Forest gap size can efficiently promote litter decomposition and nutrient release in south-western China

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Forest gaps are important in forest dynamics and management; however, the gap size that is most conducive to the decomposition of litter and promotion of nutrient cycling in forests remains poorly understood. The mass loss and nutrient release from *Pinus massoniana* and *Toona ciliata* litter in response to gap size classes were determined in south-western China during a 1.5-year litter decomposition experiment. One site with a closed canopy (CK) and seven sites with forest gaps of 100, 225, 400, 625, 900, 1 225 and 1 600 m² were established in a *P. massoniana* plantation in the Sichuan Basin of China; the CK site (fully shaded) was treated as the control. After 540 d, the mass and carbon (C), nitrogen (N) and phosphorus (P) contents in the litter of the control treatments decreased by 58.23%, 60.81%, 65.62% and 57.82% for *P. massoniana* litter and by 91.17%, 80.76%, 73.66% and 64.55% for *T. ciliata* litter, respectively, compared with the initial amounts. Most of the C, N and P were released from both tree species during the first 90 d of decomposition, although the temperature and moisture conditions were very low. The mass loss and C and N release rates for the two tree species and the P release rate from *T. ciliata* litter were higher in the 400–900 m² gap sites than in the other gap sites and the CK site, whereas the P release rate from *P. massoniana* litter was greater under large and medium-sized gaps (400–1 600 m²). The mass loss and C and N release rates for the two tree species and the P release rate from *T. ciliata* litter were positively correlated with the soil moisture content in the seven different gap size treatments, with the soil moisture content representing the best predictor of litter decomposition. Therefore, our results indicate that medium-sized gaps (400–900 m²) can promote decomposition by changing the environmental conditions and may accelerate nutrient cycling in forest ecosystems.

Keywords: gap size, litter decomposition, nutrient release, *Pinus massoniana*, *Toona ciliata*

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Introduction

Plant litter decomposition is one of the most important ecosystem processes for nutrient cycling (Chen et al. 2001; Wang et al. 2010; Berg and McClaugherty 2013) and the primary nutrient source within forest meta-ecosystems or the set of individual ecosystems connected by spatial flows of energy, materials and organisms across ecosystem boundaries (Loreau et al. 2003). Rates of litter decomposition greatly influence nutrient availability and other ecosystem processes (Vitousek and Howarth 1991), such as other biogeochemical cycles, energy flow, and primary to secondary and decomposer production (Gosz et al. 1973, 1976). The elemental composition of litter, including the carbon (C), nitrogen (N) and phosphorus (P) concentrations and the C/N ratio, not only affects rates of mass loss but also rates of nutrient cycling (Campo et al. 2007; Ping et al. 2007; Manzoni et al. 2010). Specifically, N and P are the most important limiting elements for vegetation (Vitousek and Howarth 1991) and play crucial roles in maintaining soil fertility and ecosystem productivity in most terrestrial ecosystems (Parton et al. 2007). Given the complex and diverse terrain conditions in China, applying large-area fertilisation to forestland is difficult at present.

The release and circulation of various nutrients during litter decomposition has an irreplaceable role in maintaining and improving the productivity of forestland. Generally, litter decomposition is primarily modulated by biotic factors, such as soil fauna communities, microbial activity and abiotic factors, including the physical and biochemical environment and litter quality (Prescott et al. 2000; Prescott 2002; Pablo et al. 2013; He et al. 2016). For example, Parton et al. (2007) showed that climate and litter quality explain approximately 60%–70% of global litter decomposition rates, with climate directly altering litter decay because of the sensitivity of soil biological processes to climatic factors, such as temperature or precipitation. Most empirical research on this topic has focused on annual litter amounts and composition (Berg and McClaugherty 2013), seasonal dynamics, nutrient element measurements (Campo et al. 2007; Manzoni et al. 2010) and litter dynamic impact factors (Chen et al. 2001) under different forest types. However, the effects of forest gaps on such rates are typically idiosyncratic (Hooper et al. 2000). Forest gaps are a common natural phenomenon in forest ecosystems and represent an indispensable and inevitable
stage of the forest growth cycle (Whitmore 1989). Forest gaps caused by the death of individual or multiple trees of different size classes can affect these factors and greatly influence plant litter decomposition (McCarthy 2001; Prescott 2002; Prescott et al. 2003). For example, studies have found that litter decomposition rates are lower in larger gaps than in smaller gaps or under closed canopies (Zhang and Zak 1995; Prescott et al. 2003; Ritter 2005). Therefore, understanding the nutrient cycling of forest ecosystems is of great significance for studying the effect of forest gaps on litter decomposition.

