils under *Rosaceae* and *Labiatae* agreed with the result of Masse et al. (2004) that the growth of perennial grasses decreased soil P. Due to the significantly positive correlations between P_t and P_a (r = 0.889, $P<0.0001$), the changes of P_a with plants was consistent with that of P_t, that is, *Leguminosae* > *Chenopodiaceae*, *Solanaceae* and *Lilaceae* > *Compositae* > *Gramineae*, *Rosaceae* and *Labiatae*. Among these plants, *Lilaceae* gave the highest P_i in root zone soils, which was 682 mg kg^{-1}, while *Labiatae* and *Gramineae* yielded the lowest P_i with contents of 493 and 494 mg kg^{-1}, respectively. The content of P_i in root zone soils under *Compositae*, *Rosaceae*, *Solanaceae*, *Chenopodiaceae* and *Leguminosae* ranged from 517 to 648 mg kg^{-1}. Unlike P_i, the P_o was highest in soils in *Leguminosae* and lowest in *Solanaceae* and *Chenopodiaceae*. Due to the bio-enriching of soil P by plants, the P returned to soils with litterfall mainly in the organic forms (Joseph et al., 1993; Wang et al., 2008). Therefore, for the plants with large biomass and intensive element bio-enriching and cycling, P_o in root zone soils was higher. This explains our observation that soil P_o in root zone of *Leguminosae* was much higher than that of the other plants.

The effects of different plants on P in root zone soils is achieved by processes such as inorganic P uptake by plant roots, mineral P activation by soil microbes and root secretion, organic P mineralizing by phosphatase, inorganic P fractions redistribution by soil property changes, etc. (Zhang and MacKenzie, 1997; Waisel et al., 2002; Henríquez and Killorn, 2005). Because the transport of P in soil is slight, the processes of root uptake and activation mainly occur in the rhizosphere and contribute little to P distribution in the root zone of different plants (Frossard et al., 2000; Waisel et al., 2002). Therefore, the plant-induced P changes in root zone soils can be ascribed to the returning of plant residues and changes in plant tissue P concentration, which was also supported by the significant relations between tissue P concentration and P_t (r = 0.567, p=0.003), P_a (r = 0.536, p = 0.0057), P_i (r = 0.469, p = 0.018) and P_o (r = 0.456, p = 0.022) in root zone soils.

Effects on soil enzyme activities

Table 5 presents the soil enzyme activities in the root zone of different vegetation. In soil grown plants like *Leguminosae*, *Compositae* and *Solanaceae*, more litter was concentrated in the root zone due to their abundant above- and below- ground biomass. As a result, SOC and N_t were higher in root zone soils under such plants (Tables 2 and 3). Soil biochemical and biological processes were thus advanced, resulting in the increase of A.phos activity. On the contrary, less organic carbon and nitrogen in root zone of *Labiatae* and *Rosaceae* resulted in low A.phos activity. The lowest Invert activity was observed in the root zone of *Labiatae* and *Rosaceae*, while the highest one was found in soils under *Lilaceae* rather than in soils under *Leguminosae*, *Gramineae*, *Compositae* and *Solanaceae* where high alkaline phosphatase was observed. The highest Cat activity was found in the soils under *Lilaceae*, while the lowest was found in the soils bearing *Chenopodiaceae*. Moreover, the Cat activity was not significantly different in soils under other vegetations.

Plant roots and soil microbes release enzymes to soils during their metabolism, which mainly depends on vegetation types. Microbial communities of soils differ noticeably in their abundance and composition with plant species (Grayston et al., 1998; Bardgett et al., 1999), which will eventually affect the amount and types of enzymes released to soils. Besides, the decomposition of litter in soils beneath plant canopies will alter biological and biogeochemical processes in soils and will boost or restrain the activities of soil enzymes (Miki and Kondoh, 2002; Reich et al., 2005). Among these processes, the effects of root excretion mainly occur in soils several millimeters from the root surface and can hardly modify

Table 6. Correlation coefficients between soil enzymes and soil properties and nutrient conditions.

