Research paper

Nutrient Release during Single and Mixed Leaf Litter Decomposition from *Larix principis-rupprechtii* and Other Tree Species on the Loess Plateau, China

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【Summary】

Current-year leaf litter from *Larix principis-rupprechtii* and 10 other tree species planned for a mixed forest was collected on the Loess Plateau of China and placed in nylon mesh litterbags singly or mixed according to set ratios and then buried in humus soil from a tree-free waste grassland for a 345-d incubation under constant temperature (20~25℃) and humidity (50% of the field water capacity). Results showed that during decomposition, macro-elements were generally more easily released than micro-elements. Release rates of most elements had no significant relationships with their own initial contents in the litter except for C and N, for which C had a negative correlation and N had a positive correlation. According to the comprehensive impacts of all 10 elements released during mixed litter decomposition with *L. principis-rupprechtii*, *Ulmus pumila* and *Pinus tabulaeformis* obviously accelerated nutrient release, followed by *Betula platyphylla*; *Platycladus orientalis* and *Robinia pseudoacacia* obviously inhibited nutrient release, followed by *Populus simonii*. In conclusion, those tree species that accelerate nutrient release during mixed litter decomposition should be given a higher priority for selection for mixed-forestation with *L. principis-rupprechtii*.

Key words: the Loess Plateau, *Larix principis-rupprechtii*, leaf litter decomposition, nutrient release.

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研究報告

黃土高原落葉松及其他樹種枯落葉單獨與混合分解過程中的養分釋放

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摘　要

以黃土高原主要造林樹種落葉松(*Larix principis-rupprechtii*)及其他擬混雜的10個樹種為對象，採集當年枯落葉并以無林荒草地腐殖質層土壤作為分解介質，在室內將落葉松與其他樹種枯落葉單獨或以一定比例混合後裝入尼龍網袋並埋入盛土培養缽中，進行恒溫(20~25℃)恒濕(50%田間持水量)下連續345 d分解培養試驗。結果表明：枯落葉單獨分解時，大量元素整體上較微量元素容易釋出。除C和N外，其他元素釋出速率與其初始含量無顯著相關關係(C為負相關，N正相關)。根據綜合主成分分析表明，與落葉松枯落葉混合分解總體上明顯促進養分釋放的樹種為白榆(*Ulmus pumila*)和油松(*Pinus tabulaeformis*)，其次為白樺(*Betula platyphylla*)；總體上明顯抑制養分釋放的樹種為側柏(*Platycladus orientalis*)和刺槐(*Robinia pseudoacacia*)，其次為小葉楊(*Populus simonii*)。能夠促進枯落葉養分釋放的樹種將是選擇與落葉松混雜樹種時首先考慮的物種。

關鍵詞：黃土高原、落葉松、枯落葉分解、養分釋放。

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INTRODUCTION

Many problems such as retarded growth, degradation of soil properties, and difficult regeneration have been observed in the continuous management of planted forests on the Loess Plateau of China. The cause of these phenomena in monospecific-dominant communities was defined as “soil polarization” by Liu et al. (2007), and introducing other friendly tree species to form mixed forests (e.g., conifers mixed with deciduous trees or trees mixed with shrubs) was regarded as a feasible way to resolve this problem. For this aim, interspecific relationships among different species need to be studied. Because leaf litter decomposition is a key link in the nutrient cycle and energy transformation in forest ecosystems and reflects the characteristics of nutrients returning from trees back to the soil, the nutrient release process and impacting factors during mixed decomposition of leaf litter from different tree species would be very important issues of interspecific relationships. In addition, studying nutrient release during decomposition would be helpful to understand the principle of soil polarization, forecast the trends and degrees of it in planted forests, and thus further direct suitable tree species selection for mixed forestation.

Nutrient release during single and mixed leaf litter decomposition, especially N and P, was reported by many studies (Briones and Ineson 1996, Conn and Dighton 2000, Gnankambary et al. 2008, Li et al. 2009, Bonanomi et al. 2010, Song et al. 2010). Initial nutrient contents and their related ratios (C/N, C/P, and N/P) in leaf litter are regarded as the most important factors affecting decomposition and nutrient release. Studies by Teklay and Malmer (2004) and Bayala et al. (2005) stated that leaf litter with a higher N concentration would release nutrients more rapidly. Ball et al.'s study (2009) on N and P release dynamics suggested that a certain C/N ratio was helpful for decomposition, and nutrient release rates were dependent on the initial N and P concentrations in the leaf litter. Jacob et al. (2009) reported that there were significant correlations between nutrient release rates and C-P-related element ratios, and nutrients released during decomposition of litter from different species may be controlled by C/N, C/P, and N/P ratios. Aerts and de Caluwe (1997), Xu and Hirata (2005), and Gusewell and Gessner (2009) also stated that N and P concentrations and their ratios affected decomposition and nutrient release to some extent. In contrast, a few studies suggested that there was no significant relationship between the release of nutrients and the initial C/N ratio (Ranjbar and Jalali 2012). During mixed-species decomposition, "non-additive" interactions were generally observed in previous studies (Gartner and Cardon 2004, Ball et al. 2009), which stated that nutrient release rates of mixed-species decomposition may be significantly higher or lower than predicted values calculated by rates during single-species decomposition. In general, the presence of litter with higher initial C and P contents and lower C/N and C/P ratios accelerated nutrient release during decomposition (Ball et al. 2009). However, because of differences in experimental methods, regional environments, and litter qualities of different species, results of single- and mixed-species decomposition were variable, and even totally contrasting (Wedderburn and Carter 1999, Ball et al. 2009, Li et al. 2011, Ranjbar and Jalali 2012). Thus further studies are needed to verify and expand those findings. In addition, the release of microelements during litter decomposition has not garnered sufficient attention yet (Gartner and Cardon 2004, Lehto et al. 2010), which limits comprehensive views of the entire nutrient-release process.

Larix principis-rupprechtii is one of the most widely planted tree species on the Loess Plateau of China due to its fast growth and good adaptability. However, few studies have been carried out on its litter decomposition, either singly or mixed with that of other species. Thus, *L. principis-rupprechtii* was chosen as the objective in this study, in which, leaf litter from it and 10 other tree species were used singly or mixed with each other for a 345-d decomposition incubation to test the characteristics of nutrient release and its variation with various mixtures, in an attempt to provide a scientific basis for the selection of introduced tree species for altering pure forests and constructing mixed forests.

MATERIALS AND METHODS

Leaf litter and soil sample collection

In pure forests of *L. principis-rupprechtii* and other 7 tree species (*Pinus tabulaeformis*, *Platycladus orientalis*, *Populus simonii*, *Quercus liaotungensis*, *Betula platyphylla*, *Robinia pseudoacacia*, and *Ulmus pumila*) and 3 shrub species (*Hippophae rhamnoides*, *Caragana microphylla*, and *Amorpha fruticosa*) of the Loess Plateau of China, current-year fallen leaf litter was gathered in October 2009. We removed diseased leaves and insect pests, quickly washed the samples with tap water, and then dried them at 65℃. In order to allow interactions with large contact areas during mixed decomposition, all leaf litter samples were cut into 1-cm-sized pieces or short needles.

At the same time, soil from the top layer (0~20 cm) of a typical tree-free waste grassland within five 1×1-m quadrates was collected, mixed, and sampled as the decomposition medium. After removing roots, stones, and faunal debris, the soil was ground and passed through a 5-mm mesh sieve. The soil originated from parent material of loess and had a bulk density of 1.261 g cm^{-3}, a microaggregate (1~5 mm) content of 42.80%, an organic matter content of 21.9 g kg^{-1}, and a pH of 7.8.

