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格氏栲天然林与人工林凋落物数量、养分归还及凋落叶分解

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摘要:通过对中亚热带格氏栲天然林(natural forest of *Castanopsis kawakamii*,约 150 年生)、格氏栲和杉木人工林(monoculture plantations of *C. kawakamii* and *Cunninghamia lanceolata*,33 年生)凋落物数量与季节动态、养分归还及凋落叶分解与其质量的关系为期 3a 的研究表明,林分年均凋落量及叶所占比例分别为:格氏栲天然林 11.01t/hm^2,59.70t/hm^2;格氏栲人工林 9.54%,71.98%;杉木人工林 5.47t/hm^2,58.29%。格氏栲天然林与人工林凋落量每年只出现 1 次峰值(4 月份),而杉木林的则出现 3 次(4 或 5 月份、8 月份和 11 月份)。除杉木林的 Ca 和格氏栲人工林的 Mg 年归还量最大外,N、P、K 及养分总归还量均以格氏栲天然林的为最大,杉木人工林的最小。分解 1a 后格氏栲天然林中格氏栲叶的干重损失最大(98.16%),杉木叶的最小(60.78%)。C/N 及木质素/N 比值与凋落叶分解速率呈显著负相关,而 N、水溶性化合物初始浓度与分解速率呈显著正相关。与针叶树人工林相比,天然林的凋落物数量大、养分归还量高、分解快,具有良好自我培肥地力的能力。因此,保护和扩大常绿阔叶林资源已成为南方林区实现森林可持续经营的重要措施之一。

关键词:凋落物;养分归还;凋落叶分解;格氏栲;杉木;天然林;人工林

Litter production, nutrient return and leaf-litter decomposition in natural and monoculture plantation forests of *Castanopsis kawakamii* in subtropical China

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Abstract: The amount and pattern of litterfall, its nutrient (N, P, K, Ca and Mg) returns, and leaf-litter decomposition associated with its quality were studied in a natural forest of *Castanopsis kawakamii* (NF)

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and adjacent monoculture plantations of *C. kawakamii* (CK) and Chinese fir (*Cunninghamia lanceolata*, CF) in Sanming, Fujian, China. Mean annual total litterfall over 3 years of observations (from 1999 to 2001) was 11.01 t • hm^{-2} in the NF, 9.54 t • hm^{-2} in the CK and 5.47 t • hm^{-2} in the CF respectively. Of the total annual litterfall in the three forests, leaf contribution constituted 59.70%, 71.98% and 58.29%, respectively. Litterfall in the NF and CK showed similar litterfall pattern with a distinct peak in April of each year. While for the CF, the litterfall peaks occurred in April (or May), August and November, respectively. Except for the highest annual Ca returns in the CF and Mg returns in the CK, the three forests could be arranged in this sequence with respect to annual nutrient returns: NF>CK>CF. The annual percent leaf litter mass loss was the highest for *C. kawakamii* in the NF (98.16%) and the lowest for Chinese fir (60.78%). Ratios of C/N and lignin/N had significantly negative influences on decay rate coefficients, while initial N and water soluble compounds exerted significantly positive influences. The results of this study demonstrate that the natural forest has a greater capability for maintaining site productivity than monoculture plantations due to higher amount and quality of litter coupled with greater nutrient returns and faster litter decomposition. Therefore, conservation of the natural forest is recommended as a practical measure in forest management to realize sustainable development of forestry in mountainous areas of southern China.

Key words: litterfall; nutrient return; litter decomposition; *Castanopsis kawakamii*; *Cunninghamia lanceolata*; natural forest; monoculture plantation

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Due to rapid increase of human population and subsequent demands for timber, fuel material, and other forest products, many natural forests in the world have been converted into plantations to meet these demands[1~6]. However, problems of reducing community diversity, stability and sustainability of woodlands in monoculture plantations have aroused people's worries[2~4]. In South China where high rainfall, steep slopes and fragile soil are characteristic, native broad-leaved forests have been cleared for the last several decades, and successive monoculture plantations of economical conifers are established following clear-cutting, slash burning, and soil preparation. As a consequence, yield decline and land deterioration in such disturbed ecosystem have become serious[5,6].