The formation of forest gaps not only changes plant diversity in the forest ecosystem inside and outside of the gap (Mallick et al. 2014), but also alters the decomposition environment by redistributing precipitation and light and altering the soil fauna community via changes to the substrate quality and hydrothermal dynamics of the soil (Whitmore 1989; Ritter 2005). An opening of the forest canopy results in increased total incident light levels at the ground level and can lead to increased nutrient and moisture availability. For instance, Arunachalam and Arunachalam (2000) found that the light intensity showed a gradual increase as the size of the gap increased, and the significantly higher light intensity in gaps contributed to high air and soil temperatures in the forest microenvironment. The above microclimatic factors promote the rapid decomposition process on the forest floor (Arunachalam et al. 1996). Moreover, an opening of the canopy corresponds to higher rainfall at the ground level, which can accelerate the decomposition of litter because of excessive erosion/leaching of litter (Arunachalam and Arunachalam 2000).

The microclimate of gaps may enhance seed germination and increase growth rates of herbs and woody species compared with that of the forest understory (Denslow and Spies 1990; Goldblum 2010). However, changes in abiotic and biotic conditions depend both on the gap size and within-gap position (Holeksa 2003; Kwit and Platt 2003). Arunachalam et al. (1996) have shown that the soil bacteria count is higher in gaps sized 306.9–981.8 m², and previous research by Muscolo et al. (2007) and Ou et al. (2014) have also found that the microbial biomass C, microbial biomass N and microbial biomass P are lower in larger gaps (1 520–1 600 m²). These results indicated that any change in gap size may affect nutrient cycling processes and microclimate and thus the pattern of litter decomposition in forest ecosystems. Previous studies have demonstrated that forest gaps are important controls on the dynamics of litter nutrients. For example, Zhu et al. (2013) found that in certain ecosystems, the microenvironments from the centre of a forest gap to the closed canopy differ significantly in the growing season relative to the microenvironments in winter because the centre receives more solar radiation and precipitation than the closed areas during the growing season. Thus, a greater understanding of gap sizes and their effects on the decomposition dynamics of nutrient release is needed.

Forest plantations support local and global demands for wood and account for an area of approximately 0.2 billion ha worldwide (FAO 2007), and are becoming an increasingly important component of the world’s forests. Pinus massoniana is the second most common species used for afforestation and represents a common choice for reforestation in southern China because it is fast growing and highly adaptable to various environments (Lin et al. 2004). Since the early 1950s, the planting of P. massoniana has substantially increased because of its ornamental and economic values (Tian and Xiao 1995). Based on the Eighth Nation’s Forestry Survey of China, P. massoniana covered an area of approximately 12.035 million ha by the end of 2008. This species is a highly valuable forest tree and presents economic, social and ecological benefits that could prove helpful in combating climate change (Feng et al. 2013). However, large-scale monoculture P. massoniana plantations have been linked to the spread of pests and diseases, present lower species diversity and introduce other ecological problems for native forests (Yang et al. 2012), all of which have seriously restricted the sustainable development of forestry in this region. In addition, given its low N content and high C/N ratio, the foliar litter of monoculture coniferous plantations is slowly decomposed and the litter readily accumulates in the forest, which leads to slow nutrient return and infertile soils. Related studies have shown that the annual litter of P. massoniana is 2.57 t hm⁻¹ a⁻¹ (Yang et al. 2010). Toona ciliata is a native tree species in south-western China that is strongly acid resistant and generates large inputs of fallen leaves. Toona ciliata is resistant to many heavy metals, including lead and cadmium, and the leaf litter of T. ciliata is rich in nutrients, particularly C, N and P, which can improve soil conditions (Hu et al. 2012). Therefore, T. ciliata can be used as a mixed tree species in P. massoniana plantations to create a pine–broadleaf mixed forest to promote the decomposition of coniferous leaf litter and improve the quality of infertile soils. Associated research will provide theoretical suggestions regarding managed plantations of multiple tree species in the southern region of China. Studying litter mass loss and the dynamics of C, N and P release during T. ciliata litter decomposition in different-sized gaps of P. massoniana plantations is important for understanding the mechanisms of litter decomposition and improving the management of plantations. Therefore, based on these previous studies, the aims of this study were to (1) explore the gradient of forest gap sizes, which is conducive to litter decomposition; and (2) reveal the relationships between the decomposition rates of P. massoniana and T. ciliata leaf litter and environmental factors (temperature and moisture) caused by different-sized gaps. Thus, field experiments were conducted in a pure P. massoniana plantation using freshly senesced leaf litter of P. massoniana and T. ciliata. To examine the effects of forest gap size on litter mass loss and C, N and P release, one closed canopy (CK) and seven different-sized forest gaps (100, 225, 400, 625, 900, 1 225 and 1 600 m²) were selected on the upper Yangtze River.