Leaf litter decomposition experiment

In step 1, 7.5 g of leaf litter pieces from different species were weighed for single-species decomposition except *P. tabulaeformis* and *P. orientalis* (as their litter densities were obviously larger than the others, for which 15.0 g of litter was weighed out respectively). For mixed-species decomposition, litter from other species was mixed with that from *L. principis-rupprechtii* in a set mass ratio of 1: 1. The total weight of every mixture was 7.5 g (except for *P. tabulaeformis* or *P. orientalis*, when fully mixed with each other, the mass ratio was 2: 1, and the total weight of every mixture was 15.0 g). Litter samples were placed in nylon litterbags (0.5-mm mesh, 14×20 cm), and every type had 5 replicates. In total, 105 litterbags for 21 decomposition types were set up in this experiment.

In step 2, 4.0 kg of composite soil samples were weighed separately, and distilled water was added to adjust the soil moisture to 50% of the field water capacity. Then soil samples were placed in 21 opaque plastic pots of 20×40×30 cm. Afterwards, 5 litterbags of every decomposition type were buried in soil, in which they were canted at 45° and spaced in order to make good contact with the soil medium. A plastic film with 4 air vents (of 1.5 cm in size) was used to cover every pot to preserve the soil moisture. Litter decompositions was carried out by incubation in the laboratory under the same temperature of 20~25℃ for 345 d (November 2009~October 2010). During this process, we weighed the pots every week and added water using a sprayer to maintain a constant soil moisture content.

Determination and statistical analysis

After the litterbags were harvested at the end of incubation, litter residuals were quickly washed in soil sieves (0.25-mm mesh), dried at 65℃, and weighed. Nutrient concentrations in the litter before and after decomposition were determined by the following methods. C was determined by titrimetry with potassium dichromate, N was determined using a Kjeldahl apparatus, P was determined using molydenum antimony disoascorbic acid colorimetry (MADAC), and K was determined using flame photometry after the litter had been previously digested in a mixture of H_2SO_4 and H_2O_2. Micro-elements were determined by graphite furnace-atomic absorption spectrophotometry (Bao 2000).

Nutrient release during decomposition processes was estimated using model (1) suggested by Olson (1963):

$$R = X/X_0 = e^{-kt}; \quad (1)$$

where R is the percentage of remaining nutrient (elements here) in the litter residues, X_0 and X are nutrient contents in the litter before or after decomposition, respectively, k is the release rate constant, and t is the duration of decomposition. For t = 1 yr, the annual release rates d of nutrients were obtained using equation (2), and compared to each other by a one-way analysis of variance (ANOVA) method using SPSS 19.0 software (Tukey's method was employed in multiple comparisons; SPSS, Chicago, IL, USA).

$d = 1 - e^{-k}$. (2)

In order to test the relationships between nutrient release rates and litter quality, initial element content characteristics in the litter including their ratios (C/N, C/P, and N/P) and annual release rates of every element were subjected to a Spearman correlation analysis using SPSS 19.0 software.

Based on the assumption that different litters decompose independently, we calculated the predicted nutrient release rate and increment rate (Δ%) values in mixed-species decomposition using equations (3) and (4):

$Pd_{AB} = a\ Td_A + b\ Td_B$ and (3)

$\Delta\% = 100 \times (Td_{AB} - Pd_{AB})/Pd_{AB}$; (4)

where Td_A and Td_B are the respective observed nutrient release rates of single species A and B, Pd_{AB} is the predicted release rate value of mixed decomposition, and a and b respectively stand for the mass percentage of each species of A and B in the mixtures.

Values of observed and predicted nutrient release rates were subjected to a t-test analysis using SPSS 19.0 to test whether there were significant differences between them. Positive values of Δ% meant that there were acceleration effects on nutrient release during mixed-species decomposition, while negative values meant the opposite. In order to conveniently state the effects of mixed decomposition, values of Δ% were classified into 7 grades: N, no significant difference between Td_{AB} and Pd_{AB}; SL, slight effects (there was a significant difference between Td_{AB} and Pd_{AB}, and Δ% < 10%, the same as the others); W, weak effects (Δ% = 10~15%); RS, relatively strong effects (Δ% = 15~20%); S, strong effects (Δ% = 20~25%); VS, very strong effects (Δ% = 25~30%); and ES, extremely strong effects (Δ% > 30%).

RESULTS

Nutrient release during single-species leaf litter decomposition

1. Initial nutrient contents in the leaf litter

Initial nutrient content characteristics (Tables 1, 2) may affect nutrient release rates. According to the variance analysis, the leaf litter of different tree species had the following initial nutrient characteristics before incubation: *L. principis-rupprechtii* had the highest C, P, and Mn contents and the lowest Ni and Fe contents, and C/P and N/P ratios. *P. tabulaeformis* had the highest C and Fe contents, and C/N and C/P ratios and the lowest N, P, K, Cu, Cd, and Mn contents. *P. orientalis* had the highest C and Fe contents, and the lowest Cd and Mn contents and C/P ratio. *P. simonii* contained the highest Cd and the lowest C, Zn, and Fe contents. *R. pseudoacacia* had the highest Ni content and the lowest C content. *B. platyphylla* had the highest initial C, Zn, Cd, and Mn contents and the lowest C/P ratio. *Q. liaotungensis* contained the highest C content, and the lowest Cd and Fe contents, and C/P and N/P ratios. *U. pumila* contained the highest K content and the lowest C, Zn, Cd, and Mn contents and C/N ratio. *H. rhamnoides* had the highest Fe content, and the lowest C and Cd contents and C/N ratio. *C. microphylla* had the highest C content and N/P ratio and the lowest Zn and Cd contents and C/N ratio. *A. fruticosa* contained the highest C, N, P, K, and Cu contents, and the lowest Cd and Mn contents, and C/N and C/P ratios.

According to estimations by the Olson model and equation (2), nutrient release rates during single-species leaf litter decomposition were variable (Table 3). *L. principis-rupprechtii* released C, Zn, and Ni the most slowly; *P. tabulaeformis* showed the slowest release rates of N, P, K, Cu, Cd, Fe, and Mn; *P. orientalis* released P the most rapidly; *P.*

Table 1. Initial nutrient characteristics of leaf litter of different tree species (macro-elements, g·kg^{-1})

