Dissimilation of soil humus in forest with pure stands and its relationship with other bio-chemical properties in the semi-arid windy region of the Loess Plateau, China

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Abstract. Dissimilation of soil humus in 7 typical forests with pure stands in the semi-arid windy region of the Loess Plateau in China was investigated. In addition, its relationships with other bio-chemical characteristics were assessed by canonical correlation analysis. The results was as follows: (1) *Pinus tabulaeformis* Carrière forest had the lowest humus content and the worst stability among 7 forests with pure stands; *Populus simonii* Carrière forest had low humus content and worse stability; *Robinia pseudoacacia* L. forest had moderate humus content but the best stability; *Salix matsudana* Koidz. forest had moderate humus content and bad stability; *Hippophae rhamnoides* L. forest had high humus content and the best stability; *Caragana microphylla* Lam. forest had high humus content and moderate stability; *Amorpha fruticosa* L. forest had the highest humus content and benign stability; (2) Large microbial biomass and sufficient available P would accelerate the formation of humic acid and fulvic acid, respectively. High available N, P and Fe contents and high urease and protease activity were conducive to increase the humus stability. The particularity of community environment and litter properties of pure stands were identified as the key reasons for the humus dissimilation, thus mixed-reformation or establishing ground vegetation would be feasible ways to improve humus properties in forest with pure stands.

Keywords: dissimilation of soil humus, forest with pure stands, bio-chemical properties.

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Introduction

Sporadic distributed forests with pure stands contribute greatly to the soil and water conservation and environmental protection in the semi-arid windy region of the Loess Plateau in China (Liu *et al.*, 2009). However, the soil degradation in

these forests is serious now. Humus is an essential component of soil organic matter and plays important role in the formation of soil structure, maintenance of soil moisture and temperature and the regulation of nutrients supplement, particularly for the forests in severe natural environment in the semi-arid windy region. However,

because of its particularity of community environment and litter properties, forest with pure stand risks a great possibility of soil humus dissimilation. Meanwhile, the long-time growth of pure stands will certainly affect soil microorganisms, enzymes and nutrients (Dou, 2008; Dou & Wang, 2011; Yu *et al.*, 2011), which consequently have an influence on the formation of soil humus components and their transformation. In this point of view, investigating the dissimilation of soil humus and its relationship with other soil properties are necessary to deeply analyze the mechanisms of soil degradation, and provide feasible ways for soil remediation of forest with pure stands.

In recent years, the detailed classification of humus components, humus accumulation and transformation during vegetation restoration, and biological and non-biological factors (such as geographical conditions, climate, soil, vegetation, litter quality and physical properties of environment) which affect the above processes, were investigated extensively (Wardle *et al.*, 2008; Descheemaeker *et al.*, 2009; Podrázský *et al.*, 2009). Some emerging analytical test methods were also introduced in these studies, such as pyrolysis gas chromatography technique and partial linear gradient analysis (Ponge *et al.*, 2011; Andreetta *et al.*, 2013). However, there are few studies focused on the soil humus of forests with pure stands in the semi-arid windy desert region, and rarely analyzed the overall relationship between soil humus and other biological and chemical properties. Thus, soils from 7 common natural or artificial forests with pure stands were taken as objects in this study, the dissimilation properties were analyzed according to the measurements of soil humus and other biological and chemical properties, and canonical correlation analysis was employed to study the overall relationship between them. The results may provide a scientific basis for the final-period management of forest with pure stands in this area.