Natural forest of *Castanopsis kawakamii* located in National Nature Reserve of Xiaohu in Sanming, Fujian represents the precious evergreen broad-leaved *C. kawakamii* forest in mid-subtropical China and unique in the world with its high purity (85% of relative prominence for *C. kawakamii*), old age (about 150 year) and large area (about 700 hm^2)[7,8]. For comparative research on natural and plantation forests, as well as broad-leaved and coniferous trees during the 1960s, part of natural *C. kawakamii* forest was clear-cut to establish a series of pure conifer and broad-leaved tree plantations such as Chinese fir (*Cunninghamia lanceolata*), *Fokienia hodginsii*, *C. kawakamii*, *Ormosia xylocarpa*, *Castanopsis carlesii*, *Cyclobalanopsis glauca* and *Phoebe bournei*. These plantations and adjacent natural forest had homogeneous substrate (similar mineralogy, depths, and horizonation). Several studies have reported community structure and species diversity in natural *C. kawakamii* forest[7,9,10]. Also, difference in vegetation composition, soil fertility and water conservation function between natural and planted forest ecosystems have been examined[11~13]. Especially with recent emphasis placed upon a central role of litterfall in nutrient cycling in forests, many investigations of litterfall have been carried out in natural forests of indigenous and exotic tree species, in monocultural stands as well as in mixed stands[14~16]. However, there is few information on litter comparison between natural and monocultural forests of the same tree species. Therefore, the primary aims of this study, covering a 3 year period, were to: (i) examine the patterns of litterfall in natural *C. kawakamii* forest and two monoculture plantations of *C. kawakamii* and Chinese fir; (ii) quantify nutrient return through litterfall in the three forests; and (iii) determine the relationship between decomposition rate and litter quality.

1 Materials and Methods

1.1 Site descriptions

The natural forest of evergreen broad-leaved *C. kawakamii* (NF) and two monoculture plantation forests of *C. kawakamii* (CK, 33-year-old) and Chinese fir (CF, 33-year-old) study areas were located in *Xiaohu* work area of *Xinkou* Experimental Forestry Centre of Fujian Agricultural and Forestry University, Sanming, Fujian, China (26°11′30″N, 117°26′00″E). It borders the Daiying Mountain on the southeast, and the Wuyi Mountain on the northwest. The region has a middle sub-tropical monsoonal climate, with a mean annual temperature of 19.1℃, and a relative humidity of 81 %. The mean annual precipitation is 1749 mm, mainly occuring from March to August (Fig. 1). Mean annual evapotranspiration is 1585 mm. The growing season is relatively long with an annual frost-free period of around 300 days. Soils under the NF, CK, and CF are red soil derived from sandy shale. Thickness of the soil exceeds 1.0 m. Surface soils (0～20 cm depth) in the three forests have organic matter contents of 45.95, 29.84 and 29.48 $g \cdot kg^{-1}$, total N of 1.876, 1.121 and 1.120 $g \cdot kg^{-1}$ respectively[11]. In 1999, five 20 m×20 m plots were randomly established at the midslope position in the NF, CK and CF, respectively.

The NF area was on northeastern aspects and 31° slope. The floristic composition is very abundant and there were formed 139 species/3100 m^2[7]. Further, community structure was complex and the tree layer can be divided into three sub-layers based on tree height (>18 m, 12～18 m, and 6～12 m, respectively) in which *C. kawakamii* was predominated with mean tree height, *DBH*, density, and stock of 24.3 m, 42.2 cm, 255 stems $\cdot hm^{-2}$, and 398.310 $m^3 \cdot hm^{-2}$, respectively. In addition to *C. kawakamii*, the overstory also contained other tree species, such as *Pinus massoniana*, *Schima superba*, *Lithocarpus glaber*, *Symplocos caudate*, *Machilus velatina*, *Randia cochinchinensis*, and *Symplocos stellaris*, and the stock was 165.155 $m^3 \cdot hm^{-2}$. Shrub layer had two sub-layers (respective <6 m and <2 m in height) and dominated by *Ardisia crispa*, *Vaccinium carlesii*, *Tricalysia dubia*, *Eurga nitida*, and *Ilex pubescens*, with biomass and coverage of 10.115 $t \cdot hm^{-2}$ and about 45%, respectively. The distribution of grasses was scattered and mainly consists of *Amomum villosum*, *Woodwardia japonica*, and *Dicranopteris dichotoma* in herbaceous layer, with biomass of 0.867 $t \cdot hm^{-2}$. The forest floor had biomass of 7.720 $t \cdot hm^{-2}$. In 1966, part of this NF was clear-cut, slashed, and burned. In 1967, the soil was prepared by digging holes and then 1-year-old seedlings of *C. kawakamii* and Chinese fir were planted with density of 3000 trees per hectare.

The CK area was on northeastern aspects and 30° slope. Stand density averaged 875 stems per hectare. The mean tree height and *DBH* were 18.9 m and 24.2 cm, respectively, with standing volume of 412.431 $m^3 \cdot hm^{-2}$. Forest canopy was unistratal, with coverage of 0.95. Understorey vegetation composition and structure was much simpler than in the NF. The species that dominated in shrub layer were *Maesa japonica*, *Ardisia crispa*, *Mussaenda pubescens*, and *Millettia reticulata*, with biomass of 0.780 $t \cdot hm^{-2}$. The herbaceous layer was mostly comprised of *Woodwardia japonica* and *Dicranopteris dichotoma*, and biomass was 0.292 $t \cdot hm^{-2}$. There was 7.441 $t \cdot hm^{-2}$ of biomass in the forest floor.

