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Responses of decomposition rate, nutrient return, and composition of leaf litter to thinning intensities in a *Pinus tabulaeformis* plantation

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Abstract It is important to study the effect of tree density on the substrate quality and decomposition rate of leaf litter in plantations. In 2002, an experiment of the effects of thinning intensities at four different levels (i.e., 0 (I), 35.7% (II), 49.2% (III), and 64.2% (IV)) on undergrowth were carried out in an 18-year-old *Pinus tabulaeformis* plantation at an initial density of 3130 trees/hm² in the middle of the hills of Yingpan, Yanqing County, Beijing. Three years later, the rates of decomposition, the amount of nutrients returned, and the characteristics of leaf litter were compared by a litter bag method. The results show that the annual loss of dry matter of leaf litter in plots I, II, III, and IV was 25.81%, 26.25%, 27.68%, and 25.96%, respectively. The turnover of leaf litter was 10.04, 9.84, 9.24, and 9.97 years, respectively. Therefore, it is feasible and convenient to evaluate the effect of thinning on the rate of decomposition. In the first two months, the N, P, K, and Mg nutrients were released quickly. During the entire observation period of 14 months, the return of both N and Mg nutrients in the four plots exhibited a release-accumulation type of cycle. The return of P and K indicated a trend of release-accumulation and a relative balance. However, the return of Ca was far different from that of the other nutrients in the four plots. The total nutrient return of the four elements N, P, K, and Mg in the plots was 10.806, 31.016, 31.798, and 39.365 g/kg, respectively. Specifically, the quality of leaf litter in plot I was the worst in that N and Ca accumulated only 2.567 and 0.767 g/kg, respectively. Thinning did decrease the ratios of lignin to

N and C to N and accelerated the rate of decomposition of leaf litter. The content of crude ash in leaf litter was enhanced by thinning, which prevented acid material, such as tannins and resins, from returning to the soil. The effect of thinning intensity was evaluated by the ratio of lignin to N, the ratio of C to N, and the ash content in leaf litter.

Keywords *Pinus tabulaeformis*, plantation, thinning, decomposition rate, nutrient return, C/N

1 Introduction

The chemical constituents of elements in plants reflect the mineral nutrients they absorb or accumulate from the soil in some habitat conditions (Hou, 1982). Leaves are the largest components of litter (Nie et al., 1986; Gao, 1987; Zhang et al., 2006), and their rates of decomposition are faster than those of branches and fruit (Shen et al., 1996; Liu et al., 2006). Given that the amount of nutrient restitution via leaf litter to the soil is the largest, it also received the most attention (Shanks et al. 1961; Aerts, 1997; Li et al., 2004). The loss weight rate of leaf litter in different periods is mainly affected by its composition, its decomposition, and the environment (Liu and Li, 1993; Beare et al., 2004). In the same climate zone, the quality of litter plays a major role in decomposition (Aerts, 1997). Therefore, any factor that affects the change of leaf litter quality can be considered as an element responsible for the rate of decomposition. There are many reports (Zhang et al., 2000; Sariyildiz et al., 2003; Li et al., 2004; Yang et al., 2004) about research of factors affecting the rate of decomposition caused by the differences in the quality of the litter substrate, which are essentially caused by the various tree species or by a series of species succession. However, very few studies have examined whether these differences occur in pure plantations at different densities or even the relation between these differences and litter decomposition. Based on the comparison of leaf litter

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components, the rate of decomposition, and nutrient return in Chinese pine plantation at different densities, we discuss the relationship of density, litter, and the rate of decomposition to provide theoretical evidence for tending and thinning regimes.