Material and Methods

The study area

The forests with pure stands which were studied in this research locate in the Wan-Mu Forest Farm in Jingbian County of Shaanxi Province, China (108°53'–108°56'E, 37°38'–37°63'N), belong to the semi-arid windy region, and has an annual precipitation of 316–450 mm, an annual evaporation of 1127–1546 mm, an annual average temperature of 7.8–9.1 °C, an annual accumulated temperature (≥ 10 °C) of 2600–3370 °C, and a frost-free season of 134–172 days. Soil here was classified as Entisols in the USDA Soil Taxonomy system (United States Department of Agriculture, 1999). The vegetation is typical steppe with sporadic distributed forests, and the dominant species are *Pinus tabulaeformis* Carrière, *Populus simonii* Carrière, *Salix matsudana* Koidz., *Robinia pseudoacacia* L., *Hippophae rhamnoides* L., *Caragana microphylla* Lam. and *Amorpha fruticosa* L. The main ground vegetation is *Artemisia desterorum* Spreng, *Periploca sepium* Bunge, *Setaria viridis* (L.) P.Beauv., *Lespedeza bicolor* Turcz., *Artemisia capillaries* Thunb. and *Astragalus melilotoides* Pall. The total ground vegetation coverage under forests with pure stands is generally less than 11.19%.

Sampling of soil and leaf litter

Seven typical mature forests which had similar sites conditions (at middle or lower location on the north-facing slopes with slopes about 20–30°, and sandy loam soil) were chosen (Table 1). Ages of all the forests were over 25 years, and trees were uniformly distributed in them. The density of canopy was over 0.70. In each forest, three standard plots with a size of 20 m × 20 m were established and all tree individuals were measured to obtain the average stand growth status. Within each plot, 5 quadrats with a size of 1 m × 1 m were established, and humus soil was collected from layer 0–20 cm in each quadrat and mixed after removing the plant litter, roots, and

Table 1. Growth of plantation and litter properties of different forest with pure stands. Different letters after data in the same column indicate significant differences among forests of different species ($p < 0.05$), the same below.

Tree species	Growth of plantation				Litter properties				
	Age (a)	DBH/GD (cm)	Height (m)	Litter accumu- lation (t hm ⁻²)	N Content (g kg ⁻¹)	P Content (g kg ⁻¹)	Mn Content (mg kg ⁻¹)	C/N	C/P
<i>Pinus tabuliformis</i>	31	14.35	6.6	0.05	9.79 ^e	0.49 ^e	42.24 ^e	29.15 ^a	579.03 ^a
<i>Populus simonii</i>	23	12.07	6.1	0.08	23.64 ^d	1.41 ^b	229.91 ^a	8.95 ^b	149.79 ^c
<i>Robinia pseudoacacia</i>	22	15.59	6.3	0.49	24.03 ^d	1.08 ^c	208.79 ^b	9.81 ^b	218.24 ^b
<i>Salix matsudana</i>	35	55.18	10.5	0.05	22.42 ^d	1.11 ^c	155.78 ^c	9.57 ^b	193.5 ^b
<i>Hippophae rhamnoides</i>	21	9.57	4.0	0.11	31.87 ^c	1.19 ^c	136.09 ^c	7.33 ^c	198.72 ^b
<i>Caragana microphylla</i>	21	9.24	3.8	0.09	36.75 ^b	1.11 ^c	96.29 ^d	6.27 ^c	222.89 ^b
<i>Amorpha fruticosa</i>	20	9.83	4.4	0.35	43.48 ^a	2.61 ^a	59.55 ^e	5.73 ^c	95.59 ^d

stones. Homogenized soils from different quadrats were mixed again and 3 kg soil was sampled from the mixture using the quarter method. That is, a twice-mixed soil sample was gathered from each plot, and totally 3 samples were collected from each forest with pure stands. Meanwhile, current year fallen leaf litters were collected to measure its properties (Table 1).

Measurements of soil and litter properties

Following methods were used to measure the properties of soil and leaf litter (Nanjing Institute of Soil Science, CAS, 1985; Guan, 1989; Bao, 2000):

For soil samples, humic acid, fulvic acid and humin contents were measured by $K_2Cr_2O_7$ oxidation method, pH by glass electrode method (water:soil = 2.5:1), available N content was measured by alkaline hydrolysis diffusion method, available P by a UV-VIS spectrophotometer, available K by a flame photometer, available Cu, Zn, Fe, Mn by an atomic absorption spectrophotometer. Urease activity was measured by the indophenol blue method, sucrose by $Na_2S_2O_3$ titrimetric method, peroxidase by $KMnO_4$ titrimetric method, dehydroge-

nases by TTC colorimetric method, phosphatase by disodium phenyl phosphate colorimetric method and proteases by the ninhydrin colorimetric method. Microbial biomass C was measured by CH_3Cl fumigation- K_2SO_4 extraction method.