Leaf litter	C	N	P	K	C/N	C/P	N/P
L. p.	258.66±3.25 abc	20.88±0.98 e	2.71±0.02 a	0.56±0.03 f	12.38±0.43 b	95.44±2.02 d	7.70±0.42 f
P. t.	283.76±2.60 a	9.81±0.05 f	0.50±0.01 g	0.22±0.01 h	28.93±0.13 a	567.52±1.35 a	19.62±0.14 c
P. o.	259.20±6.82 abc	28.00±0.42 cd	1.96±0.07 c	0.71±0.01 e	9.26±0.11 de	132.24±1.20 cd	14.29±0.29 d
P. s.	210.94±4.28 d	23.64±1.19 de	1.41±0.05 de	0.93±0.01 d	8.92±0.27 def	149.60±2.49 c	16.77±0.23 d
R. p.	236.07±13.62 bcd	24.03±1.13 de	1.08±0.02 f	0.40±0.01 g	9.82±0.10 cd	218.58±7.95 b	22.25±0.57 c
B. p.	266.58±11.49 ab	27.32±0.36 cd	2.45±0.07 b	1.28±0.05 c	9.75±0.29 cd	108.81±7.79 d	11.15±0.47 e
Q. l.	250.66±4.16 abc	21.23±1.93 e	2.41±0.05 b	0.87±0.03 d	11.80±1.31 bc	104.01±0.27 d	8.81±0.97 ef
U. p.	223.68±6.41 cd	30.45±0.73 c	1.45±0.04 d	1.51±0.03 a	7.34±0.03 efg	154.26±0.12 c	21.00±0.08 c
H. r.	232.63±9.10 bcd	31.87±0.93 bc	1.19±0.09 ef	0.58±0.02 ef	7.29±0.50 efg	195.48±22.29 b	26.78±1.19 b
C. m.	247.09±6.48 abc	36.75±1.16 b	1.11±0.05 f	1.32±0.03 bc	6.72±0.04 fg	222.50±3.45 b	33.11±0.34 a
A. f.	249.11±5.99 abc	43.48±0.45 a	2.61±0.05 ab	1.43±0.03 ab	5.72±0.20 g	95.44±3.99 d	16.66±0.12 d

L. p., *Larix principis-rupprechtii*; *P. t.*, *Pinus tabulaeformis*; *P. o.*, *Platycladus orientalis*; *P. s.*, *Populus simonii*; *R. p.*, *Robinia pseudoacacia*; *B. p.*, *Betula platyphylla*; *Q. l.*, *Quercus liaotungensis*; *U. p.*, *Ulmus pumila*; *H. r.*, *Hippophae rhamnoides*; *C. m.*, *Caragana microphylla*; *A. f.*, *Amorpha fruticosa*. Data are the average±SE; Tukey's method was used for the multiple-comparison test, and different letters in the same column indicate a significant difference among species.

Table 2. Initial nutrient characteristics of leaf litter of different tree species (micro-elements, mg·kg^{-1})

Leaf litter	Cu	Zn	Ni	Cd	Fe	Mn
L. p.	5.35±0.12 e	26.34±2.22 c	1.05±0.01 i	0.90±0.03 b	115.13±3.26 f	269.96±12.34 ab
P. t.	3.10±0.10 f	23.09±0.09 cd	2.45±0.02 e	0.64±0.03 d	291.65±1.05 ab	42.01±0.73 f
P. o.	5.15±0.10 e	21.90±1.27 cd	2.19±0.04 f	0.71±0.02 d	303.40±4.05 ab	31.00±1.97 f
P. s.	6.99±0.23 cd	13.76±1.37 ef	3.50±0.02 b	0.98±0.03 ab	142.06±10.67 ef	229.91±9.49 c
R. p.	6.46±0.05 d	22.30±1.88 cd	4.03±0.02 a	0.86±0.02 bc	196.80±12.88 d	208.79±6.59 c
B. p.	10.05±0.32 b	76.76±1.76 a	1.58±0.03 h	1.09±0.06 a	176.74±7.54 de	273.16±4.9 a
Q. l.	9.65±0.04 b	20.48±0.58 cde	1.93±0.05 g	0.71±0.01 d	101.94±1.47 f	234.64±11.11 bc
U. p.	7.09±0.08 cd	9.21±0.06 f	1.66±0.06 h	0.69±0.03 d	191.35±12.63 d	35.74±1.88 f
H. r.	9.34±0.10 b	19.41±1.05 de	3.50±0.02 b	0.68±0.01 d	319.74±12.35 a	136.09±11.31 d
C. m.	7.39±0.12 c	11.99±0.88 f	2.71±0.03 d	0.75±0.02 cd	268.15±13.72 bc	96.29±3.93 e
A. f.	15.18±0.23 a	47.71±1.67 b	3.24±0.03 c	0.68±0.01 d	222.30±9.77 cd	59.55±3.54 ef

See footnotes to Table 1.

simonii showed the highest release rates for K, Cd and Mn; *R. pseudoacacia* released N, P, K, Cu, Zn, Cd, Fe, and Mn relatively more slowly; *B. platyphylla* showed the highest release rates of K; *Q. liaotungensis* released Fe the most slowly; *U. pumila* showed the highest release rates for C, N, P, K, and Cd; *H. rhamnoides* released all elements the most rapidly except N, P, and Mn; *C. microphylla* showed the fastest release rates of C, N, P, K, and Cd; and *A. fruticosa* released Zn relatively faster and K, Ni, and Mn relatively more slowly.

2. Effects of initial nutrient contents in the leaf litter on nutrient release during decomposition

Relationships between the initial nutrient

Table 3. Nutrient release rates during single-species leaf litter decomposition ($d = 1 - e^{-k}$)

Leaf litter	C	N	P	K	Cu	Zn	Ni	Cd	Fe	Mn
L. p.	0.5084±0.0029 i	0.5192±0.0048 g	0.6560±0.0006 f	0.9497±0.0034 c	0.4206±0.0044 h	0.3677±0.0015 i	0.2600±0.0008 k	0.5203±0.0023 c	0.2865±0.0002 i	0.5020±0.0025 g
P. t.	0.5203±0.0002 h	0.4059±0.0016 h	0.5175±0.0002 h	0.9182±0.0009 e	0.2737±0.0016 i	0.3863±0.0025 h	0.5027±0.0004 h	0.3069±0.0008 e	0.2667±0.0010 j	0.1434±0.0005 k
P. o.	0.9042±0.0012 c	0.9212±0.0007 c	0.8991±0.0039 a	0.9675±0.0033 b	0.8180±0.0015 d	0.8565±0.0001 d	0.8319±0.0004 d	0.8880±0.0009 b	0.8007±0.0005 d	0.4897±0.0020 h
P. s.	0.9511±0.0009 b	0.9394±0.0021 b	0.8171±0.0002 b	0.9904±0.0040 a	0.8895±0.0018 b	0.8491±0.0036 d	0.9054±0.0006 b	0.9628±0.0019 a	0.7468±0.0024 e	0.9267±0.0012 a
R. p.	0.6433±0.0011 g	0.5203±0.0008 g	0.5667±0.0029 g	0.9408±0.0012 cd	0.4503±0.0038 g	0.5037±0.0016 g	0.5098±0.0005 g	0.4059±0.0003 d	0.2987±0.0007 h	0.3704±0.0024 i
B. p.	0.8494±0.0033 d	0.8477±0.0025 d	0.8560±0.0014 b	0.9928±0.0006 a	0.7960±0.0002 e	0.8527±0.0021 d	0.6461±0.0019 f	0.8690±0.0071 b	0.5344±0.0047 f	0.8600±0.0029 d
Q. l.	0.7211±0.0029 f	0.6702±0.0006 f	0.7193±0.0006 e	0.9371±0.0015 d	0.5000±0.0026 f	0.5500±0.0037 f	0.3859±0.0001 i	0.5084±0.0013 c	0.2572±0.0003 j	0.5620±0.0001 f
U. p.	0.9675±0.0025 a	0.9720±0.0005 a	0.8964±0.0017 a	0.9902±0.0007 a	0.8880±0.0032 b	0.7606±0.0010 e	0.8031±0.0002 e	0.9502±0.0137 a	0.8362±0.0027 c	0.6982±0.0037 e
H. r.	0.9665±0.0008 a	0.9477±0.0030 b	0.8175±0.0000 b	0.9918±0.0008 a	0.9438±0.0012 a	0.9419±0.0003 a	0.9347±0.0003 a	0.9618±0.0014 a	0.9382±0.0020 a	0.9130±0.0009 b
C. m.	0.9594±0.0037 ab	0.9637±0.0008 a	0.8892±0.0033 a	0.9945±0.0017 a	0.8686±0.0035 c	0.8969±0.0006 b	0.8537±0.0014 c	0.9422±0.0002 a	0.8953±0.0011 b	0.8816±0.0011 c
A. f.	0.7683±0.0020 e	0.7125±0.0020 e	0.7909±0.0017 d	0.9491±0.0036 c	0.8168±0.0013 d	0.8841±0.0014 c	0.3673±0.0018 j	0.5016±0.0026 c	0.4319±0.0002 g	0.2446±0.0013 j