Materials and methods

Study site

The study was conducted in the Laifu region of Gao County, Sichuan Province, south-western China (104°42′ to 104°48′E, 28°11′ to 28°47′N; 380–650 m above sea level) along the upper reaches of the Yangtze River in the
low-lying, hilly land of the Sichuan Basin. The mean annual air temperature and precipitation at the site are approximately 18.1 °C and 1 070 mm, respectively, and the mean monthly maximum and minimum air temperatures are 36.8 °C (July) and 7.8 °C (January), respectively. The climate is generally characterised as subtropical humid monsoon, and the soil is a Lixisol (FAO 2006). Prior to the establishment of the P. massoniana plantation in 1974, the site was dominated by a secondary mixed forest. When the experiment was established, the average height of the P. massoniana trees was 16 m, the canopy cover was 60%–80%, and the shrub–grass layer cover was 40%–70%. The shrubs were dominated by Mallotus japonicus, Rubus pinnifolius and Myrsine africana; the herbs were dominated by Phytolacca acinosa, Dicranopteris pedata, Miscanthus sinensis, Arthraxon hispidus, Pteridium aquilinum and Setaria plicata.

In October 2011, eight experimental treatments were established: one CK (control plots of 400 m²) and seven forest gaps (small: 100 and 225; medium: 400, 625 and 900; and large: 1 225 and 1 600 m²). The forest gaps were created by cutting and then removing all trees and harvesting the residue. The forest floor remained undisturbed and in its natural condition, and the plot shape was approximately square. All treatments were replicated three times.

In August 2013, soil samples were collected from a depth of 0–5 cm from all treatments via cutting rings, and the bulk density and porosity of the samples were measured (Table 1). For each treatment, the relative light intensity (i.e. the actual light intensity at the centre of each forest gap/the light intensity in an adjacent open space) was measured with a DSZ-10 illuminance meter (Shanghai Precision Instrument Co. Ltd, Shanghai, China) between 10:30 and 11:00 under clear sky conditions (Table 1) (Cui et al. 2014a). The mean altitude, slope and aspect of the three replicates of each treatment were also measured (Table 1).

**Experimental design and sampling**

From September to October 2013, freshly senesced leaves of P. massoniana and T. ciliata were collected from the forest floor in the study area. The leaves were then air-dried for two weeks at room temperature. The nylon mesh bag technique was used to quantify the foliar litter mass loss and C, N and P release. Approximately 10.0 g of air-dried material was placed in each sealed 20 cm × 25 cm bag (mesh size: 0.5 mm top and 0.04 mm bottom). All litter leaves were carefully mixed to ensure sample uniformity before they were placed in the mesh bags. For each of the eight treatments, the bags were placed uncovered with the bottom side down on the undisturbed litter layer from the gap centre to the centre of the CK at 2–5 cm intervals on 17 November 2013. A total of 720 litterbags were used (8 treatments × 5 sampling dates × 3 replicate plots per treatment × 3 replicate samples per plot × 2 tree species).

Foliar litter temperatures were determined by iButton thermometers (Maxim Integrated, San Jose, CA, USA) placed in the litterbags in each gap centre and at the centre of the CK, and temperatures were recorded every 2 h. Soil samples at a depth of 0–5 cm were collected via a cutting ring to determine the soil water content from all treatments on 17 February 2014, 17 May 2014, 17 August 2014, 17 November 2014, and 12 February 2015. The soil water content (%) for the same positions was measured by the dry weighing method and calculated as (wet weight − dry weight) / wet weight × 100.

Three litterbags were randomly sampled from each plot using the three-point method on 17 February 2014, 17 May 2014, 17 August 2014, 17 November 2014 and 12 February 2015, which were 90, 180, 270, 360 and 540 d after the bags were placed in the plots; the litterbags were sealed in plastic bags and returned to the laboratory. Three positions based on three sides of a triangle within each gap centre and the CK were randomly selected for litterbag collection. After removing the arthropods and foreign roots from the litterbags, the retrieved litter was oven dried at 65 °C for 48 h, and then ground and passed through a 1-mm sieve to determine its dry mass and C, N and P concentrations. The initial characteristics of the litter were determined following the same procedure.