For litter samples, C content was measured by titrimetry method, N by a Kjeldahl apparatus, P, K, and Mn were measured by the same instruments as soil. Every parameter was measured from 3 replicates.

Data processing

Average value of every parameter was obtained by the measured values from 3 plots, SPSS 19.0 software was employed for a one-way ANOVA analysis to test the significance of differences between soils ($p < 0.05$), in which LSD method was used for *post hoc* analysis. Furthermore, canonical correlation analysis was employed to investigate the overall relationships between humus and other biological and chemical properties. Origin Pro 8.50 was used for drafting.

Results

Dissimilation characteristics of soil humus from different forest with pure stands

Soil humus from 7 long-time grown forests with pure stands showed significant dissimilation (Figure 1). Among them, *H. rhamnoides* forest soil exhibited the highest content of humic acid (HA, 1.52 g kg⁻¹), followed by *R. pseudoacacia*, *C. microphylla*, *A. fruticosa*, *P. simonii* and *Salix matsudana* forests soil (0.78–1.27 g kg⁻¹), *P. tabuliformis* forest soil had the lowest HA content (0.61 g kg⁻¹). *A. fruticosa* forest soil exhibited the highest content of fulvic acid (FA, 2.53 g kg⁻¹), followed by *R. pseudoacacia*, *H. rhamnoides*, *C. microphylla*, *P. simonii* forests soil (1.86–2.35 g kg⁻¹), while *P. tabuliformis* and *S. matsudana* forests soil exhibited the lowest FA content (1.35–1.54 g kg⁻¹). *A. fruticosa* forest showed the highest content of humin (HM, 5.01 g kg⁻¹), followed by *P. simonii*, *C. microphylla*, *R. pseudoacacia*, *S. matsudana*

and *H. rhamnoides* forests soil (3.19–4.42 g kg⁻¹), while *P. tabuliformis* forest soil had the lowest content of HM (2.58 g kg⁻¹).

Relative to fluvic acid, humic acid showed higher aromatization and condensation degree, the ratio of HA/FA and humification degree ($Q_p = \text{HA}/\text{humus}$) thus were used as representations of humus quality property. Higher HA/FA and Q_p indicated higher stability of humus. Variance analysis indicated that the HA/FA of soil from *H. rhamnoides* forest was significantly higher than the other soils (0.67), followed by soils from *R. pseudoacacia*, *S. matsudana* and *C. microphylla* forests (0.55–0.58), while *P. simonii*, *A. fruticosa* and *P. tabuliformis* forests soil exhibited the lowest HA/FA (0.39–0.47). The Q_p of soils from *R. pseudoacacia* and *H. rhamnoides* forests were the highest (0.19–0.21), while that of the other soils had no significant differences, however, *P. simonii* forest soil exhibited the lowest Q_p (0.12).

Figure 1. Humus properties of soil from 7 forest with pure stands. Note: *P.t* – *Pinus tabuliformis*, *P.s* – *Populus simonii*, *R.p* – *Robinia pseudoacacia*, *S.m* – *Salix matsudana*, *H.r* – *Hippophae rhamnoides*, *C.m* – *Caragana microphylla*, *A.f* – *Amorpha fruticosa*. HA – humic acid, FA – fulvic acid, HM – humin.

Table 2. Chemical properties of soils from 7 forests with pure stands.