The CF area was on northeastern aspects and 35°slope, with average stand density of 1117 stems per hectare. Mean tree height and *DBH* were 21.9 m and 23.3 cm, respectively. The stand stock and canopy coverage was 425.912 $m^3 \cdot hm^{-2}$ and 0.85, respectively. The shrub layer had a biomass of 1.993

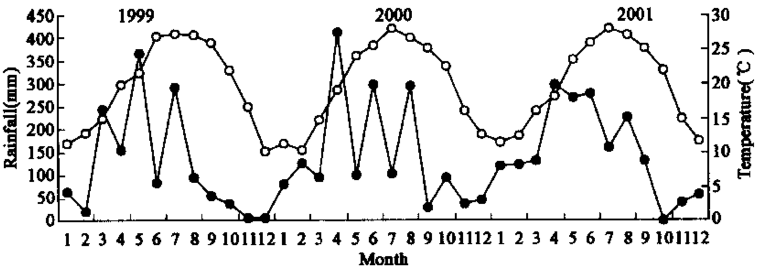

Fig. 1 Temperature and rainfall patterns for the study area

—●— Monthly rainfall —○—Monthly mean temperature

t • hm^{-2}, where *Ficus hirta*, *Rubus palmatus*, and *Ilex pubescens* were predominated. Herbaceous layer was dominated by *Dicranopteris dichotoma*, *Angiopteris fokiensis*, and *Blechnum orientale*, with biomass of 2.478 t • hm^{-2}. The forest floor had a biomass of 3.155 t • hm^{-2}.

1.2 Litter collection

Fifteen 0.5 m×1.0 m litter traps made of nylon mesh (1 mm mesh size) were arranged cater-cornered in each stand and were raised 25cm above the ground, and the litterfall was collected at monthly intervals from January 1999 to December 2001. The collected litter at each time was oven-dried at 80 ℃ to constant weight. At the end of each month, the oven-dried litter was combined and sorted into leaves, small branches ($<$ 2 cm in diameter), flowers, fruits, and miscellaneous material (insect fecal, unidentified plant parts, etc.). Furthermore, collected leaf and small-branch litter in the NF were separated into two classes, viz. *C. kawakamii* and other tree species in tree layer. Thereafter monthly mass of each fraction was determined and sub-samples were used for nutrient analysis.

1.3 Leaf-litter decomposition

The litterbag technique was used to quantify litter decomposition rate. In April 1999, freshly fallen/senescent foliage from *C. kawakamii* and other tree species in the NF and from tree species in two plantations were collected on nylon mesh screens for decomposition experiment. Sub-samples from leaf-litter of each species were retained for the determination of initial chemical composition. Except for leaf-litter of single tree species of *C. kawakamii* in the NF and CK, and Chinese fir, leaves of other species of trees in the NF and mixed-leaf of equal amount of the individual *C. kawakamii* and other tree species in the NF were employed for decomposition experiment. A known amount of air-dried leaf litter (20 g) of each species or species combination was put into a 20cm×20cm, 1.0 mm mesh size nylon bag. For each type, 80 bags were prepared and randomly placed on the forest floor in the respective stands at the end of April 1999. After 30, 60, 90, 150, 210, 270, 330, 390, 510, 630, and 750 days after placement of samples, 6 litterbags of each type were recovered at random from each forest site, and transported to the laboratory. The adhering soil, plant detritus and the "ingrowth" roots were excluded, and the bags were then oven-dried at 80 ℃ to constant weight for the determination of remaining weight.

1.4 Chemical analyses

Litter sub-samples for determination of nutrient and chemical composition were oven-dried, ground and passed through a 1mm mesh screen. For the determination of C, the plant samples were digested in $K_2Cr_2O_7$-H_2SO_4 solution using an oil-bath heating and then C concentration was determined by titration. For determination of N, P, K, Ca, and Mg, the samples were digested in the solution of H_2SO_4-$HClO_4$, and then N concentration was determined on the KDN-C azotometer, P concentration was analyzed colorimetrically with blue phospho-molybdate, K concentration by flame photometry, and Ca and Mg concentrations were determined by the atomic absorption method[17]. The initial organic constituents of fresh leaf litter samples including lignin, cellulose, hemicellulose, coarse protein, alcohol and water soluble compounds were determined by proximate chemical analysis[18].

1.5 Statistical analyses and calculations

The data on mass of total litterfall and each of its fractions were analysed for differences between forests using one-way ANOVA. The percentage of leaf litter mass remaining during the first year and initial chemical composition of fresh leaf litter were also analysed using one-way ANOVA. The multiple comparison was determined with SSR test at a significance level of 0.05[19]. Statistical analysis of data expressed as percentages was performed after square-arcsine-root transformation.