See footnotes to Table 1.

contents in the litter and nutrient release rates during decomposition (Tables 4, 5) indicated that release rates of C and N had significant positive correlations with the initial N and K contents, and significant negative correlations with the initial C and Zn contents and C/N ratio. The P release rate had significant positive correlations with the initial N and K contents and a negative correlation with the initial C/N ratio. The Cu release rate had a significant positive correlation with the initial N content, significant negative correlations with C and Zn contents, and an extremely significant negative correlation with the initial C/N ratio. The Zn release rate was very closely related to the initial N content positively and the initial C/N ratio negatively. The Ni release rate was significantly related to the initial N/P ratio positively and the initial Zn content negatively. There were significant negative correlations between the Cd release rate and initial C and Zn contents. The Fe release rate showed an extremely significant correlation with the initial N content and a significant

Table 4. Spearman correlation coefficients between nutrient release rates (NRRs) and initial macro-element characteristics (contents g kg^{-1} and ratios) in leaf litter

NRR	Initial characteristics of macro-elements						
	C	N	P	K	C/N	C/P	N/P
C	-0.618*	0.682*	-0.173^{NS}	0.636*	-0.755**	0.255^{NS}	0.545^{NS}
N	-0.627*	0.700*	-0.091^{NS}	0.700*	-0.773**	0.187^{NS}	0.500^{NS}
P	-0.218^{NS}	0.636*	0.164^{NS}	0.655*	-0.609*	-0.036^{NS}	0.164^{NS}
K	-0.336^{NS}	0.555^{NS}	0.045^{NS}	0.509^{NS}	-0.600^{NS}	0.096^{NS}	0.327^{NS}
Cu	-0.718*	0.655*	-0.082^{NS}	0.555^{NS}	-0.791**	0.109^{NS}	0.464^{NS}
Zn	-0.282^{NS}	0.864**	-0.018^{NS}	0.509^{NS}	-0.864**	0.064^{NS}	0.436^{NS}
Ni	-0.518^{NS}	0.391^{NS}	-0.491^{NS}	0.173^{NS}	-0.491^{NS}	0.524^{NS}	0.627*
Cd	-0.627*	0.373^{NS}	0.018^{NS}	0.445^{NS}	-0.536^{NS}	0.046^{NS}	0.264^{NS}
Fe	-0.518^{NS}	0.736**	-0.200^{NS}	0.445^{NS}	-0.764**	0.310^{NS}	0.618*
Mn	-0.573^{NS}	0.236^{NS}	-0.018^{NS}	0.373^{NS}	-0.400^{NS}	0.068^{NS}	0.236^{NS}

* $P < 0.05$ (2-tailed); ** $P < 0.05$ (2-tailed); NS, not significant; n = 11.

Table 5. Spearman correlation coefficients between nutrient release rates (NRRs) and initial micro-element contents in leaf litter

NRR	Initial micro-elements contents (mg kg^{-1})					
	Cu	Zn	Ni	Cd	Fe	Mn
C	0.318^{NS}	-0.718*	0.182^{NS}	-0.091^{NS}	0.327^{NS}	-0.355^{NS}
N	0.327^{NS}	-0.727*	0.114^{NS}	0.023^{NS}	0.236^{NS}	-0.300^{NS}
P	0.218^{NS}	-0.445^{NS}	-0.196^{NS}	0.105^{NS}	0.264^{NS}	-0.355^{NS}
K	0.336^{NS}	-0.336^{NS}	-0.023^{NS}	0.416^{NS}	0.155^{NS}	0.136^{NS}
Cu	0.336^{NS}	-0.664*	0.333^{NS}	-0.027^{NS}	0.282^{NS}	-0.236^{NS}
Zn	0.545^{NS}	-0.255^{NS}	0.351^{NS}	-0.164^{NS}	0.555^{NS}	-0.255^{NS}
Ni	-0.009^{NS}	-0.655*	0.433^{NS}	0.064^{NS}	0.464^{NS}	-0.227^{NS}
Cd	0.145^{NS}	-0.664*	0.059^{NS}	0.247^{NS}	0.055^{NS}	-0.018^{NS}
Fe	0.164^{NS}	-0.564^{NS}	0.246^{NS}	-0.032^{NS}	0.536^{NS}	-0.355^{NS}
Mn	0.327^{NS}	-0.564^{NS}	0.068^{NS}	0.438^{NS}	-0.155^{NS}	0.355^{NS}

See footnotes to Table 4.

positive correlation with the N/P ratio. In contrast, it had an extremely significant negative correlation with the initial C/N ratio. There were no significant correlations between the rates of K and Mn release and the initial nutrient contents of the litter materials. Furthermore, there were no significant correlations between the element release rate with their own initial contents except C and N, in which C was negative and N was positive.

Effects of mixed-species leaf litter decomposition from *L. principis-rupprechtii* and other species on nutrient release

1. Effects on C, N, P, and K release

Effects of mixed-species leaf litter decomposition from different tree species with *L. principis-rupprechtii* on macro-elements release (Tables 6, 7) showed that: *P. tabulaeformis* accelerated C release strongly and N release weakly, while it slightly inhibited P release; *P. orientalis* weakly inhibited P release; *R. pseudoacacia* had a relatively strong negative effect on N release and a very strong negative effect on P release; *B. platyphylla* accelerated C release slightly and N release weakly; it also showed a relatively strong acceleration of P release; *Q. liaotungensis* had a relatively strong negative effect on P release; *U. pumila* showed relatively weak acceleration of N release and a relatively strong negative effect on P release; *H. rhamnoides* and *C. microphylla* had strong and extremely strong negative effects on P release, respectively; while, *P. simonii* and *A. fruticosa* showed no significant effects on any element release in mixed decomposition.

2. Effects on Cu, Zn, Ni, Cd, Fe, and Mn release

Effects of mixed-species leaf litter decomposition on micro-element release rates (Tables 8, 9) showed that *P. tabulaeformis* greatly accelerated Cd, Fe, and Mn release, while it greatly inhibited Ni release. *P. orientalis* greatly inhibited Cu, Zn, Ni, and Fe release and Mn release weakly; it also had a very strong negative effect on Cd release. *P. simonii* showed relatively strong inhibition of Cu release, and it inhibited Zn and Ni release slightly, Fe release extremely, and Mn release weakly. *R. pseudoacacia* slightly accelerated Cu and Fe release, strongly accelerated Mn release, and had extremely negative effects on Zn, Ni, and Cd release. *B. platyphylla* had a slight positive effect on Cu release, a weak positive effect on Zn release, an extremely positive effect on Ni release, and a relatively strong negative effect on Fe release. *Q. liaotungensis* had a weakly positive effect on Cd release, an extremely positive effect on Fe release, a slightly negative effect on Cu release, an extremely negative effect on Zn release, and a relatively strong negative effect on Ni release. *U. pumila* accelerated Cu, Cd, and Mn release slightly and Ni release extremely; it also showed a very strong acceleration of Zn release and weak inhibition of Fe release. *H. rhamnoides* showed extreme acceleration of Ni release, extreme inhibition of Zn release, relatively strong inhibition of Fe release, and weak inhibition of Mn release. *C. microphylla* inhibited Cu release slightly, Ni release weakly, and Fe and Mn release very strongly. *A. fruticosa* showed relatively strong inhibition of Zn release, strong inhibition of Ni release, slight inhibition of Fe release, and very strong inhibition of Mn release.