Species	pH	Available N (g kg ⁻¹)	Available P (g kg ⁻¹)	Available K (g kg ⁻¹)	Available Cu (mg kg ⁻¹)	Available Zn (mg kg ⁻¹)	Available Fe (mg kg ⁻¹)	Available Mn (mg kg ⁻¹)
<i>Pinus tabuliformis</i>	8.29 ^a	46.73 ^d	2.23 ^{bc}	67.23 ^f	0.39 ^c	1.69 ^d	6.27 ^{de}	11.09 ^d
<i>Populus simonii</i>	8.13 ^a	54.42 ^c	1.79 ^c	115.68 ^b	0.81 ^a	2.61 ^{ab}	12.41 ^c	20.42 ^b
<i>Robinia pseudoacacia</i>	8.12 ^a	57.42 ^b	2.18 ^{bc}	95.69 ^d	0.53 ^b	1.15 ^e	4.65 ^f	10.63 ^d
<i>Salix matsudana</i>	8.27 ^a	55.30 ^b	4.55 ^a	153.68 ^a	0.66 ^b	1.66 ^d	7.46 ^d	12.33 ^c
<i>Hippophae rhamnoides</i>	8.14 ^a	56.62 ^b	2.56 ^b	75.20 ^e	0.80 ^a	2.98 ^a	15.28 ^b	23.30 ^a
<i>Caragana microphylla</i>	8.12 ^a	53.94 ^c	1.32 ^d	106.44 ^c	0.35 ^c	2.02 ^{cd}	5.23 ^e	10.67 ^d
<i>Amorpha fruticosa</i>	8.38 ^a	74.33 ^a	4.93 ^a	118.85 ^b	0.37 ^c	2.29 ^{bc}	31.31 ^a	10.18 ^d

Table 3. Enzyme activity and microorganism properties of soil from 7 forests with pure stands.

Species	Urease (mg kg ⁻¹)	Sucrase (ml g ⁻¹)	Catalase (ml g ⁻¹)	Peroxidase (ml kg ⁻¹)	Dehydrogenase (μg g ⁻¹)	Phosphatase (mg kg ⁻¹)	Protease (mg g ⁻¹)	Microbial biomass C (mg kg ⁻¹)
<i>Pinus tabuliformis</i>	15.70 ^d	2.35 ^b	2.09 ^b	1.99 ^d	177.96 ^b	0.23 ^b	0.24 ^b	16.34 ^d
<i>Populus simonii</i>	28.82 ^c	2.54 ^b	2.07 ^b	3.50 ^b	159.94 ^c	0.17 ^c	0.17 ^c	24.01 ^c
<i>Robinia pseudoacacia</i>	36.92 ^a	1.60 ^{cd}	2.13 ^b	4.48 ^a	175.74 ^b	0.16 ^e	0.18 ^c	23.05 ^c
<i>Salix matsudana</i>	32.29 ^{bc}	4.62 ^a	2.01 ^c	2.33 ^{cd}	272.57 ^a	0.28 ^a	0.14 ^d	15.42 ^d
<i>Hippophae rhamnoides</i>	36.44 ^a	1.82 ^c	2.12 ^b	2.49 ^c	177.05 ^b	0.18 ^c	0.11 ^d	27.71 ^b
<i>Caragana microphylla</i>	35.57 ^b	1.36 ^d	2.16 ^b	2.49 ^c	179.15 ^b	0.22 ^b	0.27 ^a	25.41 ^{bc}
<i>Amorpha fruticosa</i>	38.72 ^a	1.24 ^e	2.31 ^a	1.00 ^e	188.26 ^b	0.15 ^e	0.21 ^b	29.33 ^a

Soil biological and chemical properties of different forest with pure stands

The chemical and biological properties (except for pH) of soils from 7 forests with pure stands showed significant dissimilation. In chemical properties (Table 2), *A. fruticosa* forest soil had the highest available N content, while *P. tabuliformis* forest soil had the lowest. *S. matsudana* and *A. fruticosa* forests soil exhibited the highest available P contents, while *C. microphylla* forest soil had the lowest. Available K content was highest in the soil of *S. matsudana* forest and was least in *P. tabuliformis* forest soil. Soils from *P. simonii* and *H. rhamnoides* forests exhibited the highest available Cu contents, while those from *C. microphylla*, *A. fruticosa* and *P. tabuliformis* forests had the lowest. *H. rhamnoides* forest soil had the highest available Zn content, while *R. pseudoacacia* forest soil had the lowest. Soil from

A. fruticosa forest was found to be richest in available Fe, while that from *R. pseudoacacia* forest was poorest. *H. rhamnoides* forest soil exhibited the highest available Mn content, while *P. tabuliformis*, *R. pseudoacacia*, *C. microphylla* and *A. fruticosa* forests soil contained the lowest.