**Sample analyses and calculations**

All chemical analyses were performed according to Lu (1999). In brief, the C concentration was determined using the dichromate oxidation–ferrous sulphate titration method, the N concentration was determined using the Kjeldahl method, and the P concentration was determined using the molybdenum blue colourimetric method. All analyses were performed in triplicate. The initial concentrations of C, N and P in the litter of P. massoniana and T. ciliata are shown in Supplementary Table S1. The mass loss and release rates of C, N and P (R_m) were calculated as follows:

### Table 1: Summary of area, locations and environmental characteristics of the plots used in this study (Values presented are means ± SE). CK = closed canopy as control

| Index                          | CK         | 100        | 225        | 400        | 625        | 900        | 1 225       | 1 600       |
|-------------------------------|------------|------------|------------|------------|------------|------------|-------------|-------------|
| Bulk density (g cm⁻³)         | 1.40 ± 0.14| 1.20 ± 0.09| 1.28 ± 0.08| 1.35 ± 0.11| 1.41 ± 0.11| 1.31 ± 0.17| 1.29 ± 0.26| 1.41 ± 0.04|
| Total porosity (%)            | 50.1 ± 2.8 | 52.2 ± 1.8 | 50.0 ± 1.3 | 52.6 ± 4.9 | 45.7 ± 7.7 | 49.9 ± 4.6 | 51.4 ± 4.8  | 45.9 ± 1.7  |
| pH                            | 4.1 ± 0.1  | 4.2 ± 0.3  | 4.2 ± 0.2  | 4.1 ± 0.1  | 4.3 ± 0.2  | 4.4 ± 0.3  | 4.0 ± 0.1   | 4.6 ± 0.2   |
| Altitude (m)                  | 427 ± 2    | 423 ± 1    | 438 ± 2    | 408 ± 2    | 424 ± 1    | 441 ± 3    | 418 ± 2     | 430 ± 1     |
| Slope (°)                     | 23.0 ± 1.5 | 24.5 ± 2.0 | 26.0 ± 1.0 | 23.5 ± 2.5 | 24.0 ± 1   | 21.5 ± 1.0 | 27.0 ± 1.0  | 26.0 ± 1.5  |
| Aspect¹                       | SE         | SW         | SE         | SW         | SE         | S          | SE          | SE          |
| Relative light intensity (%)  | 16.2 ± 1.1 | 71.1 ± 2.1 | 75.5 ± 1.4 | 77.5 ± 1.5 | 80.1 ± 1.1 | 81.3 ± 1.3 | 82.7 ± 1.0  | 84.2 ± 0.9  |

¹ SE = south-east, SW = south-west, S = south
\[ R_{\text{lt}}(\%) = \left( M_0 \times C_0 - M_t \times C_t \right) / M_0 \times C_0 \times 100 \]

where \( M_0 \) is the initial mass of litter; \( C_0 \) is the initial concentration of C, N or P; \( M_0 \) is the remaining mass of litter at the time of sampling; and \( C_t \) is the concentration of C, N or P at the time of sampling.

To exclude the effects of gap size on the mass loss and nutrient release rates for each specific period, the monthly loss rates of mass, C, N and P (\( V_t \)) were calculated using the following equation:

\[ V_t(\%) = \left( \left[ (R_{\text{lt}t-1}) - R_{\text{lt}t} \right] / D \right) \times 30 \]

where \( R_{\text{lt}t} \) and \( R_{\text{lt}t-1} \) represent the rates of release for C, N or P for the current and previous sample dates, respectively; \( D \) is the number of days between the specified and previous sample dates; and \( R_{\text{lt}0} \) is the initial mass loss rate or the initial C, N or P release rate.

**Statistical evaluation**

Prior to the statistical analysis, the data were tested for homogeneity of variance using Levene’s test and transformed when applicable (Bhunia 2013). A two-way analysis of variance (ANOVA) was used to analyse the effects of decomposition time and gap-size classes on mass loss and released C, N and P using the IBM SPSS Statistics 21.0 software (IBM Corporation, Armonk, NY, USA). Any data sets found to be non-significant in this test were log-transformed before further analysis to help satisfy the requirement for homogeneity of variance. Following the results of the ANOVA, Tukey’s honestly significant difference (HSD) test (\( \alpha = 0.05 \)) was used for multiple comparisons to examine significant responses. Then, simple Pearson correlation coefficients were calculated between the mass loss or release rates of C, N and P and environmental factors using IBM SPSS Statistics software.