3. Comprehensive analysis of the effects of mixed-species leaf litter decomposition on nutrient release

Release rates of different elements were variable during single-species decomposition and became more complicated when 2 types of litter were mixed, in that the release of some elements was accelerated, while that of others was inhibited. In order to assess the

Table 6. Effects of mixed leaf litter decomposition from *Larix principis-rupprechtii* and other tree species on macro-element release

Tree leaf litter		Release model $\ln R = -kt$	Annual nutrient release rate *d*		
			Observed value T_{AB}	Predicted value P_{AB}	Increment ratio Δ%
P. t.	C	lnR = -1.0472 *t*	0.6284**	0.5166	21.64 S
	N	ln*R* = -0.6979 *t*	0.4829*	0.4437	8.83 W
	P	lnR = -0.7754 *t*	0.5195*	0.5637	-7.84SL
	K	ln*R* = -2.7742 *t*	0.9274	0.9287	-0.14 N
P. o.	C	ln*R* = -1.6286 *t*	0.7855	0.7723	1.71 N
	N	ln*R* = -1.8342 *t*	0.8234	0.7872	4.60 N
	P	lnR = -1.3943 *t*	0.7323*	0.8181	-10.49 W
	K	ln*R* = -3.9457 *t*	0.9760	0.9616	1.44 N
P. s.	C	ln*R* = -1.3993 *t*	0.7336	0.7298	0.52 N
	N	ln*R* = -1.3246 *t*	0.7168	0.7293	-1.71 N
	P	lnR = -1.2941 *t*	0.7057	0.7366	-4.19 N
	K	ln*R* = -3.4700 *t*	0.9624	0.9701	-0.77 N
R. p.	C	ln*R* = -0.8877 *t*	0.5679	0.5759	-1.39 N
	N	ln*R* = -0.6168 *t*	0.4418**	0.5198	-15.01 RS
	P	lnR = -0.6077 *t*	0.4370**	0.6114	-28.52 VS
	K	ln*R* = -2.9634 *t*	0.9393	0.9453	-0.60 N
B. p.	C	ln*R* = -1.4229 *t*	0.7395*	0.6789	8.93 SL
	N	ln*R* = -1.4502 *t*	0.7461*	0.6835	9.16 W
	P	lnR = -2.1959 *t*	0.8745**	0.7560	15.67 RS
	K	ln*R* = -3.7336 *t*	0.9707	0.9713	-0.06 N
Q. l.	C	ln*R* = -1.0578 *t*	0.6320	0.6148	2.80 N
	N	ln*R* = -0.9853 *t*	0.6060	0.5947	1.90 N
	P	lnR = -0.8667 *t*	0.5592**	0.6877	-18.69 RS
	K	ln*R* = -3.4010 *t*	0.9598	0.9434	1.64 N
U. p.	C	ln*R* = -1.4104 *t*	0.7360	0.7380	-0.27 N
	N	ln*R* = -1.8971 *t*	0.8336*	0.7456	11.80 W
	P	lnR = -1.0398 *t*	0.6257**	0.7762	-19.39 RS
	K	ln*R* = -5.0246 *t*	0.9913	0.9670	2.43 N

* or **, significant ($p < 0.05$) or extremely significant ($p < 0.01$) difference between T_{AB} and P_{AB}. N, no significant difference between Td_{AB} and Pd_{AB}; SL, slight effects (there was a significant difference between Td_{AB} and Pd_{AB}, and Δ% < 10%, the same as others); W, weak effects (Δ% = 10~15%); RS, relatively strong effects (Δ% = 15~20%); S, strong effects (Δ% = 20~25%); VS, very strong effects (Δ% = 25~30%); ES, extremely strong effects (Δ% > 30%). For tree names, see footnotes to Table 1.

comprehensive effects of mixed decomposition on nutrient release as a whole, increment ratios (Δ%) between predicted and observed values of nutrient release rates during mixed-species decomposition were subjected to a principal component analysis (PCA) using SPSS 19.0, and comprehensive principal component *F* values of every species which

Table 7. Effects of mixed leaf litter decomposition from *Larix principis-rupprechtii* and other shrub species on macro-element release

Shrub leaf litter		Release model ln R = $-kt$	Annual Nutrient release rate d		
			Observed value T_{AB}	Predicted value P_{AB}	Increment ratio Δ%
H. r.	C	ln$R$ = -1.4680 t	0.7503	0.7357	1.98 N
	N	ln$R$ = -1.5430 t	0.7674	0.7335	4.62 N
	P	lnR = -0.9244 t	0.5826**	0.7368	-20.93 S
	K	ln$R$ = -4.2706 t	0.9823	0.9708	1.15 N
C. m.	C	ln$R$ = -1.3862 t	0.7303	0.7339	-0.49 N
	N	ln$R$ = -1.4924 t	0.7560	0.7415	1.96 N
	P	lnR = -0.7991 t	0.5301**	0.7726	-31.39 ES
	K	ln$R$ = -4.3644 t	0.9838	0.9721	1.17 N
A. f.	C	ln$R$ = -1.0152 t	0.6170	0.6384	-3.35 N
	N	ln$R$ = -0.9493 t	0.5923	0.6159	-3.83 N
	P	lnR = -1.3265 t	0.7146	0.7235	-1.23 N
	K	ln$R$ = -4.0179 t	0.9776	0.9494	2.82 N

See footnotes to Table 6 for an explanation of the statistical information.
See footnotes to Table 1 for shrub species names.

indicated the synthetic effects of mixed leaf litter decomposition on nutrient release were calculated using model (5):

$$F = 0.4096F_1 + 0.2531F_2 + 0.1891F_3 + 0.1482F_4; \quad (5)$$

where F_1~F_4 are principal component values obtained by the PCA. Results were sorted in the following order:

$F_{U.\ pumila}$ (1.2886) > $F_{P.\ tabulaeformis}$ (1.1303) > $F_{B.\ platyphylla}$ (0.8105) > $F_{H.\ rhamnoides}$ (0.2722) > $F_{Q.\ liaotungensis}$ (-0.0417) > $F_{C.\ microphylla}$ (-0.1044) > $F_{A.\ fruticosa}$ (-0.1580) > $F_{P.\ simonii}$ (-0.7201) > $F_{R.\ pseudoacacia}$ (-1.2245) > $F_{P.\ orientalis}$ (-1.2529).

This showed that when mixed with *L. principis-rupprechtii*, leaf litter from *U. pumila* and *P. tabulaeformis* significantly accelerated nutrient release as a whole, followed by *B. platyphylla*. The acceleration of litter from *H. rhamnoides* was negligible. Litter from *P. orientalis* and *R. pseudoacacia* significantly inhibited the release as a whole, followed by *P. simonii*. Inhibition of litter from *A. fruticosa*, *C. microphylla*, and *Q. liaotungensis* was negligible.