Soil enzyme	pH	CEC	SOC	LOC	MLOC	HLOC	N_t	N_o	N_n
A.phos	-0.754***	0.783***	0.921***	0.919***	0.938***	0.951***	0.896***	0.899***	0.383
Invertase	-0.639***	0.878***	0.916***	0.911***	0.935***	0.898***	0.919***	0.918***	0.521**
Catalase	-0.391*	0.440*	0.385	0.293	0.340	0.362	0.336	0.340	-0.03

	N_a	P_t	P_i	P_o	P_a	C/N	C/P	A.phos	Invertase
A.phos	0.679***	-0.001	-0.169	0.247	-0.109	0.055	0.908***		
Invertase	0.735***	0.224	0.048	0.386	0.007	-0.034	0.795***	0.894***	
Catalase	0.271	-0.266	-0.370	0.011	-0.424*	0.251	0.487*	0.347	0.373

CEC, Cation exchange capacity; SOC, soil organic carbon; LOC, labile organic carbon; MLOC, medium labile organic carbon; HLOC, high labile organic carbon; N_t, total nitrogen; N_o, organic nitrogen; N_n, nitrate nitrogen; N_a, ammonium nitrogen; P_t, total phosphorus; P_i, inorganic phosphorus; P_o, organic phosphorus; P_a, available phosphorus; C/N, organic carbon and nitrogen ratio; C/P, organic carbon and phosphorus ratio; A.phos, alkaline phosphatase.

the enzyme activities in the root zone. Therefore the difference of various enzyme activities in the root zone is dominated by plant induced litter decomposition and microbial community's difference that will rely on soil properties and nutrient conditions. This statement is also supported by the results of Ross (1966). He proved that variations in activity of soil enzymes could be explained by variations in soil organic carbon, and, in some cases, other factors associated with different soil groups. Hence, we analyzed the relationships between soil enzyme activities and soil properties and nutrient conditions to further illustrate the effects of plants on enzymes in root zone soils.

The activities of A.phos and Invert were significantly positively or negatively related to soil pH, CEC, soil organic carbon, N_t and C/P ratio (Table 6). These results may give evidence to the fact that the effects of plants on soil enzymes are mainly exerted through influencing soil properties and nutrient conditions. Nevertheless, Cat activity was only related with pH, CEC, P_a and C/P ratio due to its special characteristics in soils. A path analysis was conducted to separate the direct and indirect influences so as to further reveal the underlying relationship between the variables and enzyme activities and thus the effects of plants. Because significant positive interrelationship was observed among SOC, LOC, MLOC and HLOC (the correlation coefficients between SOC and LOC, MLOC, HLOC are 0.966, 0.979, and 0.964, respectively, $p<0.0001$) and between N_t and N_o (Table 4), pH, CEC, SOC, N_t, N_a and C/P ratio were chosen for the path analysis.

Due to the particular origins and functions of specific enzymes, the influencing patterns of soil properties and nutrients on enzyme activities varied with enzymes (Table 7), indicating that the influencing mechanisms of vegetation differed with enzymes. The direct pass coefficient between soil properties and A.phos showed that SOC contributed most to the A.phos activities, which agreed with the observation of higher A.phos activities in the soil with higher SOC in this experiment. Although CEC exerted a large negative direct influence on A.phos, the indirect pass coefficients of CEC passed through SOC was positive and high, which led to the significant positive association between CEC and A.phos activities. Soil pH posed negative direct effects and great negative indirect effects via SOC on A.phos and this indirect effect was much larger than those via other properties. As a result, pH showed significant negative correlation with A.phos. Although CEC and SOC were significantly positively related, the indirect effects of soil properties passed through CEC and SOC were opposite and the effects through SOC were stronger than that through CEC. So we concluded that SOC in the root zone soil not only exerts a direct influence on A.phos, but also exerts indirect influence via other soil properties, thus suggesting that the difference of A.phos in root zone is mainly dependent on the response of SOC to vegetation types.