**Results**

**Temperature and moisture**

The highest average temperature inside the litterbags was observed during the decomposition period from 180 to 270 d (23.94 °C; summer), and the lowest average temperature was observed in the period from 0 to 90 d (8.95 °C; winter). Although the average temperature inside the litterbags did not change significantly with increasing gap size for all decomposition stages (Figure 1a), the highest average temperature inside the litterbags was recorded for the 1 225 m² gap except for the last two decomposition stages (Supplementary Table S2).

Soil moisture showed an increasing trend from the CK to the 100 m² gap, after which it decreased as the gap size increased (Figure 1b). The mean soil moisture was higher in gaps of 100 m² (20.22% to 25.43%) than in the other gaps, except for the last period. The highest soil moisture was observed in the period from 270 to 360 d (25.43%; autumn), and the lowest soil moisture was observed in the period from 90 to 180 d (13.95%; spring) (Supplementary Table S3).

**Litter mass loss rate in different-sized gaps**

Over the 1.5-year incubation period, the foliar litter mass of the different-sized gaps decreased from the initial dry mass by 53.77% (100 m²) and 67.03% (400 m²) for *P. massoniana* and by 90.29% (100 m²) and 95.45% (400 m²) for *T. ciliata*, whereas the CK showed decreases of 53.53% (*P. massoniana*) and 84.53% (*T. ciliata*). The mass loss from *P. massoniana* in the 400 m² gap occurred at a faster rate than that of the other gaps over the period from 270 to 540 d (Figure 2a), whereas the loss from *T. ciliata* in the 400–900 m² gaps occurred at a faster rate than that of the other gaps at all decomposition stages (Figure 2b). The medium-sized forest gaps (400–900 m²) promoted the decomposition of litter. Compared with the CK, intermediate gaps (400–900 m²) had a higher mass loss rate in both types of litter. The litter mass loss rates from *T. ciliata* were the highest during the 1.5-year decomposition process (Figure 2a and b). Gap size had a significant effect on the mass loss rate regardless of litter type (Table 2). The highest mass loss rates of *P. massoniana* and *T. ciliata* litter were observed in 400–900 m² gaps at different periods of decomposition (Figure 2).

**Carbon, nitrogen and phosphorus release rate in different-sized gaps**

The release rates of C, N and P are shown in Figure 3. The initial concentration of total C, total N and total P and N/P ratio in the litter of *T. ciliata* were significantly higher than those of *P. massoniana*, whereas the C/N and C/P ratio were significantly lower than those in *P. massoniana* (Supplementary Table S1). Over the 1.5-year
decomposition experiment, the release rates of C, N and P for *Pinus massoniana* litter ranged from 56.87% (100 m²) to 68.49% (400 m²), 62.19% (225 m²) to 69.51% (400 m²), and 56.60% (100 m²) to 61.95% (1 600 m²), respectively, whereas that of *Toona ciliata* litter ranged from 77.05% (225 m²) to 86.61% (625 m²), 70.91% (900 m²) to 81.10% (400 m²), and 55.14% (225 m²) to 74.80% (400 m²) in the different-sized gaps, respectively. Under the CK, the release rates of C, N and P from *P. massoniana* and *T. ciliata* ranged from 53.68% to 79.03%, 60.99% to 62.90%, and 52.18% to 61.10%, respectively. *Toona ciliata* litter had higher nutrient release rates than *P. massoniana* litter.

The gap-size classes had a significant effect on the nutrient release rates regardless of the litter type (Table 2). The highest release rate of C for *P. massoniana* litter was observed in the 400 and 900 m² gaps except for 270 d of decomposition, the highest release rate of N was observed in the 625 m² gaps at all decomposition stages, and the highest release rate of P was observed in the 100 (90 d), 625 (180 and 360 d) and 1 600 m² gaps (270 and 540 d). Although *T. ciliata* litter had a higher C release rate in the 400–900 m² gaps at all decomposition periods, the highest N release rates were observed in the 100 and 400–900 m² gaps, and the highest P release rates were observed in the 100 and 400–625 m² gaps (Figure 3). Therefore, the C and N release rates for the two litters and the P release rate for *T. ciliata* litter were highest in the medium-sized gaps (400–900 m²). However, the highest rates of P release from *P. massoniana* litter were observed in the large gaps relative to the other gap sizes during the last three collection periods.