In biological properties (Table 3), *R. pseudoacacia*, *H. rhamnoides* and *A. fruticosa* forests soil exhibited the highest urease activity, whereas *P. tabuliformis* forest soil showed the lowest. *S. matsudana* forest soil had the highest sucrase activity, while *A. fruticosa* forest soil had the lowest. *A. fruticosa* forest soil had the highest catalase activity, while *S. matsudana* forest soil showed the lowest. *R. pseudoacacia* forest soil showed the highest peroxidase activity, while *A. fruticosa* forest soil showed the lowest. The dehydrogenase activity was highest in *S. matsudana* forest soil but was

Table 4. Canonical correlation coefficients and their significance test.

Canonical vector No.	Canonical correlation coefficients	Wilk's Lambda	Chi-square Test χ^2	df	p
1	1.000	0.000	452.981	80	0.000**
2	0.999	0.000	150.170	60	0.000**
3	0.997	0.000	90.939	42	0.000**
4	0.989	0.006	46.031	12	0.009**
5	0.851	0.275	11.611	12	0.477

least in *P. simonii* forest soil. *S. matsudana* forest showed the highest soil phosphatase activity while *R. pseudoacacia* and *A. fruticosa* forests showed the lowest. *C. microphylla* forest exhibited the highest soil protease activity, while *H. rhamnoides* forest showed the lowest. *A. fruticosa* forest soil had the highest microbial biomass C content, while *P. tabuliformis* and *S. matsudana* forests soil had the lowest.

Canonical correlation analysis of humus and other biological and chemical properties

Data from 21 plots of 7 forests with pure stands were divided into 2 groups: *U* stands for the integrated soil nutrients and biological properties (Tables 2 and 3) and *V* stands for the integrated soil humus properties (Figure 1), and canonical correlation analysis was employed to analyze the correlations between groups. In the results (Table 4, equations 1–8), variables that had greater coefficients (absolute value) in each group indicated the main factors of this canonical variable group. Variables with the same signs in U_i and V_i had positive correlations, whereas those with different signs indicated negative. The results showed that, in the integrated soil nutrients and biological properties groups (U_1 – U_4), available N, P, Fe and Mn contents of soil (X_2 , X_3 , X_7 and X_8 , respectively), urease and protease activities (X_9 and X_{15}) and microbial biomass C content (X_{16}) were the main factors, while the contents of humic acid and fulvic acid (Y_1 and Y_2), and HA/FA and the humification degree Q_p (Y_4 and

Y_5) were the main factors in the integrated humus properties groups (V_1 – V_4).

Canonical correlation analysis showed that, microbial biomass C and available Fe contents had positive correlations with humic acid content, which meant these 2 factors were beneficial to the formation of humic acid. Available P content had positive correlations with fulvic acid content and HA/FA, and it was beneficial to the formation of fulvic acid and the humus stability. Available N had a positive correlation with Q_p , so did available Fe content and activity of urease and proteinase, showing that these factors would also improve the stability of humus.

$$U_1 = -0.169X_1 + 0.951X_2 - 0.337X_3 + 0.681X_4 + 0.575X_5 - 0.355X_6 - 0.216X_7 + 1.453X_8 + 0.77X_9 - 0.656X_{10} - 0.049X_{11} - 0.377X_{12} + 0.227X_{13} + 0.006X_{14} + 1.043X_{15} - 2.035X_{16} \quad (1)$$

$$V_1 = -2.385Y_1 + 0.069Y_2 + 0.585Y_3 + 0.467Y_4 + 1.238Y_5 \quad (2)$$

$$U_2 = 0.228X_1 - 0.958X_2 + 3.647X_3 + 1.712X_4 - 1.255X_5 + 1.416X_6 - 3.173X_7 - 1.359X_8 - 2.191X_9 - 1.454X_{10} - 0.431X_{11} + 0.163X_{12} - 1.451X_{13} - 0.686X_{14} - 1.726X_{15} + 1.493X_{16} \quad (3)$$