The monthly nutrient input to the forest floor was computed by multiplying monthly values of each fraction mass with its corresponding nutrient concentrations. Annual nutrient input was the sum of 12 monthly nutrient inputs. The model for constant potential weight losses is represented by the following equation[20]:

$$x/x_0 = \exp\ (-kt),$$

where x is the weight remaining at time t, x_0 is the initial weight, the constant k is the decomposing coefficient, and t is the time. This equation was fitted in the data of one-year mass disappearance. Correlation coefficients (r) between k and the chemical properties of leaf litter (e.g., initial N, initial P, initial lignin, C/N, and lignin/N ratios) were also calculated.

2 Results

2.1 Litterfall

There were significant differences ($P<0.05$) in the litter production among study forests (Table 1). Average annual litterfall (1999～2001) ranged from 5468 kg • hm^{-2} of the CF to 11008 kg • hm^{-2} of the NF and decreased in the order: NF>CK>CF. Of the total annual litterfall in the three forests, leaf litter constituted 59.70%, 71.98% and 58.29%, branch 23.07%, 22.35% and 24.99%, reproductive parts 7.86%, 1.63% and 6.07% and the miscellaneous fraction 9.37%, 4.04%, and 10.65%, respectively.

Table 1 Quantity (kg • hm^{-2} • a^{-1}) **and composition** (%, in parentheses) **of litterfall in three forests**

Forest type	Leaf	Leaf of other tree species*	Subtotal of leaf	Small branch	Branch of other tree species*	Subtotal of branch	Flower	Fruit	Miscell-aneous	Total
NF	5400.44± 274.46 (49.06)	1170.78± 249.39 (10.64)	6571.22± 562.33a (59.70)	2298.38± 393.15 (20.88)	240.68± 39.35 (2.19)	2539.06± 146.21a (23.07)	203.86± 125.99a (1.85)	661.50± 337.32a (6.01)	1032.57± 137.69a (9.37)	11008.21± 529.36a (100)
CK	6864.78± 159.29 (71.98)		6864.78± 159.29a (71.98)	2132.04± 356.94 (22.35)		2132.04± 356.94a (22.35)	13.16± 9.36b (0.14)	141.79± 153.73b (1.49)	385.74± 42.19b (4.04)	9537.51± 532.39b (100)
CF	3187.69± 424.09 (58.29)		3187.69± 424.09b (58.29)	1366.66± 62.00 (24.99)		1366.66± 62.00b (24.99)	79.11± 2.19c (1.45)	252.70± 15.99bc (4.62)	582.29± 136.64bc (10.65)	5468.45± 431.40c (100)

Notes: Values are means ±s.d. of five plots at each forest over 3 years. Means followed by different letters on the same column indicate significant differences at $P<0.05$. NF, natural forest of *Castanopsis kawakamii*; CK, *C. kawakamii* plantation forest; CF, Chinese fir (*Cunninghamia lanceolata*) plantation forest. The abbreviations are the same as elsewhere. Other tree species in the NF indicate those species in the tree layer except for *C. kawakamii* and the same as elsewhere

Total litterfall followed an unimodal distribution pattern for the NF and CK, with a distinct peak in April every year (Fig. 2). The CF showed a trimodal pattern and these litterfall peaks occurred in April or

May, August, and November, respectively (Fig. 2).

2.2　Nutrient return through litterfall

Mean annual amounts of nutrients returned to the forest floor during 3-year period in the CF were much lower than for the CK and, notably, the NF (Table 2～4). Returns of N, P, and K through total litterfall in the NF were two to three times higher than those in the CF. In contrast, Ca returns were the highest in the CF (Table 4). The CK had much higher returns of Mg than other two forests (Table 3).

Comparison of annual nutrient return between different litter fractions indicated that for all the species the leaf fraction had the highest amount of N, P, K, Ca, and Mg return for all forests (Table 2～4). The CK had the highest N, P, K and Mg returns through leaf litter. The leaf fraction of the CF returned higher amount of Ca than those of the NF and CK.

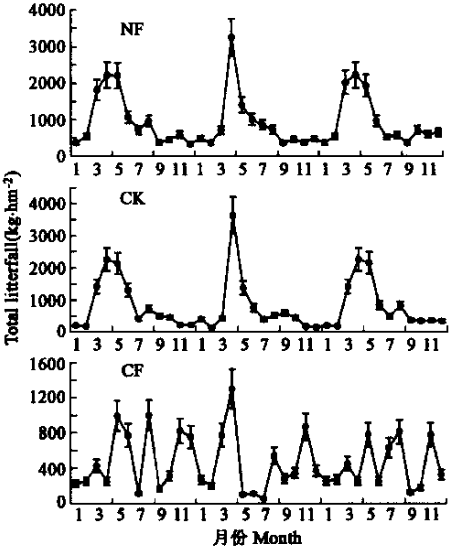

Fig. 2　Monthly total litterfall in the three forests

Error bars indicate ± s. d. , *n*=15 per forest

2.3　Chemical composition of leaf litter

Initial chemical composition of leaf litter in the three forests varied considerably (Fig. 3). Concentration of Ca in leaf litter of Chinese fir was