**Monthly decomposition rate of the two tree species**

In this study, the highest monthly loss rate ($V_L$) of *P. massoniana* litter was observed during the first 90 d (5.38%) and during the last stage of decomposition (5.65%), whereas the highest value for *T. ciliata* litter was observed only during the first 90 d (14.23%) (Figure 4). The highest $V_L$ of C, N and P were detected during the first 90 d (9.30%, 15.20% and 14.76% for *P. massoniana* litter, respectively, and 17.18%, 15.34% and 12.18% for *T. ciliata* litter, respectively). The enrichment of P occurred in the *P. massoniana* foliar litter at 90–180 d and 270–360 d, whereas it occurred in the *T. ciliata* litter only at 180–270 d.

**Temperature/soil moisture and their correlation with the mass loss and nutrient release rates**

According to the correlation analysis, only the P release rate of *P. massoniana* litter and temperature inside the litterbags showed a significant positive correlation. Regardless of species, the mass loss and release rates of C and N were strongly positively correlated with the soil water content, which indicated that soil moisture affected the mass loss and nutrient release in *P. massoniana* and *T. ciliata* leaf litter (Table 3).

**Discussion**

Our results showed that the gap size had a significant effect on the mass loss and release processes of C, N and P in *P. massoniana* and *T. ciliata* leaf litter. Regardless of the litter type, the mass loss of middle-sized gaps (400 m²) was faster than that of other gaps. When compared with

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**Figure 2:** Mass loss rates of *Pinus massoniana* and *Toona ciliata* litter in different-sized forest gaps over the 1.5-year study. Bars with different letters indicate a significant difference among the different-sized gaps in the same decomposition period ($p < 0.05$).

**Table 2:** Results of two-way ANOVA of the effects of sampling time and different-sized gaps on the mass loss rates and C, N, P release rates for *Pinus massoniana* and *Toona ciliata* leaf litter. The data presented are F-values. $M_{LR}$ = mass loss rate, $C_{LR}$ = C release rate, $N_{LR}$ = N release rate, $P_{LR}$ = P release rate, G = gap size, T = sampling time, G (T) = gap size as a fixed factor with sampling time as a nested factor.

| Factor | Pinus massoniana | Toona ciliata |
|--------|------------------|--------------|
|        | $M_{LR}$ | $C_{LR}$ | $N_{LR}$ | $P_{LR}$ | $M_{LR}$ | $C_{LR}$ | $N_{LR}$ | $P_{LR}$ |
| T      | 921.20** | 1 063.52** | 324.28** | 17.02** | 1 695.17** | 478.29** | 425.45** | 86.95** |
| G (T)  | 7.68**   | 9.88**   | 5.91**  | 2.27*   | 29.63**  | 20.62**  | 17.63**  | 4.36*   |

* $p < 0.05$, ** $p < 0.01$
the CK, intermediate gaps (400–900 m²) also had a higher mass loss rate in the two types of litter. Moreover, the C and N release rates for the two litters and the P release rate for *T. ciliata* litter were highest in the medium-sized gaps (400–900 m²). However, higher rates of P release from *P. massoniana* litter were observed in the large gaps than the other gaps during the last three periods. These results indicated that a medium-sized gap (400–900 m²) is conducive to optimal mass loss and nutrient release during the litter decomposition process.

**Effects of gap sizes on decomposition of *P. massoniana* and *T. ciliata* leaf litter**

Forest canopy gaps are considered one of the most important factors affecting forest ecosystem dynamics (Hill et al. 2005), and the gap size is the most important characteristic of these gaps. The microclimatic environment of light and humidity differs with the gap size and affects the soil nutrient characteristics, soil fauna and microbial activity and litter decomposition. Several studies have demonstrated that temperature and moisture are the most important factors that control litter mass loss, and gap size affects litter temperature and soil moisture because the amount of light and rainfall received on the forest floor is directly related to the size of the canopy opening (Adair et al. 2008; Cusack et al. 2010). First, the soil moisture content in the 100 m² gap is higher than that of the other gap sizes (Figure 1b), and canopy shelter can reduce the light intensity in small gaps (100–400 m²), especially in the 100 m² gap, which limits the activity of soil fauna and microbes adapted to dry environments (Zhu et al. 2003). Second, the large gaps (1 225–1 600 m²) received more solar radiation (Table 1), thus leading to large temperature differences between day and night.