Like the influence on A.phos, SOC also showed the highest positive direct pass coefficient to Invert activity (Table 7). However, N_t also gave large and positive direct effects and indirect effects on Invert through which other properties passed. Higher soil N can provide sufficient N for microbes and favor the decomposition of organic material in soil that increases Invert activities. Nevertheless, N_t had the largest indirect pass coefficient passed through SOC, indicating that the effect of N_t on Invert was also passed through SOC. On the other hand, C/P ratio had large negative direct and opposite indirect effects on Invert through which other properties passed, which may somewhat alleviate the direct effects posed by other soil properties.

In addition, the SOC exerted the largest negative direct influence on catalase activities, while CEC, N_t and C/P ratio exerted large positive direct influence (Table 7). Despite significant positive interrelations observed among soil organic carbon, N_t and CEC (Table 4), the influencing pattern of organic carbon on Cat was also opposite to CEC and N_t. Due to their interaction, SOC and N_t were not closely related with Cat. However, CEC and C/P ratio

Table 7. Path coefficients and correlation coefficient of soil properties and nutrients to soil enzyme activities.

Soil enzyme	Soil property	Direct path coefficient	Indirect path coefficient						Correlation coefficient
			Via pH	Via CEC	Via SOC	Via N_t	Via N_n	Via C/P	
Alkaline phosphatase	pH	-0.250		0.274	-0.610	-0.106	-0.051	-0.010	-0.754
	CEC	-0.461	0.148		0.844	0.156	0.086	0.010	0.783
	SOC	0.914	0.167	-0.425		0.169	0.084	0.012	0.921
	N_t	0.175	0.152	-0.410	0.886		0.083	0.011	0.896
	N_n	0.117	0.110	-0.337	0.657	0.124		0.008	0.679
	C/P	0.013	0.188	-0.358	0.844	0.148	0.072		0.908
Invertase	pH	-0.169		-0.006	-0.487	-0.190	-0.056	0.269	-0.639
	CEC	0.010	0.100		0.674	0.278	0.093	-0.277	0.878
	SOC	0.730	0.113	0.010		0.302	0.091	-0.329	0.916
	N_t	0.312	0.103	0.009	0.707		0.090	-0.302	0.919
	N_n	0.127	0.074	0.008	0.525	0.221		-0.219	0.735
	C/P	-0.356	0.127	0.008	0.674	0.264	0.078		0.795
Catalase	pH	0.198		-1.112	3.093	-0.777	0.036	-1.830	-0.391
	CEC	1.870	-0.118		-4.277	1.139	-0.061	1.886	0.440
	SOC	-4.632	-0.132	1.727		1.239	-0.060	2.244	0.385
	N_t	1.278	-0.120	1.666	-4.489		-0.059	2.060	0.336
	N_n	-0.083	-0.087	1.369	-3.329	0.908		1.494	0.271
	C/P	2.429	-0.149	1.452	-4.279	1.084	-0.051		0.487

CEC, cation exchange capacity; SOC, soil organic carbon; N_t, total nitrogen; N_n, nitrate nitrogen; C/P, organic carbon and phosphorus ratio.

had large indirect influences passed through N_t and C/P ratio and through CEC and N_t, respectively, which counteracted the negative effects of both properties through SOC and resulted in the significant positive relations with Cat. Consequently, Cat activity was mainly affected by SOC, CEC, C/P ratio and N_t and through which the effects of plants was exerted.

Relationship between plants and soil properties

Due to the large number of soil properties and the important correlation among them, principal component analysis was performed to simplify the interpretation of the entire dataset. The result of PCA showed that the eigenvectors of the first 3 principal component together explained 86.4% (>85%) of total covariance (Table 8). The first principal component was composed of CEC, SOC and three labile carbon fractions, N_t, A.phos, and Invert. The second principal component was composed of P_t, P_a and P_i. The third principal component was composed of Cat. In the first component, SOC was closely related with LOC, MLOC and HLOC, therefore, SOC and CEC can be used to interpret the changes in soil physico-chemical properties. Besides, SOC is also significantly related with N_t, N_n and N_a, hence SOC can also explain the changes in soil N nutrition. In the second component, P_t was used to indicate soil P nutrition because it was significantly related with P_a and P_i. The A.phos and Invert were also closely related and were all included in the first component, however, Cat was included in the third component, therefore A.phos and Cat could be used to indicate soil biological properties. Together, CEC, SOC, P_t, A.phos and Cat can be used to indicate soil physico-chemical, nutritional and biological properties, and were chosen for the correspondence analysis to further reveal the relationship between plants and soil properties.