Table 2　Mean annual nutrient return through litterfall in the NF (kg · hm^{-2})

Year	Components	N	P	K	Ca	Mg	Subtotal
Jan. ～Dec. 1999	Leaf	41.38±3.74	3.56±0.27	35.16±2.82	18.39±1.56	6.52±0.57	105.01
	Leaf of other tree species	10.42±0.44	1.00±0.04	4.51±0.16	6.02±0.22	1.42±0.06	23.37
	Small branch	12.42±0.79	0.98±0.06	4.62±0.31	8.48±0.46	1.40±0.10	27.9
	Branch of other tree species	1.87±0.13	0.15±0.01	0.68±0.05	1.21±0.07	0.22±0.02	4.13
	Flower	1.59±0.24	0.18±0.04	0.40±0.11	0.38±0.06	0.16±0.02	2.71
	Fruit	1.63±0.12	0.24±0.03	2.30±0.26	0.56±0.06	0.35±0.04	5.08
	Miscellaneous material	11.40±0.62	1.37±0.09	6.25±0.32	4.46±0.16	1.03±0.06	24.51
	Subtotal	80.71	7.48	53.92	39.50	11.10	192.71
Jan. ～Dec. 2000	Leaf	35.67±3.73	2.79±0.33	33.62±3.77	15.71±1.57	5.71±0.65	93.5
	Leaf of other tree species	7.96±0.44	0.72±0.08	3.69±0.21	4.55±0.23	1.04±0.06	17.96
	Small branch	12.40±0.98	0.65±0.03	3.89±0.23	7.48±0.42	1.42±0.12	25.84
	Branch of other tree species	1.35±0.13	0.09±0.01	0.64±0.06	1.00±0.09	0.18±0.02	3.26
	Flower	4.68±1.42	0.53±0.23	1.28±0.37	1.28±0.26	0.51±0.15	8.28
	Fruit	3.75±0.44	0.34±0.04	4.94±0.68	1.20±0.14	0.57±0.08	10.8
	Miscellaneous material	8.45±0.50	1.02±0.12	5.52±0.36	3.38±0.16	0.87±0.06	19.24
	Subtotal	74.26	6.14	53.58	34.60	10.30	178.88
Jan. ～Dec. 2001	Leaf	41.35±4.43	2.83±0.21	26.79±2.55	17.88±1.79	5.70±0.52	94.55
	Leaf of other tree species	6.35±0.42	0.63±0.03	2.56±0.13	4.15±0.19	0.91±0.05	14.60
	Small branch	13.45±0.73	1.14±0.05	4.48±0.30	11.11±0.52	1.67±0.10	31.85
	Branch of other tree species	1.13±0.12	0.10±0.01	0.31±0.04	0.90±0.07	0.16±0.02	2.60
	Flower	2.50±0.41	0.35±0.06	0.77±0.15	0.57±0.10	0.22±0.03	4.41
	Fruit	5.07±0.40	0.43±0.04	6.13±0.56	2.09±0.19	0.84±0.10	14.56
	Miscellaneous material	10.51±0.98	0.85±0.09	4.14±0.33	3.76±0.23	0.89±0.07	20.15
	Subtotal	80.36	6.33	45.18	40.46	10.39	182.72
	Mean of 3-year subtotal	78.44	6.65	50.89	38.19	10.60	184.77

Table 3 Mean annual nutrient return through litterfall in the CK (kg·hm^{-2})