2 Study area

Our study area was located in Yingpan, Yanqing County, Beijing (40°16'N, 115°40'E). This area is a typically loess region of hills and gullies, at elevations of approximately 800 m above sea level. The highest point is the Foye peak at 1252 m. The site is characterized by a warm temperate continental monsoon climate with a mean annual temperature of 6.7°C, a minimum temperature of $\geq 0^\circ\text{C}$ and a maximum temperature of $\geq 10^\circ\text{C}$ and accumulated temperatures of 3310.7°C and 2939.7°C, respectively. The major soil type is a leached cinnamon soil developed from weathered sandstone. The original vegetation is typical of the flora of Northern China. The dominant plants are *Pinus tabulaeformis*, *Quercus mongolica*, *Rhamnus corylus*, *Vitex nigundo* var. *heterophylla*, *Carex lanceolata*, and *Polygonatum composita*.

The shrub layer of our experimental plantation is dominated by *Spiraea salicifolia*, *Lespedeza bicolor*, *Abelia biflora*, and *Elsholtzia stauntoni*. In the spring of 1987, 3-year-old *P. tabulaeformis* seedlings were planted (1.5 m \times 2 m), forming a plantation area of 12 hm². The survival rate in the plantation is about 90%. In February 2002, the plantation was thinned from below, at four thinning intensities (i.e., 0, 35.7%, 49.2%, and 64.2%). After thinning, the plantations developed into a closed forest. At the beginning of March 2005, four 20 \times 20-m representative plots were chosen for study. The basic conditions investigated are shown in Table 1.

3 Materials and methods

A litter bag technique (Dong et al., 1996) was used to measure the rates of decomposition. Natural litter fall of the plots was collected in the beginning of April 2005. Nylon bags (20 \times 20 cm, 0.5-mm mesh) containing 50 g of leaf litter were randomly placed on the plantation floor at the end of April 2005; 120 litterbags per plot were used in

full contact with the humus layer. For each plot, six litterbags were recovered at 2-month intervals; soil particles and other materials were removed, and the remaining litter was oven dried to measure the residual amounts.

To calculate the dynamics of decomposition of the litter, we used an accumulated mass loss (%) method (Dong et al., 1986; Shen et al., 1996). Ground subsamples were analyzed for total N with Kjeldahl digestion. Total P content was determined by colorimetry with the molybdo-phosphoric blue color method and total K, Ca, and Mg with an atomic absorption spectrophotometer (Bao, 2000). The water content of leaf litter was calculated when it reached a constant weight after oven drying at 80°C for 8 h. Total carbon was determined using a SSM-TOC method. Crude ash content was obtained by a day ashing method. Acid-soluble cellulose was determined using the techniques of Weende. The lignin content was estimated by an acid digestion method.

4 Results and analysis

4.1 Effect of thinning on mass loss rate of leaf litter

In our 18-year-old *P. tabulaeformis* plantation, the response curves of leaf litter and the rates of decomposition in the thinning experiment have the following three characteristics (Fig. 1): 1) both fast and slow rates of decomposition occurred during the year, the dynamics of decomposition were consistent with characteristic changes in precipitation during the year, implying that temperature and humidity are important factors to litter decomposition. 2) During the following year, the rate of litter decomposition was lower in comparison with the synchronization of the previous year (May, June, and July). The entire process of mass loss during the decomposition of litter can be divided into two stages. The most important and fast mass loss stage was a biotic action process, and the second stage consisted of the biological effect of decomposition (Peng and Liu, 2002). The initial decomposed substances were mostly water-soluble material of easily decomposed carbohydrates. The concentration of N, P, and S mainly affected the rate of decomposition. As the decomposition continued, the material difficult to decompose accumulated and slowed down the rates of decomposition. 3) During the

Table 1 General conditions of *P. tabulaeformis* plantation

plot	density/ (trees \cdot hm ⁻²)	reserve density/ (trees \cdot hm ⁻²)	thinning intensity/%	altitude height/m	slope position	aspect	gradient/ $^\circ$	soil thickness/cm
I (slight)	3130	3130	0	877	middle	N	24	56
II (middle)	2917	1875	35.7	880	middle	N	16	53
III (intensive)	3000	1525	49.2	880	middle	N	19	51
IV (super intensive)	3000	1075	64.2	890	middle	N	15	52

entire stage of decomposition, the rates of decomposition varied with different thinning intensities in this even-aged plantation. The results in Table 2 show that the annual dry matter loss of leaf litter in plots I, II, III, and IV was 25.81%, 26.25%, 27.68%, and 25.96%, respectively. The rate of decomposition was the highest in plot III, moderate in plot II, and low in plot I.