![Figure 3: Release rates of carbon (a), nitrogen (b), and phosphorus (c) of *Pinus massoniana* and *Toona ciliata* litter in different-sized forest gaps over the 1.5-year study. Bars with a different letter indicates a significant difference among the different-sized gaps in the same decomposition period (*p* < 0.05)
Moreover, the evaporation of rain and dew in the large gaps exacerbated changes in the topsoil water content of those gaps (Peng et al. 2003; Zhu et al. 2003). The wetting and drying process apparently inhibits the decomposition of litter by soil fauna and impedes soil nutrient mineralisation, thereby reducing nutrient availability and biological activity, which is consistent with the conclusions of Arunachalam et al. (1996), Gray et al. (2002) and Ou et al. (2014). Furthermore, correlation analysis indicated that soil moisture was positively correlated with the loss rates of mass, C, N and P during the decomposition of P. massoniana and T. ciliata litter (Table 3). Thus, soil moisture may be the dominant factor affecting the decomposition rates in different-sized gaps.

The moderate temperature and humidity of medium-sized gaps were apparently favourable for soil faunal activity and decomposition rates in different-sized gaps. Toona ciliata and P. massoniana plantations. M(LR) = mass loss rate, C(LR) = C release rate, N(LR) = N release rate, P(LR) = P release rate.

Table 3: Correlation coefficients of the mass loss and carbon, nitrogen and phosphorus release rates with temperature in litterbags and soil moisture content in P. massoniana plantations. M_{L(R)} = mass loss rate, C_{L(R)} = C release rate, N_{L(R)} = N release rate, P_{L(R)} = P release rate.

Dynamic changes in mass loss and nutrient release of the two tree species

In this study, the highest monthly loss rate \( (V_L) \) of P. massoniana litter was observed in the first 90 d (5.38%) and the last stage of decomposition (5.65%), whereas the highest value for T. ciliata litter was observed only in the first 90 d (14.23%) (Figure 4), which can be explained by at least three distinct processes. First, the presence of fresh litter with relatively more labile C components may undergo relatively rapid C release (Rouifed et al. 2010; Zhu et al. 2012). Our results also showed that the highest \( V_L \) of C was detected during the first 90 d regardless of the litter type. Second, soluble organic ingredients were likely rapidly released, which contributed to a high mass loss rate in the early period of decomposition (Li et al. 2007). Third, litter with higher initial N concentrations usually shows higher mass loss and respiration rates than litter with lower N concentrations, although the importance of the initial N concentration decreased with time (Vestgarden 2001; Ross et al. 2002), which may explain the rapid surface evaporation, thereby resulting in higher soil water content in the forest (Cui et al. 2014b). The combination of higher and more stable moisture with less variable and more stable temperatures may favour microbial activity (Zhang and Zak 1995). The conclusions of Zhang and Zak (1995) and Arunachalam et al. (1996) have also shown that gap sizes greater than 30 m in diameter lead to significant reductions in soil microbial biomass, whereas gap sizes of 306.9–981.8 m² lead to increases in microbial biomass. Previous investigations by Muscolo et al. (2007) and Ou et al. (2014) have also shown lower levels of microbial biomass C, microbial biomass N and microbial biomass P in larger gaps (1 520–1 600 m²). These changes could weaken the soil microbial decomposition of litter in these larger gaps and may also explain why the small- and large-sized gaps exhibited lower mass loss and release rates of C, N and P during the 1.5-year study period, whereas the medium-sized gaps exhibited the highest mass loss and release rates of C, N and P. Cui et al. (2014a) showed that medium-sized forest gaps have high plant cover and species richness because the lack of light in small forest gaps is not conducive to the growth of species exhibiting shade intolerance; however, the illumination of large forest gaps is too strong to favour species with strong shade tolerance. Thus, the ecological stability of medium-sized forest gaps is stronger and more suitable for the survival of soil organisms (Connell 1978), which results in greater fragmentation of soil animals in litter and the promotion of litter decomposition.

**Figure 4:** Monthly loss rates of mass and carbon, nitrogen and phosphorus of P. massoniana and T. ciliata litter in different-sized forest gaps during the 1.5-year study. Bars with a different letter indicates a significant difference among the different decomposition periods \( (p < 0.05) \).
decomposition of T. ciliata litter in the early stage. However, the thick cuticle and wax layer on the surface of the leaf litter inhibited the decomposition of P. massoniana leaf litter in the first year. Over time, decomposition, leaching, weathering and breakdown by soil fauna will occur, which results in the foliar litter structure becoming more conducive to soil microbial attachment and leads to accelerated soil microbial decomposition of P. massoniana leaf litter (Wang et al. 2010). Therefore, in the last period of this study, the mass loss rate of P. massoniana leaf litter increased significantly because the decomposers could more easily decompose the litter.