Correspondence analysis is a statistical visualization method for picturing the associations between the levels of a two-way contingency table. Correspondence analysis is a geometric technique for displaying the rows and columns of a two-way contingency table as points in a low-dimensional space, such that the positions of the row and column points are consistent with their associations in the table. The goal is to have a global view of the data that is useful for interpretation (Benzecri, 1992). The results of correspondence analysis between soil properties and plants are presented in Figure 2. It clearly show that *Leguminosae*, *Gramineae*, *Compositae*, *Solanaceae*, *Chenopodiaceae* and *Lilaceae* contained similar information with that of SOC, P_t and A.phos, suggesting that the six families influence soil properties in a similar way and should be classified into the same group when studying soil plant relationships. This is consistent with our observation that most soil properties were higher in

Table 8. Results of principal component analysis among soil properties.

Analysis item	First component	Second component	Third component
Cumulative proportion of covariance (%)	59.55	81.30	86.39
pH	-0.24	0.22	0.13
CEC	0.31	0.08	0.25
SOC	0.33	0.00	0.01
LOC	0.32	-0.03	-0.17
MLOC	0.33	-0.02	-0.10
HLOC	0.32	-0.01	-0.07
N_t	0.32	0.05	0.02
N_n	0.16	0.26	-0.24
N_a	0.26	0.04	0.10
P_t	0.07	0.52	0.22
P_a	0.02	0.51	0.01
P_i	-0.01	0.51	0.18
Alkaline phosphatase.	0.31	-0.09	-0.19
Invertase	0.32	0.02	0.00
Catalase	0.14	-0.27	0.83

CEC, cation exchange capacity; SOC, soil organic carbon; LOC, labile organic carbon; MLOC, medium labile organic carbon; HLOC, high labile organic carbon; N_t, total nitrogen; N_n, nitrate nitrogen; N_a, ammonium nitrogen; P_t, total phosphorus; P_a, available phosphorus; P_i, inorganic phosphorus.