Year	Components	N	P	K	Ca	Mg	Subtotal
Jan.～Dec. 1999	Leaf	59.06±5.62	4.39±0.39	44.02±3.90	21.50±2.17	11.44±0.96	140.41
	Small branch	13.98±1.10	1.14±0.09	5.50±0.46	9.60±0.66	2.89±0.24	33.11
	Flower	0.09±0.01	0.02±0.01	0.03±0.01	0.03±0.01	0.02±0.01	0.19
	Fruit	0.18±0.02	0.02±0.01	0.22±0.03	0.11±0.02	0.07±0.01	0.60
	Miscellaneous material	4.22±0.42	0.56±0.05	2.57±0.23	1.70±0.15	0.59±0.06	9.64
	Subtotal	77.53	6.13	52.34	32.94	15.01	183.95
Jan.～Dec. 2000	Leaf	42.37±4.15	3.37±0.41	44.44±5.50	20.72±2.78	10.23±1.19	121.13
	Small branch	10.25±0.61	0.61±0.05	3.73±0.24	7.50±0.46	2.20±0.15	24.29
	Flower	0.25±0.09	0.06±0.02	0.09±0.03	0.08±0.02	0.05±0.02	0.53
	Fruit	0.45±0.07	0.04±0.01	0.51±0.09	0.24±0.07	0.16±0.02	1.40
	Miscellaneous material	4.25±0.45	0.51±0.07	2.11±0.18	1.52±0.15	0.52±0.05	8.91
	Subtotal	57.57	4.59	50.88	30.06	13.16	156.26
Jan.～Dec. 2001	Leaf	54.03±5.15	3.92±0.25	35.33±3.08	20.30±2.00	10.47±0.81	124.05
	Small branch	13.98±1.33	1.14±0.11	3.06±0.26	8.43±0.46	2.51±0.21	29.12
	Flower	0.10±0.02	0.02±0.01	0.02±0.01	0.03±0.01	0.02±0.01	0.18
	Fruit	1.72±0.24	0.14±0.02	2.24±0.35	1.09±0.14	0.71±0.12	5.90
	Miscellaneous material	5.28±0.58	0.49±0.06	2.25±0.25	1.77±0.18	0.64±0.07	10.43
	Subtotal	75.11	5.70	42.90	31.62	14.35	169.68
	Mean of 3-year subtotal	70.07	5.47	48.71	31.54	14.17	169.96

Table 4 Mean annual nutrient return through litterfall in the CF (kg·hm^{-2})

Year	Components	N	P	K	Ca	Mg	Subtotal
Jan.～Dec. 1999	Leaf	30.20±1.67	1.63±0.07	12.08±1.36	35.72±2.45	7.36±0.42	86.99
	Small branch	7.14±0.43	0.61±0.04	3.12±0.29	9.23±0.61	1.95±0.13	22.05
	Flower	0.90±0.04	0.06±0.01	0.19±0.02	0.80±0.04	0.15±0.02	2.10
	Fruit	2.11±0.17	0.18±0.02	1.46±0.10	1.01±0.11	0.39±0.04	5.15
	Miscellaneous material	5.51±0.60	0.49±0.13	1.69±0.16	6.25±0.60	1.17±0.16	15.11
	Subtotal	45.86	2.97	18.54	53.01	11.02	131.40
Jan.～Dec. 2000	Leaf	18.49±1.10	1.32±0.09	7.64±0.53	36.47±2.57	5.50±0.36	69.42
	Small branch	6.29±0.56	0.42±0.04	2.92±0.20	10.24±0.83	1.72±0.15	21.59
	Flower	0.89±0.07	0.04±0.01	0.16±0.02	0.52±0.06	0.09±0.01	1.70
	Fruit	1.53±0.15	0.11±0.01	1.21±0.17	0.92±0.15	0.36±0.05	4.13
	Miscellaneous material	3.89±0.26	0.24±0.02	1.04±0.10	5.67±0.32	0.97±0.07	11.81
	Subtotal	31.09	2.13	12.97	53.82	8.64	108.65
Jan.～Dec. 2001	Leaf	16.97±0.90	1.05±0.06	6.57±0.78	25.45±1.47	4.02±0.21	54.06
	Small branch	5.66±0.35	0.40±0.02	1.88±0.14	7.73±0.41	1.38±0.08	17.05
	Flower	0.72±0.04	0.05±0.01	0.11±0.01	0.71±0.06	0.14±0.02	1.73
	Fruit	1.67±0.14	0.14±0.02	1.13±0.08	0.84±0.07	0.30±0.03	4.08
	Miscellaneous material	7.82±0.67	0.56±0.04	2.49±0.17	9.02±0.68	1.67±0.13	21.56
	Subtotal	32.84	2.20	12.18	43.75	7.51	98.48
	Mean of 3-year subtotal	36.60	2.43	14.56	50.19	9.06	112.84

significantly higher than those of other species ($P < 0.05$). Total C concentration showed the similar trend. However, no significant differences in concentrations of N and P among these leaves were observed. For concentrations of organic components, there were only significant differences among alcohol and among water-soluble compounds ($P < 0.05$).