DISCUSSION AND CONCLUSIONS

On single-species leaf litter decomposition

Our study showed that during the single-species decomposition process, among the macro-elements, K was the most active and easily released, while P was generally less active and difficult to release, and C and N were moderate and often synchronous in their release. Among 6 microelements, Zn, Cd, and Cu were the most active, followed by Ni, while Fe and Mn were the least active and difficult to release. Analyzing these results, the rapid release of K is a common observation (Qiu et al. 2012), because K exists mainly as ions in plants and is not associated with structural components (Osono and Takeda 2005). P mainly exists in phospholipids, nucleic acids, and proteins, thus is released more slowly relative to other nutrients. C and N are the nutrient sources of microorganisms and mainly exist as proteins or other forms together; thus, they exhibit synchronous dynamics during decomposition. Among the 6 micro-elements,

Table 8. Effects of mixed-species leaf litter decomposition from *Larix principis-rupprechtii* and other tree species on micro-element release

Tree leaf litters		Release model $\ln R = -kt$	Annual nutrient release rate d		
			Observed value T_{AB}	Predicted value P_{AB}	Increment ratio Δ%
P. t.	Cu	ln*R* = -0.3938 *t*	0.3255	0.3227	0.88 N
	Zn	ln*R* = -0.4767 *t*	0.3792	0.3801	-0.24 N
	Ni	ln*R* = -0.3043 *t*	0.2624**	0.4218	-37.79 ES
	Cd	ln*R* = -0.8623 *t*	0.5778**	0.3780	52.85 ES
	Fe	ln*R* = -0.4435 *t*	0.3582**	0.2733	31.06 ES
	Mn	ln*R* = -0.5373 *t*	0.4157**	0.2629	58.10 ES
P. o.	Cu	ln*R* = -0.5302 *t*	0.4115**	0.6855	-39.97 ES
	Zn	ln*R* = -0.5702 *t*	0.4346**	0.6936	-37.34 ES
	Ni	ln*R* = -0.2946 *t*	0.2552**	0.6413	-60.21 ES
	Cd	ln*R* = -0.7955 *t*	0.5486**	0.7654	-28.32 VS
	Fe	ln*R* = -0.2342 *t*	0.2088**	0.6293	-66.83 ES
	Mn	ln*R* = -0.5773 *t*	0.4386*	0.4938	-11.18 W
P. s.	Cu	ln*R* = -0.7980 *t*	0.5498**	0.6551	-16.07 RS
	Zn	ln*R* = -0.8555 *t*	0.5749*	0.6084	-5.50 SL
	Ni	ln*R* = -0.7494 *t*	0.5273*	0.5827	-9.50 SL
	Cd	ln*R* = -1.2855 *t*	0.7235	0.7416	-2.44 N
	Fe	ln*R* = -0.1818 *t*	0.1662**	0.5167	-67.83 ES
	Mn	ln*R* = -1.0044 *t*	0.6337*	0.7144	-11.29 W
R. p.	Cu	ln*R* = -0.6175 *t*	0.4607*	0.4355	5.81 SL
	Zn	ln*R* = -0.3046 *t*	0.2626**	0.4357	-39.72 ES
	Ni	ln*R* = -0.2705 *t*	0.2370**	0.3849	-38.42 ES
	Cd	ln*R* = -0.3794 *t*	0.3157**	0.4631	-31.83 ES
	Fe	ln*R* = -0.3777 *t*	0.3146*	0.2926	7.51 SL
	Mn	ln*R* = -0.7646 *t*	0.5345**	0.4362	22.53 S
B. p.	Cu	ln*R* = -0.9903 *t*	0.6285*	0.6083	3.32 SL
	Zn	ln*R* = -1.1750 *t*	0.6912*	0.6102	13.27 W
	Ni	ln*R* = -1.0008 *t*	0.6324**	0.4531	39.59 ES
	Cd	ln*R* = -1.1881 *t*	0.6952	0.6947	0.08 N
	Fe	ln*R* = -0.4120 *t*	0.3377*	0.4105	-17.73 RS
	Mn	ln*R* = -1.2138 *t*	0.7029	0.6810	3.22 N
Q. l.	Cu	ln*R* = -0.5053 *t*	0.3966*	0.4603	-13.83 SL
	Zn	ln*R* = -0.1625 *t*	0.1500**	0.4589	-67.32 ES
	Ni	ln*R* = -0.3008 *t*	0.2598**	0.3230	-19.57 RS
	Cd	ln*R* = -0.8641 *t*	0.5785*	0.5144	12.48 W
	Fe	ln*R* = -0.4710 *t*	0.3757**	0.2719	38.18 ES
	Mn	ln*R* = -0.7253 *t*	0.5158	0.5320	-3.05 N
U. p.	Cu	ln*R* = -1.2344 *t*	0.7090*	0.6543	8.36 SL
	Zn	ln*R* = -1.2246 *t*	0.7061**	0.5642	25.16 VS
	Ni	ln*R* = -1.4869 *t*	0.7739**	0.5316	45.60 ES
	Cd	ln*R* = -1.5458 *t*	0.7869*	0.7353	7.02 SL
	Fe	ln*R* = -0.6665 *t*	0.4865*	0.5614	-13.34 W
	Mn	ln*R* = -1.0515 *t*	0.6506*	0.6001	8.42 SL

See footnotes to Table 6 for an explanation of the statistical data.
See footnotes to Table 1 for tree species names.

Table 9. Effects of mixed-species leaf litter decomposition from *Larix principis-rupprechtii* and other shrub species on micro-element release

Shrub leaf litter		Release model ln R = $-kt$	Annual Nutrient release rate d		
			Observed value T_{AB}	Predicted value P_{AB}	Increment ratio Δ%
H. r.	Cu	ln$R$ = -1.1582 t	0.6859	0.6822	0.55 N
	Zn	ln$R$ =-0.5102 t	0.3996**	0.6548	-38.97 ES
	Ni	ln$R$ = -1.6321 t	0.8045**	0.5974	34.67 ES
	Cd	ln$R$ = -1.3776 t	0.7478	0.7411	0.91 N
	Fe	ln$R$ = -0.6925 t	0.4997**	0.6124	-18.40 RS
	Mn	ln$R$ = -0.9415 t	0.6100*	0.7075	-13.78 W
C. m.	Cu	ln$R$ = -0.9051 t	0.5955*	0.6446	-7.62 SL
	Zn	ln$R$ = -1.0460 t	0.6487	0.6323	2.59 N
	Ni	ln$R$ = -0.6777 t	0.4922*	0.5569	-11.61 W
	Cd	ln$R$ = -1.3118 t	0.7307	0.7313	-0.08 N
	Fe	ln$R$ = -0.5696 t	0.4342**	0.5909	-26.51 VS
	Mn	ln$R$ = -0.7278 t	0.5171**	0.6918	-25.26 VS
A. f.	Cu	ln$R$ = -0.8880 t	0.5885	0.6187	-4.88 N
	Zn	ln$R$ = -0.7121 t	0.5094**	0.6259	-18.61 RS
	Ni	ln$R$ = -0.2726 t	0.2386**	0.3137	-23.94 S
	Cd	ln$R$ = -0.6870 t	0.4969	0.5110	-2.74 N
	Fe	ln$R$ = -0.3840 t	0.3189*	0.3592	-11.22 SL
	Mn	ln$R$ = -0.3048 t	0.2627**	0.3733	-29.62 VS

See footnotes to Table 6 for an explanation of the statistical information.
See footnotes to Table 1 for shrub species names.