The findings also showed that the nutrient release rates of both leaf litter types were initially rapid and then slowed, which is consistent with the results reported by Li et al. (2007) and Huang et al. (2010). In the early period of decomposition, carbohydrates and small molecules in litter are easily and rapidly decomposed by microorganisms and leached by rainfall. With the extension of decomposition time, most of the remaining recalcitrant components in leaf litter will lead to a decrease in the rate of decomposition. Cotrufo and Ineson (1995) found that the initial N content is an important factor that controls the decomposition rate of litter in the early period of decomposition. However, low N contents can decrease the decomposition rates in later stages of leaf litter decay. In this study, the enrichment of P was observed in P. massoniana foliar litter from 90 to 180 d and from 270 to 360 d and in T. ciliata litter from 180 to 270 d, which may be related to the several stages of accumulation, fixation and release that occur in N, P and other nutrient elements (Sun and Liu 2007). During the decomposition process of litter, the content of P decreased due to leaching and other effects; thus, to maintain their own activity, heterotrophs absorb N and P from other sources (such as small animals, soil and water bodies) by the action of exchange and adsorption of decomposing organic matter (Lin et al. 2010). Therefore, enrichment occurs during certain decomposition periods. The lower N and P contents of P. massoniana litter may be the reason for the more obvious P-enrichment phenomenon. Berg (2000) also believed that N and P are immobilised by microorganisms as limiting nutrient elements in the growth and development of microbial communities, and the N and P contents of litter generally increase gradually during decomposition.

**Differences in mass loss and nutrient release rates between the two tree species**

After 1.5 years of decomposition, the mass loss and C, N, and P release rates were 58.23%, 60.81%, 65.62% and 57.82% for P. massoniana litter, respectively, and 91.17%, 80.76%, 73.66% and 64.55% for T. ciliata litter, respectively. The results showed that the decomposition rate of T. ciliata litter was greater than that of P. massoniana litter, which is consistent with the results of Ma et al. (2015). The decomposition rate of litter is affected by internal factors and external environmental factors (Austin and Vivanco 2006). The internal factors are primarily the physical and chemical properties of litter, such as the litter nutrient content and the C/N ratio (McClaugherty et al. 1985). In the early stage of decomposition, N is closely correlated with the growth and reproduction of microorganisms, and litter with high N contents tends to decompose more rapidly. Hättenschwiler (2005) reported that approximately 80% of the decay rate of litter was determined by the C/N ratio, with a low C/N ratio indicating more rapid litter decomposition. Silveira et al. (2011) found that the initial P content is an important indicator of litter quality and litter with a high initial P content often has a high decomposition coefficient. In our study, the initial N content of P. massoniana litter was significantly lower than that of T. ciliata litter, whereas the C/N ratio was significantly higher (Supplementary Table S2), which were likely the primary factors for the slower decomposition of pine litter. In addition, current knowledge indicates that most coniferous trees can produce allelopathic compounds (Kil and Yim 1983), which are not beneficial for decomposition. Furthermore, the decomposition of litter is affected by the texture and structure of the litter. Soil fauna control decomposition processes largely through the breakdown and digestion of litter and subsequent stimulation of microbial activities. Compared with the T. ciliata litter, the P. massoniana foliar litter had a harder texture and therefore was less conducive to soil faunal breakdown. In addition, the hard texture of P. massoniana litter can result in less nutrient leaching (Wang et al. 2013). The texture of the T. ciliata foliar litter was softer than that of pine; therefore, it was more easily decomposed by soil microorganisms and presented greater leaching by rainfall than P. massoniana litter.

**Conclusions**

In summary, most of the mass loss and the nutrient release rates of both leaf litter types were initially rapid and then slowed, and the decomposition rate of T. ciliata litter was greater than that of P. massoniana litter, which is consistent with previous research (Li et al. 2007; Huang et al. 2010; Ma et al. 2015). The mass loss and nutrient release of the litter of the two tree species were generally highest in the medium-sized gaps, which indicated that medium-sized gaps (400–900 m²) could be the optimal size to promote the nutrient release of litter for the two native species in P. massoniana plantations. The forest gap size regulates the dynamics of nutrient release in litter by changing the environmental heterogeneity within the forest gaps, and such effects are dependent on the initial litter quality. The results provide evidence that creating medium-sized forest gaps can be beneficial for managing mixed pine–broadleaf forests in the southern region of China.

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