2.4 Leaf-litter decomposition

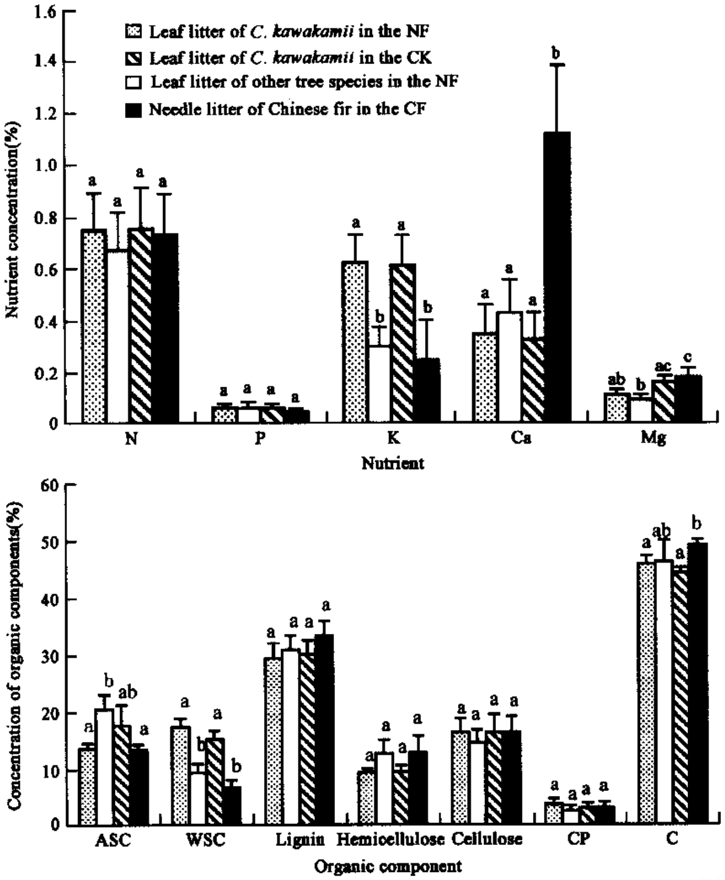

Fig. 3 Initial chemical composition of leaf litter from the three forests

Notes: Error bars indicate ± s. d., $n = 5$; Concentrations followed by different letters denote a significant difference at $P<0.05$; ASC, Alcohol soluble compounds; WSC, Water soluble compounds; CP, coarse protein

The significantly fastest decomposition was found for leaf litter of *C. kawakamii* in the NF, with only 1.84% of the initial mass remained at the end of the first year of study ($P<0.05$). Mass loss in Chinese fir needle-litter was the least, with 39.22% of initial mass undecomposed after one year (Fig. 4). Leaf-litter decomposition over the 750-day period for all species was characterized by an initial faster rate of disappearance, followed by a subsequent slower rate. For instance, leaves of *C. kawakamii* in the NF and CK, and of mixed leaves, lost 90.61%, 86.03%, and 74.34% of their initial weight in the first 150 day period, respectively, compared with 9.36%, 13.58%, and 25.14% in the later 600 day period.

3 Discussion

3.1 Litterfall

Litterfall production in forest ecosystem is determined by climatic condition, species composition, and successional stage in its development[21~23]. In this study, the observed litterfall of the natural forest (11.01t • hm^{-2} • a^{-1}) was in the upper part of the range recorded for subtropical evergreen broadleaved forests[24~27] and even equivalent to or higher than that in some tropical rain forests elsewhere in the world[23, 28]. While compared with adjacent *C. kawakamii* plantation (71.98%) in the same study area and a Castanopsis eyrei forest (76.20%) in Wuyi mountain[27], leaf fall in the NF represented a smaller proportion (59.70%) of the total litter, but higher than that in evergreen broadleaved forest (52.70%) in Dinghu mountain[29]. The litter production in the CK and CF was lower than that in the NF, but similar to that recorded in climatically comparable plantations[24~26, 30]. The high diversity of tree species, soil fertility level, and standing biomass (563.465 $m^3 \cdot hm^{-2}$) in the NF compared with monoculture plantations may explain the higher litterfall in the NF[7~10, 31]. Significant differences in litterfall between CK and CF could be attributed to tree characteristics. In general, broadleaved trees had higher litterfall than that of coniferous trees[16, 22].

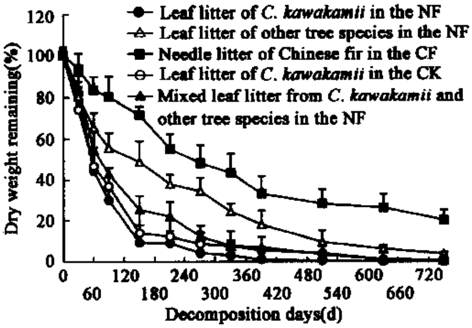

Fig. 4 Percentage of dry mass remaining in various leaf litter groups during 750 days of decomposition