Zn and Cu exist mainly in dehydrogenases and oxidases, and their mobilities are better than others. Fe and Mn generally contribute to the formation of inactive macromolecule compounds, and this may explain why they were released with greater difficulty.

We observed that there were no significant correlations between nutrient release rates and their own initial contents except for C and N, which did not agree with previous studies on Ca, Mg, Na, and K release by Osono and Takeda (2005) and Ranjbar and Jalali (2012). This suggests that elements with a high initial content in litter might not generally be released more rapidly during decomposition. We noted that initial C, N, and K contents and the C/N ratio had significant or extremely significant correlations with the release rates of C, N, P, Cu, Zn, Cd, and Fe, which indicated that litter quality had an important impact on nutrient release. Initial C/P and N/P ratios did not show significant effects on the release rates of most elements except for Ni and Fe, so they could not be regarded as criteria for evaluating the effects of litter quality on nutrient release under the conditions of this study. These results partly agreed with findings of Parton et al. (2007), Bonanomi et al. (2010), and Devi and Yadava (2010), but were contrary to those of Jacob et al. (2009) and Ranjbar and Jalali (2012), which might have been due to differences in biological properties of various litter materials. Aerts and de Caluwe (1997) suggested that C/P and N/P ratios mainly affected the decomposition process in the early stage (within 3 months), but when the decomposition reached 1 yr, the impact of C/N becomes more obvious. Our experiments lasted for about 1 yr, and the results also supported the findings reported by Aerts and de Caluwe (1997). This might have been caused by non-synchronization between nutrient release and decomposition processes (Briones and Ineson 1996), because some investigations stated that there was a turning point for the impact of the N/P ratio on nutrient release, and around that point, an N-limited process and a P-limited process would switch from one to the other (Gusewell and Gessner 2009). This may help explain the poor correlation between the N/P ratio and nutrient release.

Previous studies suggested that Zn-input would significantly change the biomass carbon, respiration, and community structure of soil microorganisms (Chen et al. 2002). However, the result was obtained only under higher Zn concentrations. In this study, we observed significant negative correlations between the initial Zn content and release rates of C, N, Cu, Ni, and Cd, and this might have partly been caused by the change in soil biological properties, but we cannot rule out the possibility that there are just pure mathematical relationships between them. This still needs further research to clarify it.

On mixed-species leaf litter decomposition

Our results also supported previous findings that there were significant "non-additive" interspecific effects in mixed-species leaf litter decomposition and nutrient release (Liao et al. 2000, Gartner and Cardon 2004, Kominoski et al. 2007, Ball et al. 2009). Furthermore, we observed that the effects of mixed-species decomposition on micro-element release were more obvious than those on macro-element release. It is widely accepted that litter with a high initial quality will accelerate decomposition and nutrient release, while litter of poor quality will inhibit these processes (Ball et al. 2009). However, in this study, litter from *P. tabulaeformis*, with the highest initial C content and C/N ratio and the lowest N content, had the worst litter quality compared to other species. When mixed with *L. principis-rupprechtii*, we noted that this mixture strongly promoted nutrient release as a whole, especially the release of Cd, Fe, and Mn. It only slightly inhibited the release of P. In addition, *P. orientalis*, which had a moderate litter quality, inhibited nutrient release as a whole, especially the release of P and the 6 microelements. These phenomena corroborated previous findings of Musvoto et al. (2000) and Bayala et al. (2005), but were in contrast with findings reported by Kwabiah et al. (1999) and Ball et al. (2009).

It is remarkable that this study only accessed the effects of initial nutrient contents and their ratios in the litter on nutrient release during decomposition, but actually, it is also affected by the contents of lignin (Aerts and de Caluwe 1997, Gnankambary et al. 2008, Hattenschwiler and Jorgensen 2010), cellouslose (Xu and Hirata 2005), tannins (Loranger et al. 2002), phenols (Hoorens et al. 2003, Gnankambary et al. 2008), and cutins (Gallardo and Merino 1993) which have complicated structures and compositions; thus, further studies are still needed to improve our findings.

Nutrient transformation between different litters in the mixture is widely accepted as an explanation for the impacts of mixed-species decomposition on nutrient release. According to this, nutrients that are released from a litter of high quality can be immobilized in low-quality litter by microbiological activities, which therefore influence nutrient release rates of the mixture (Hattenschwiler et al. 2005, Schimel and Hattenschwiler 2007). Besides, decomposition of leaf litter is a complex process, and it is also obviously influenced by the soil properties of the incubation medium. Li et al. (2012) observed that after a 120-d incubation of litter mixtures from *L. principis-rupprechtii* and *P. orientalis* or *P. tabulaeformis*, properties of the soil, such as microbe quantity, enzyme activity, pH etc., had been altered to some extent or significantly. Kourtev et al. (2000) investigated the effects on soil properties of mixed-species litter decomposition from *Berberis thunbergii*, *Microstegium vimineum*, *Quercus prinus*, and *Betula lenta*, and suggested that the activities of soil cellulase, aminopeptidase, and phosphatase activity were altered after incubation. Similar changes in soil urease, invertase, and dehydrogenase were reported by Hu et al. (2006) in a study on the mixed litter decomposition from *Codonopsis lancceolata*, *Alnus cremastogyne*, and *Liquidambar formosana*. Kaneko and Salamanca (1999) observed that soil biological abundance obviously improved after mixed litter decomposition. These alterations in the soil in turn affected the processes of decomposition and nutrient release, as mixing of different litters could lead to a complement in nutrient types and contents, which provided a more-favorable environment for soil microorganisms with different nutritional requirements. In this way, the microbe quantity and activity, and community structure were optimized, and a good microbial system in turn accelerated the decomposition of the leaf litter (Yang et al. 2011). In addition, changes in soil enzyme activity would affect decomposition and nutrient release of some specific substances.

Our results indicated that viewed only in terms of the effects of mixed-species leaf litter decomposition on nutrient release, *L. principis-rupprechtii* is suitable to form mixed forests with *U. pumila*, *P. tabulaeformis*, or *B. platyphylla*, but is not suitable with *P. orientalis*, *R. pseudoacacia*, or *P. simonii*. However, because a concordant interspecific relationship covers many aspects, we still need to study competition of ecological factors including light, heat, water, air, nutrients, and others between species that are planned to form mixed forests.

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LITERATURE CITED

Aerts R, de Caluwe H. 1997. Nutritional and plant-mediated controls on leaf litter decomposition of *Carex* species. Ecology 78(1):244-60.

Ball BA, Bradford MA, Hunter MD. 2009. Nitrogen and phosphorus release from mixed litter layers is lower than predicted from single species decay. Ecosystems 12(1):87-100.

Bao SD. 2000. Soil and agricultural chemistry analysis, 3rd edition. Beijing, China: China Agriculture Press. 116-151 p. [in Chinese].

Bayala J, Mando A, Teklehaimanot Z, Ouedraogo SJ. 2005. Nutrient release from decomposing leaf mulches of karate (*Vitellaria paradoxa*) and nere (*Parkia biglobosa*) under semi-arid conditions in Burkina Faso, West Africa. Soil Biol Biochem 37:533-9.