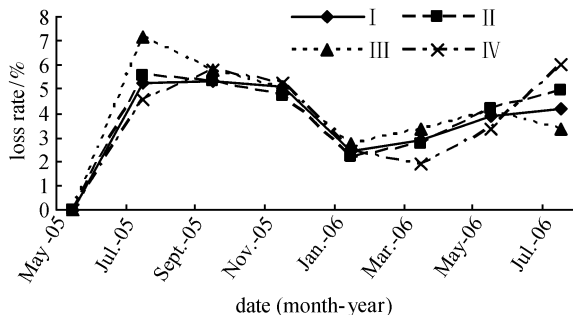


Fig. 1 Weight loss rate of needle litter in a *P. tabulaeformis* plantation

The annual decomposition dynamics were fitted to an Olson exponential decay model (Olson, 1963), where we used the model to estimate the half decomposition period ($t_{0.5}$ and $t_{0.05}$) of litter. According to Table 2, the fastest effect was 9.24 years to decompose 95% of the litter in plot III, but plot I required 10.04 years. Owing to the slow decomposition rate, a great amount of litter was accumulated, and the rate of nutrient transfer to soil was declined

(Liu and Li, 1993). A feasible thinning intensity can promote the decomposition of leaf litter in the *P. tabulaeformis* plantation and will inevitably accelerate the release and return speed of nutrients and therefore improve soil fertility. This effect is important in the difficult-to-decompose leaf litter of *P. tabulaeformis*.

4.2 Effect of thinning on nutrient return of leaf litter

Similar trends are presented for the N, P, K, and Mg contents, with the exception of the dynamic Ca return from the leaf litter in the four plots (Figs. 2–6). The return of N exhibited three cycles with release, accumulation, and diminishing fluctuations over its later range (Fig. 2). The high rate of P release occurred in the first two months but subsequently increased from September to November and remained relatively neutral from November to July in the following year, indicating a balance in the trend of release-accumulation-release (Fig. 3). For K, a high release rate was found during the first two months; after that, it showed a low-level cycle of release-accumulation. The high potential of K leaching from litter decomposition is probably responsible for its movable ionic form, leading to high amounts of return. Perhaps because of the presence of a great deal of nutrient K from soil leaching, the amounts of nutrient K accumulated. Compared with other nutrient, the variation in the Ca content showed a different trend in the entire decomposition process, which suggests that density has an obvious effect on the Ca return. The Mg release was similar to that of N, but the cycle lasted two times (Figs. 2 and 6).

Table 2 Parameters of the rate of decomposition of leaf litter in a *P. tabulaeformis* plantation

plot	initial weight/g	final weight/g	correlation	decomposition time/year	decomposition rate/(g·g ⁻¹ ·year ⁻¹)	half decomposition period/year	turnover/year	loss rate/%
I	252.66	187.46	0.817*	1.167	0.298	2.32	10.04	25.81
II	256.42	189.12	0.864*	1.167	0.304	2.28	9.84	26.25
III	257.31	186.08	0.931**	1.167	0.324	2.14	9.24	27.68
IV	255.46	189.14	0.879*	1.167	0.301	2.31	9.97	25.96

Note: * $p \geq 0.05$; ** $p \geq 0.01$.