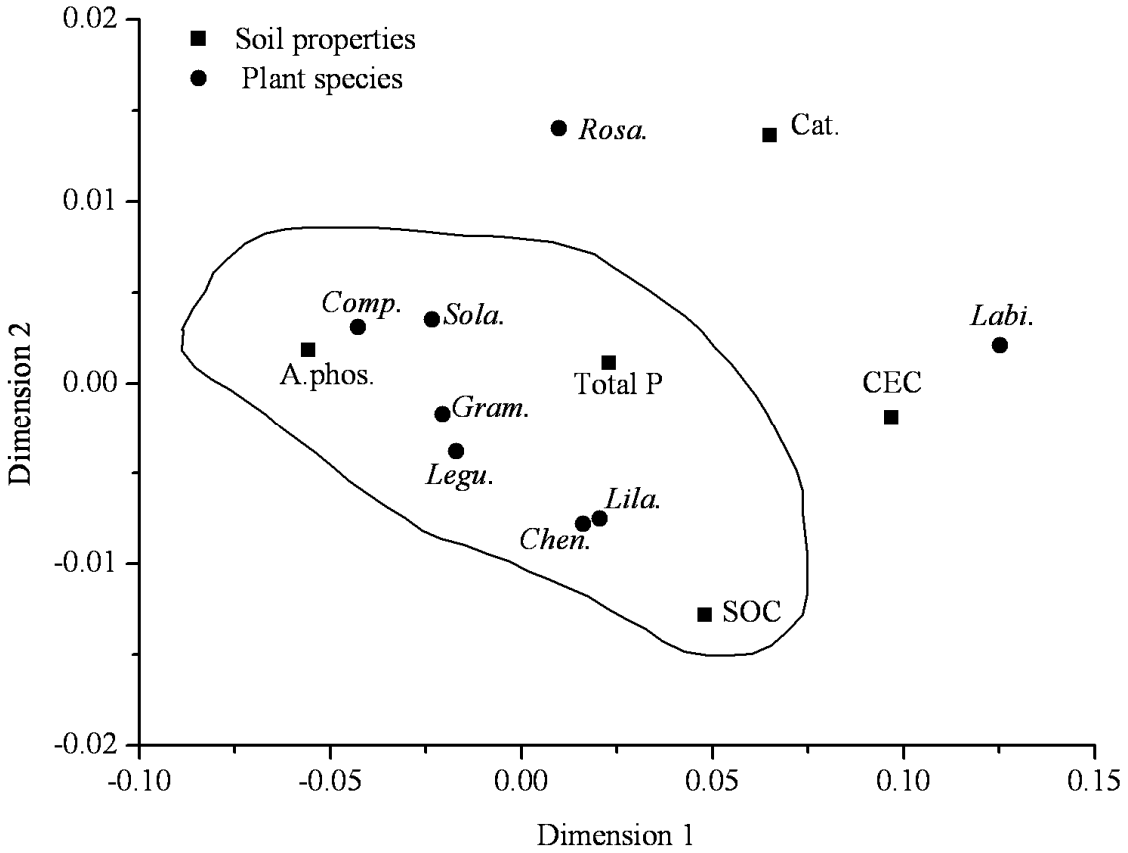

Figure 2. Correspondence analysis between vegetation and soil properties. CEC, cation exchange capacity; SOC, soil organic carbon; Cat, catalase; A.phos: alkaline phosphatase; *Chen.*, *Chenopodiaceae*; *Comp.*, *Compositae*; *Gram., Gramineae*; *Labi.*, *Labiatae*; *Legu.*, *Leguminosae*; *Lila.*, *Lilaceae*; *Rosa.*, *Rosaceae*; *Sola.*, *Solanaceae*.

soils under most of these plants. Due to the slight influence on soil properties, the information contained in *Labiatae* and *Rosaceae* did not overlap with soil properties as implied in Figure 2. Moreover, the position of CEC and Cat in Figure 2 is far away from the area where SOC, P_t and A.phos were focused, indicating that CEC and catalase can partly illustrate the changes in soil properties. The results in Figure 2 further indicate that the combination of SOC, P_t and A.phos can represent the physico-chemical, nutritional and biological properties. All these relationships provide evidence for the statement that plants affect soil properties mainly through influencing SOC in our experiment.

Conclusion

The effects of plants on soil properties in root zone were plant- and soil-property dependent. The CEC, SOC, LOC, MLOC, HLOC, N_t, A.phos and Invert were all higher in soil under *Lilaceae*, *Leguminosae*, *Gramineae*, *Compositae*, *Solanaceae* and *Chenopodiaceae* than soils under *Labiatae* and *Rosaceae*. The P_t, P_i and P_a were all higher in soil under *Lilaceae*, *Leguminosae*, *Solanaceae* and *Chenopodiaceae* than soils under *Gramineae*, *Labiatae* and *Rosaceae*. The combination of SOC, P_t and A.phos can represent the physico-chemical, nutritional and biological properties and could be used to assess changes of soil properties induced by different plants. In general, *Leguminosae*, *Gramineae*, *Compositae*, *Solanaceae*, *Chenopodiaceae* and *Lilaceae* show a similar pattern in influencing soil properties. The SOC presents significant direct and indirect influences on soil nutritional and biological properties. Therefore, the influence of plants on soil properties is mainly exerted through influencing SOC. *Leguminosae* and *Lilaceae* helped the improvement of soil properties, while *Labiatae* and *Rosaceae* show the opposite potential on soil properties in the Loess Plateau.

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