Bonanomi G, Incerti G, Antignani V, Capodilupo M, Mazzoleni S. 2010. Decomposition and nutrient dynamics in mixed litter of Mediterranean species. Plant Soil 331(1-2):481-96.

Briones MJI, Ineson P. 1996. Decomposition of eucalyptus leaves in litter mixtures. Soil

Biol Biochem 28:1381-8.

Chen F, Cao H, Pu LJ, Peng BZ. 2002. Effects of Zn^{2+} on microbial biomass carbon and respiration in soil. Chin J Inorg Chem 18(4):404-8. [in Chinese with English summary].

Conn C, Dighton J. 2000. Litter quality influences on decomposition, ectomycorrhizal community structure and mycorrhizal root surface acid phosphatase activity. Soil Biol Biochem 32:489-96.

Devi NB, Yadava PS. 2010. Influence of climate and litter quality on litter decomposition and nutrient release in sub-tropical forest of northeast India. J For Res 21(2):143-50.

Gallardo A, Merino J. 1993. Leaf decomposition in two Mediterranean ecosystems of southwest Spain: influence of substrate quality. Ecology 4(1):152-61.

Gartner TB, Cardon ZG. 2004. Decomposition dynamics in mixed-species leaf litter. Oikos 104(2):230-46.

Gnankambary Z, Bayala J, Malmer A, Nyberg G, Hien, V. 2008. Decomposition and nutrient release from mixed plant litters of contrasting quality in an agroforestry parkland in the south-Sudanese zone of West Africa. Nutr Cycl Agroecosyst 82(1):1-13.

Gusewell S, Gessner MO. 2009. N: P ratios influence litter decomposition and colonization by fungi and bacteria in microcosms. Funct Ecol 23(1):211-9.

Hattenschwiler S, Jorgensen HB. 2010. Carbon quality rather than stoichiometry controls litter decomposition in a tropical rain forest. J Ecol 98(4):754-63.

Hattenschwiler S, Tiunov AV, Scheu S. 2005. Biodiversity and litter decomposition in terrestrial ecosystems. Annu Rev Ecol Evol Sci 36:191-218.

Hoorens B, Aerts R, Stroetenga M. 2003. Does initial litter chemistry explain litter mixture effects on decomposition? Oecologia 137(4):578-86.

Hu YL, Wang SL, Zeng DH. 2006. Effects of single Chinese fir and mixed leaf litters on soil chemical, microbial properties and soil enzyme activities. Plant Soil 282(1-2):379-86.

Jacob M, Weland N, Platner C, Schaefer M, Leuschner C, Thomas FM. 2009. Nutrient release from decomposing leaf litter of temperate deciduous forest trees along a gradient of increasing tree species diversity. Soil Biol Biochem 41(10):2122-30.

Kaneko N, Salamanca EF. 1999. Mixed leaf litter effects on decomposition rates and soil microarthropod communities in an oak-pine stand in Japan. Ecol Res 14(2):131-8.

Kominoski JS, Pringle CM, Ball BA, Bradford MA, Coleman DC, Hall DB, et al. 2007. Nonadditive effects of leaf litter species diversity on breakdown dynamics in a detritus-based stream. Ecology 88:1167-76.

Kourtev PS, Ehrenfeld JG, Huan WZ. 2000. Enzyme activities during litter decomposition of two exotic and two native plant species in hardwood forests of New Jersey. Soil Biol Biochem 34:1207-18.

Kwabiah AB, Voroney RP, Palm CA, Stoskopf NC. 1999. Inorganic fertilizer enrichment of soil: effect on decomposition of plant litter under subhumid tropical conditions. Biol Fert Soils 30(3):224-31.

Lehto T, Aphalo PJ, Saranpaa P, Laakso T, Smolander A. 2010. Decomposition and element concentrations of Norway spruce needle litter with differing B, N, or P status. Plant Soil 330:225-38.

Li LJ, Zeng DH, Yu ZY, Fan ZP, Yang D, Liu YX. 2011. Impact of litter quality and soil nutrient availability on leaf decomposition rate in a semi-arid grassland of Northeast China. J Arid Environ 75:787-92.

Li QL, Moorhead DL, DeForest JL, Henderson R, Chen JQ, Jensen R. 2009. Mixed litter decomposition in a managed Missouri

Ozark forest ecosystem. For Ecol Manage 257(2):688-94.
Li Q, Liu ZW, Mi CH. 2012. Effects of mixing leaf litter from *Pinus sylvestris* var. *mongolica* and *Larix principi-rupprechtii* with that of other trees on soil properties in the Loess Plateau. Acta Ecol Sin 32(19):6067-75. [in Chinese with English summary].
Liao LP, Ma YQ, Wang SL, Gao H, Yu XJ. 2000. Decompositions of leaf litter of Chinese fir in mixture with major associated broad-leaved plantation species. Acta Phytoecol Sin 24(1):27-33. [in Chinese with English summary].
Liu ZW, Duan EJ, Fu G, Cui FF, Gao WJ. 2007. A new concept: soil polarization in planted pure forest. Acta Pedol Sin 44(6):1119-26. [in Chinese with English summary].
Loranger G, Ponge JF, Imbert TD, Lavelle P. 2002. Leaf decomposition in two semi-evergreen tropical forests: influence of litter quality. Biol Fert Soils 35:247-52.
Musvoto C, Campbell BM, Kirchmann H. 2000. Decomposition and nutrient release from mango and miombo woodland litter in Zimbabwe. Soil Biol Biochem 32:1111-9.
Olson JS. 1963. Energy storage and the balance of producers and decomposition in ecological systems. Ecology 44:332-41.
Osono T, Takeda H. 2005. Decomposition of organic chemical components in relation to nitrogen dynamics in leaf litter of 14 tree species in a cool temperate forest. Ecol Res 20:41-9.
Parton W, Silver WL, Burke IC, Grassens L, Harmon ME, Currie WS, et al. 2007. Global-scale similarities in nitrogen release patterns during long-term decomposition. Science 315:361-4.
Qiu S, McComb AJ, Bell RW. 2012. Leaf litter decomposition and nutrient dynamics in woodland and wetland conditions along a forest to wetland hillslope. ISRN Soil Sci 2012:1-8.
Ranjbar F, Jalali M. 2012. Calcium, magnesium, sodium, and potassium release during decomposition of some organic residues. Commun Soil Sci Plan 43(4):645-59.
Schimel JP, Hattenschwiler S. 2007. Nitrogen transfer between decomposing leaves of different N status. Soil Biol Biochem 39:1428-36.
Song FQ, Fan XX, Song RQ. 2010. Review of mixed forest litter decomposition researches. Acta Ecol Sin 30(4):221-5.
Teklay T, Malmer A. 2004. Decomposition of leaves from two indigenous trees of contrasting qualities under shaded coffee and agricultural land-uses during the dry season at Wondo Genet, Ethiopia. Soil Biol Biochem 36:777-86.
Wedderburn ME, Carter J. 1999. Litter decomposition by four functional tree types for use in silvopastoral systems. Soil Biol Biochem 31(3):455-61.
Xu X, Hirata E. 2005. Decomposition patterns of leaf litter of seven common canopy species in a subtropical forest: N and P dynamics. Plant Soil 273:279-89.
Yang YH, Zheng L, Duan, YZ. 2011. Leaf litter decomposition and nutrient release of different stand types in a shelter belt in Xinjiang arid area. Chin J Appl Ecol 22(6):1389-94. [in Chinese with English summary].