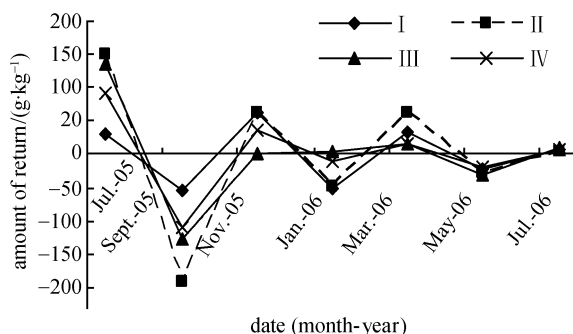


Fig. 2 Dynamic of N return of needle litter in a *P. tabulaeformis* plantation

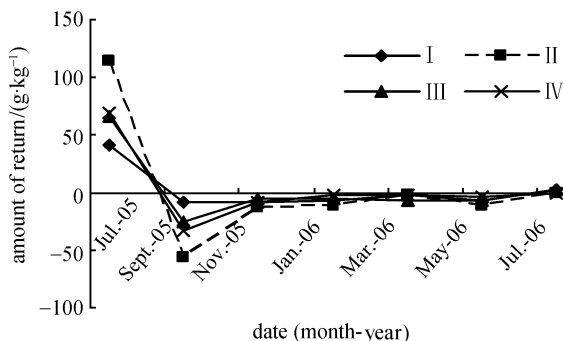


Fig. 3 Dynamic of P return of needle litter in a *P. tabulaeformis* plantation

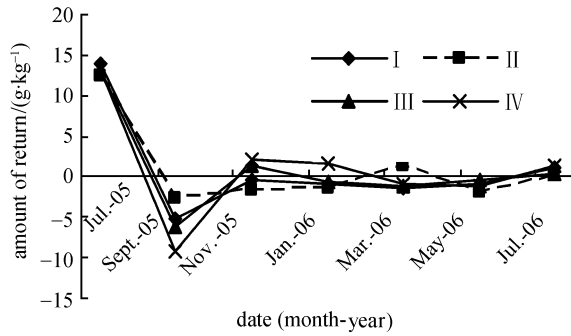


Fig. 4 Dynamic of K return of needle litter in a *P. tabulaeformis* plantation

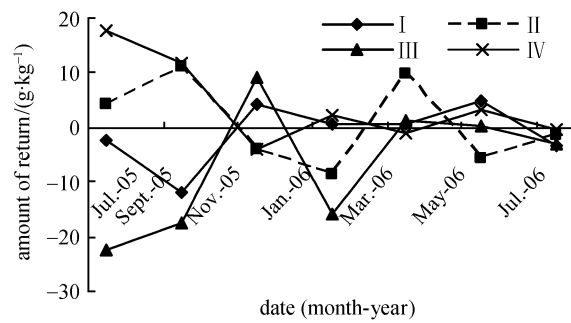


Fig. 5 Dynamic of Ca return of needle litter in a *P. tabulaeformis* plantation

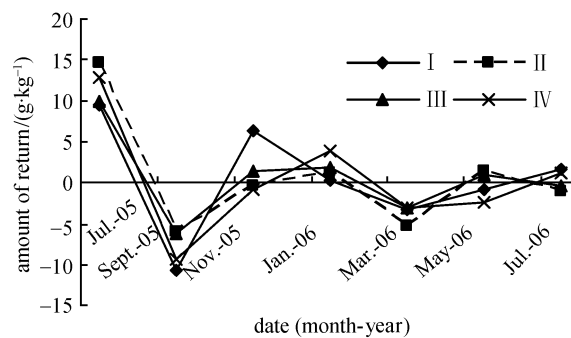


Fig. 6 Dynamic of Mg return of needle litter in a *P. tabulaeformis* plantation

The annual amounts of nutrient return per unit mass through litter fall of the five elements (N, P, K, Ca, and Mg) are shown in Table 3. The highest amount of release of N

Table 3 Nutrient return of leaf litter in a *P. tabulaeformis* plantation at different forest densities (unit: $\text{g}\cdot\text{kg}^{-1}$)

plot	N	P	K	Ca	Mg	total
I	-2.567	7.955	5.101	-0.767	1.084	10.806
II	5.378	12.226	6.206	1.924	5.282	31.016
III	1.968	17.409	6.325	1.436	4.660	31.798
IV	8.364	18.917	6.039	5.267	0.778	39.365

Note: Positive values represent release of elements; negative values represent absorption of elements.