$$V_2 = -2.385Y_1 + 0.069Y_2 + 0.585Y_3 + 0.467Y_4 + 1.238Y_5 \quad (4)$$

$$U_3 = -0.536X_1 + 1.991X_2 - 2.651X_3 - 0.732X_4 + 1.485X_5 - 1.005X_6 + 2.452X_7 + 1.489X_8 + 2.898X_9 + 1.034X_{10} + 0.039X_{11} - 0.160X_{12} + 0.585X_{13} - 0.461X_{14} + 2.782X_{15} - 3.292X_{16} \quad (5)$$

$$V_3 = -2.536Y_1 - 0.945Y_2 + 2.853Y_3 - 2.887Y_4 + 5.152Y_5 \quad (6)$$

$$U_4 = 0.194X_1 - 0.423X_2 - 1.336X_3 + 0.866X_4 + 0.049X_5 - 0.703X_6 + 1.487X_7 + 0.289X_8 - 0.880X_9 + 0.005X_{10} + 0.298X_{11} - 0.012X_{12} + 0.538X_{13} + 0.830X_{14} - 0.001X_{15} + 1.352X_{16} \quad (7)$$

$$V_4 = 2.039Y_1 - 1.707Y_2 + 0.898Y_3 - 0.547Y_4 - 0.758Y_5 \quad (8)$$

Discussion and conclusions

Dissimilation of soil humus from 7 forests with pure stands

Our results showed that humus of soils from 7 forests with pure stands had significant dissimilation in terms of its content and composition, which were agreed with the previous findings (Li *et al.*, 1992; He, 2002). This may be caused by the differences in the litter mass and quality of different forests. Trap *et al.* (2013) studied the dissimilation of *Humus Index* (Ponge *et al.*, 2002) using partial least squares regression method, and indicated the litter substrate quality contributed to it greatly. Research of Descheemaeker *et al.* (2009) demonstrated that litter quality was the main factor affecting the humus formation. Among numerous litter quality indicators, contents of N and P, and ratios of C/N and C/P were most frequently used. In 7 kinds of litter, litter from *H. rhamnoides*, *C. microphylla* and *A. fruticosa* had high N and P contents, low C/N and C/P ratios, and large masses (Table 1), thus they formed humus with large contents and high humification degree. In contrast, litter from *P. tabulaeformis* had the lowest N and P contents, the highest C/N and C/P ra-

tios and low mass, thus it formed less and unstable humus, which was agreed with the findings of Trap *et al.* (2013) and Descheemaeker *et al.* (2009). Organisms need to immobilize a large amount of N and P for their physiological needs when decomposing litters. Litter with low substrate quality could not supply enough nutrients source to accelerate the microbial activity, and it consequently reduced the production of intermediates that were necessary (such as quinones and amino acids) for the formation of humus. This would of course cause lower accumulations of humus and influenced their stability.

However, even having low substrate quality, litter of *R. pseudoacacia* still formed humus with high quantity and stability, while litter of *P. simonii*, which exhibited higher substrate quality, only formed low quantity of humus with worse stability, this phenomenon was against with the findings of Trap *et al.* (2013). These results may be caused by many factors. Firstly, the accumulation of litter would influence the humus quantity. Secondly, contents of given nutrient element showed complex impacts on litter decomposition and humus accumulation. For instance, according to previous research (Prescott, 2010), high N content was benefit for the humification, because N might combine with lignin and polyphenols and became recalcitrant materials, and inhibited activity of decomposition enzymes in the later period of decomposition. However, in the early period of litter decomposition, high content of N in litter would promote decomposition by stimulating microbe activity. Thirdly, though some recalcitrant matters such as lignin, cellulose and polyphenols, that with lower quality, were difficult to decompose and utilized by microbes, they were important in humus formation. Review of Dou & Wang (2011) and Hattenschwiler & Jorgensen (2010) indicated that low-molecular or easily decomposed matters such as sugars and starches, were hardly involved in humification, while lignin and polyph-

nols were considered as the main sources of humus. Finally, for the differences of growth period and biological characteristics of tree species, they had different demands for nutrients (Podrázský *et al.*, 2009; Liu, 2009). Previous studies illustrated that forest at fast-growing stage usually led to a decrease of available nutrients in soil, and consequently inhibited the activity of decomposers. This would further inhibit organic matters decomposition, and thus affected the formation of humus precursors (Trap *et al.*, 2013).