(8.364 g/kg) was found in plot IV, whereas that in plot II (5.378 g/kg) took second place. N and Ca accumulated 2.567 and 0.767 g/kg, respectively, in the leaf litter of plot I. The amount of P released per unit weight increased with thinning intensity. The peak amounts of K and Mg released appeared in plots III and II, but the low points appeared in plots I and IV. The total nutrient returns of the four elements (N, P, K, and Mg) in the plots were 10.806, 31.016, 31.798, and 39.365 g/kg, respectively. Among these elements, P has the maximum amount of release, and K took second place. However, the returns of N, Mg, and Ca seemed to change irregularly. Specifically, the total amounts released should not be considered an absolute indicator for the effect of thinning intensity for it cannot reflect the composition ratio of elements, and the nutrient utilization by plants was unbalanced.

4.3 Thinning effect on major chemical constituents of leaf litter

Thinning changed the material composition of leaf litter, and the chemical constituents varied with thinning intensity. The crude ash content of leaf litter in plots I, II, III, and IV was 5.21%, 6.14%, 6.11%, and 6.07%, respectively, and exhibited an irregular, inverted V-type response. However, the insoluble acid ash exhibited a slanting peak V-type response. *P. tabulaeformis* is an oligotrophic tree, with a crude ash content inside of about 5% (Wu et al., 2005). The absolute content of crude ash in the leaf litter was less than 5.21% in the control plot (i.e., plot I) but increased to 6.14% after thinning in plot II. The enhanced crude ash content resulted in a decline of acid material such as tannins and resins returning to the soil, which reduced the trend of soil acidification, caused by the higher rate of decomposition (Table 4).

Table 4 Chemical composition of leaf litter in a *P. tabulaeformis* plantation

plot	crude ash/%	acid-insoluble ash/%	acid-soluble cellulose/%	cellulose/%	lignin/%	coarse fat/%	coarse protein/%	C/%	N/%	lignin/N	C/N
I	5.21aA	1.89bB	55.00bB	21.90bA	31.30cC	14.04dD	3.47aA	49.09bB	1.79aA	17.45	27.38
II	6.14bB	1.63aA	55.80bB	23.80cB	30.40bB	9.43bB	4.12bcB	48.07aA	1.84aA	16.51	26.10
III	6.11bB	1.59aA	50.60aA	21.20aA	27.80aA	8.21aA	4.22cB	49.79cC	1.94bB	14.36	25.72
IV	6.07bB	1.94bB	55.20bB	21.40abA	31.80dC	10.10cC	3.89bB	49.43bcBC	1.82aA	17.52	27.23

Note: Means within a column with capital and small letters show significant difference using the LSD test at the 0.01 and 0.05 probability level, respectively.

Swift et al. (1981) referred to the chemical properties of litter as substrate quality and defined the relative ability of litter to be decomposed as dependent on a combination of easily decomposed components (e.g., N and P) and difficult decomposed organic components (lignin, cellulose, hemicellulose and polyphenols, and others) and even related it to the nutrient content and structure of tissues. Both acid detergent fibers and cellulose showed their highest content in plot II, whereas plot I took second place, and plot III presented the lowest content. The content of lignin and crude fat performed a V-type response. Especially, the leaf litter from plot III had the lowest concentration of acid-soluble cellulose, cellulose, lignin, and coarse fat. Given the contrast with the concentration of easily decomposed components such as coarse protein and N, we conclude that plot III had the best substrate quality.

The ratios of lignin to N and C to N were completely opposite to the rates of decomposition (i.e., the lowest ratios of C to N and lignin to N coincided with the highest rates of decomposition) (Table 2). Thinning affects the rates of litter decomposition by changing the ratios of lignin to N and C to N. Plot III had the lowest lignin/N and C/N ratios and also the highest rates of decomposition and nutrient release. Therefore, the effect of the interaction between the C source and nutrient contents is more important than their single actions. It is important to evaluate the effect of thinning intensity by analyzing the initial properties of leaf litter in *P. tabulaeformis* plantations, especially the ratios of lignin to N and C to N.

5 Conclusions and discussion

Element movements often present different patterns in decomposition processes, such as leaching-accumulation-release, accumulation-release, or direct release. N concentration in decomposing litter showed a decreasing trend (0–90 d) and an increasing trend (90–150 d); the release-accumulation pattern played out three times in one year, which is different from other decomposition patterns: a constant accumulation during a whole year occurred in *Cunninghamia lanceolata* (Yang et al., 2004), an initial immobilization followed by a gradual release was evident in *Fokienia hodginsii* (Yang et al., 2004), *Eucalyptus grandis* (Liu et al., 2006), and *Cyclobalanopsis glauca* (Zhao et al., 2006). After the decomposition of organic compounds, all nutrient elements were gradually released to the soil for reutilization. The concentration of increased N may have occurred when the release rate was slower than the mass loss of litter (Dong et al., 1986). Because of the rapid ability of metal ions to be leached, the concentration of K and Mg showed a declining trend in the early period and a rising trend at the latter stages. A similar trend was noticed in the case of *P. massoniana* (Shen et al., 1996). However, the concentration of K and Mg showed a monotone decreasing trend in

Cyclobalanopsis glauca but increased in *Cunninghamia lanceolata*. Analysis of *Eucalyptus grandis* at four densities by Liu et al. (2006) found that density had its greatest effects on P, but the effect of litter on the decomposition dynamics of N, K, Ca, and Mg at different densities was different. The tendency of N, P, K, and Mg decomposition was similar, but the amounts released or accumulated changed. Thinning has its greatest effect on the decomposition of Ca, for which the decomposition dynamics were different at the various densities.

The climate conditions, appearances, species, aspects, position, and other facets are factors of litter decomposition. Liu et al. (2006) reported that density was correlated with leaf and branch litter decomposition, but the reasons for the difference were not discussed. Litter decomposition in our *P. tabulaeformis* plantation was limited by internal factors of litter, whereas thinning optimized the litter quality. This could be interpreted from two aspects: first, thinning alters the microenvironment and forest soil that results in a change of tree growth and a decrease in the contents of components difficult to decompose. With the lower ratios of lignin/N and C/N (Table 4), the rate of litter decomposition in plots II, III, and IV were 1.70%, 7.25%, and 0.58% (Table 2) higher than those of the unthinned part of the plantation. At the same time, the amounts of nutrients returned increased 1.87, 1.94, and 2.64 times, respectively (Table 3). On the other hand, needles contain large amounts of acid material such as tannins and resins. With an increase in the rate of decomposition, the return of decomposed needles inevitably leads to a decrease in the pH of soils. However, the content of crude ash in the leaf litter was enhanced by thinning (Table 4). Crude ash neutralizes acid material, which may be one of the effects of thinning. Higher litter rates of decomposition promote the speed of available nutrients returning to the soil, solving the contradiction between litter accumulation and decomposition as the key measure to improve the ability of soil self-fertility in this *P. tabulaeformis* plantation. The results from this study show that thinning is the ideal model to solve the problem of soil self-fertility.

The external environment can be divided into two kinds: biological and abiological. The process of litter decomposition is largely the action of fungi and microorganisms. Their own ratios of C/N or C/P were usually smaller than that of litter and they have higher demands in terms of nutrients (Li and Chen, 2004). Density had significant effect on the initial concentration of N. Its concentration was 1.94% in the needles of *P. tabulaeformis* trees at a density of 1525 trees/hm². The high initial N content in litter is responsible for the high level of decomposition because of enhanced microbial growth and activity. Additionally, many studies have reported that the physical environment (variable latitude and elevation, water, temperature, light, etc.) can impact litter decomposition (Peng and Liu, 2002; Li and Chen, 2004). Thinning may cause changes in hydrothermal conditions, but further

quantitative studies of whether the rate of decomposition is affected by the microenvironment should be carried out. Litter decomposition in our study was limited by internal and external factors. It is of vital importance to prove that the substrate quality of even-aged *P. tabulaeformis* plantations and the contribution ratios of the indirect factors mentioned earlier have an effect on the rate of decomposition.

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