Impacts of soil biological and chemical properties on humus dissimilation characteristics

Our results indicated that the increase of available N content could promote the humification degree, while increase of available P accelerated fulvic acid formation, which was similar to the findings of Ma *et al.* (2013) and Dang *et al.* (2012). Since increase of N and P would accelerate the growth of microbes and their activity, and provided N sources for humus formation. Meanwhile, available Mn had negative correlation with humic acid. Mn was the core component of Mn-peroxidase, and thus its content greatly influenced the decomposition of lignin, and consequently affected the formation and transformation of humus (Trap *et al.*, 2013). Humus from *P. simonii* forest had low contents and humification degree, those might be caused by the high content of Mn in the litter and forest soil. On contrary, high content of soil available Fe was conducive to the formation of humic acid. This indicated that Fe might be a component or activator of enzymes, but further research is needed to understand the specific mechanism.

Quantity and activity of microbes influenced the formation and transformation of humus, since organic matters entered into soil are decomposed by bacteria and fungi to provide precursors of humus, and various enzymes play important role in this process (Yan, 1997). For the differ-

ences in biological properties of tree species, the long-time growth of pure stands would lead to alterations of microbe characteristics. Simultaneously, the variety of enzymes and their activities are changed due to the differences in the enzymes released from roots and the alteration of microflora, and it consequently affected humus dissimilation. For example, the white-rot fungus prefers to decompose lignin completely, while the brown-rot fungi are more suitable for forming humus (Berg & McClaugherty, 2008). Both of *Trichoderma* spp. and *Streptomyces griseofuscus* were conducive to humus formation, however, the former prefers to form humic acid, while the latter prefers to form fulvic acid (Guan & Dou, 2006).

Our results indicated that the increase of microorganism was conducive to humus formation, and the increase of protease and urease activity was conducive to humification, which were agreed with the results of Yan (1997) and Yu *et al.*'s (2011). It suggested that nitrogen deficiency might be one of the key factors limiting humification process in this area. After long-time growth, the urease activity of soil from *R. pseudoacacia* forest (36.92 mg kg⁻¹) was relatively higher than that from other forests (Table 2), while the protease and urease activities of soil from *P. simonii* forest were relatively lower than that from other forests (28.82 mg kg⁻¹ and 0.17 mg g⁻¹, respectively). These could explain why the humus from *R. pseudoacacia* forest had higher humus contents and stability, whereas that from *P. simonii* forest had low content and worse stability. Under the conditions of this study, we had not find significant correlations of soil humus contents and components properties with peroxidase, catalase, sucrose, dehydrogenase and phosphatase, which was not agreed with the results of Yan (1997) and Yu *et al.*'s (2011). There would be 2 reasons for this: firstly, enzyme activity was affected by soil nutrients and their combination with humus, *etc.* (Tabatabai *et al.*, 2002), and their

connections with humus could not be detected directly. Secondly, some substances essential for microbes and plants were recycled in bio-systems, and they were rarely involved in humus formation, thus the related enzymes did not show significant correlations with humus properties.

In conclusion, differences in litter quality and soil biological and chemical properties polarizations caused by long-time growth of pure stands were the key factors leading to soil humus dissimilation. Reforming forest with pure stands by mixed-forestation or establishing ground vegetation (under-planting grasses and shrubs) could increase the chemical diversity of litter and stimulate their decomposition and transformation (Yang *et al.*, 1996), which were benefit to form better humus. In short-term management, increasing nitrogen and phosphorus application would be advisable to improve the condition of humus formation rapidly.

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