For the NF and CK, a major peak of litterfall was observed in April every year during the 3-year period, corresponding to the phenomenon that most of old leaves were replaced by new ones in the spring. This rhythm was coincided with that of subtropical rain forest of Hexi[26]. While in a *Castanopsis eyrei* forest in Wuyi mountain and a *Populus bonatii* forest in Ailao mountain, litterfall showed a bimodal pattern with peaks occurring in April and November[24, 27]. Variations in litterfall pattern among these forest types of subtropical China seemed to further testify the opinion of Lin *et al.* who considered natural forest of *C. kawakamii* in Sanming as a transitional type from southern subtropical rain forest to mid-subtropical evergreen broadleaved forest[7]. Available studies concerning Chinese fir plantations mostly showed that this conifer yielded two litterfall peaks in a year[25, 30], whereas our study showed a third, smaller peak in August, which was probably due to the highest actual evapotranspiration (AET) and slow-growth characteristic of Chinese fir in the period[30, 33]. Year-to-year variations in litter production and litterfall pattern for the three forests may be related to annual change in rainfall and its pattern. In 2000, the significant rise in litterfall in April and decline in May in the three forests (Fig. 2) were primarily caused by effect of rainfall. For understanding the annual variations in litterfall production and its pattern, more long-term studies are necessary.

3.2 Nutrient return through litterfall

Mean annual nutrient returns through litterfall in NF (184.77 $kg \cdot hm^{-2}$) were higher than those in subtropical rain forest of Hexi (176.16 $kg \cdot hm^{-2}$)[26], primary *Lithocarpus xylocarpus* forest in Ailao mountain (178.76 $kg \cdot hm^{-2}$)[24] and a *Castanopsis eyrei* forest in Wuyi mountain (82.37 $kg \cdot hm^{-2}$)[27], but much lower compared with old-growth evergreen broadleaved forest in Dinghu mountain (219.61 $kg \cdot hm^{-2}$)[29]. The nutrient input from the CK (169.96 $kg \cdot hm^{-2}$) was twice as large as that of a 30-year-old *Populus bonatii* stand[24]. The CF had a nutrient input close to that of pure Chinese fir plantations in Tianlin and Huitong[25, 32]. The higher calcium return (50.19 $kg \cdot hm^{-2} \cdot a^{-1}$) in the CF than that in other two forests reflected higher amount of this element taken up by Chinese fir[33], which was in agreement with the results of Tian *et al.*[32]. As P is the major limiting nutrient for tree growth of many subtropical forests, P return through litterfall has an important impact on soil nutrient characteristics, especially in the surface layers[27]. In this study, annual returns of P from litterfall in the three forests were all higher than that in broadleaved *Castanopsis eyrei* forest in Wuyi Mountain (1.39 $kg \cdot hm^{-2}$)[27]. However, annual P returns in the CF (2.43 $kg \cdot hm^{-2}$) were much lower than that in monsoon broadleaved evergreen forest in Dinghu Mountain (5.89 kg · hm^{-2})[29]. The variations therein may be related to the difference in site conditions and tree species.

3.3 Leaf-litter decomposition related to its quality

At a regional scale with similar climatic conditions, litter decomposition rates are primarily controlled by litter quality through its effects on the activities of soil organisms[34, 35]. Rapid mass loss in the earlier stage was largely associated with easily decomposed compounds, such as alcohol/water soluble compounds and hemicellulose, while the relatively slow mass loss in the later stage was probably correlated with recalcitrant compounds, such as lignin and cellulose[34, 36]. The higher amounts of alcohol/water soluble compounds seemed to stimulate the litterfall decomposition process, which was shown by 9.39% and 13.97% of dry weight remaining for leaves of *C. kawakamii* in the NF and CK respectively after 150 days of the onset of decomposition (Fig. 4). However, for all leaf-litter species, strong relationships of initial contents of alcohol-soluble compounds, cellulose, hemicellulose, and coarse protein with decay rates cannot be recognized in our study, except for water-soluble compounds. Tripathi and Singh also found a positive effect of water-soluble substances on initial litter decomposition[37].

High initial concentrations of N in litter or P in litter at sites with low P availability have generally been considered to increase decomposition rates[35, 36, 38]. Correlation studies confirmed that initial N and P concentrations ($r = 0.474$ and 0.258, respectively) exerted positive influences on litter decay rate coefficients in this study. Unlike N and P, high initial lignin concentration is expected to retard the decomposition process, because lignin is an interfering factor in the degradation of cellulose and other carbohydrates, as well as proteins[39]. Leaves of *C. kawakamii* and other tree species in the NF had lower initial lignin-concentration than needle of Chinese fir, which was in agreement with the lowest decay rate of needle litter of Chinese fir ($r=-0.235$). In addition, ratios of C/N ($r=-0.821$) and lignin/N ($r=-0.563$) showed significant negative relationships with decay rate coefficient (k). Many previous workers also have elucidated such relationships[40~42]. In this paper, the annual decomposition rate of mixed leaf litter (92.24%) was relatively faster as compared to that of leaf litter of other tree species in the NF (80.24%), showing somewhat stimulative decomposition of mixed foliar litters. A further study should be conducted to explore the possible interactions of mixed litters with different quality. Moreover, better quality of leaf litter and higher litterall in the NF contributed to greater quantities and higher activities of soil microorganism, which in turn promoted litter decomposition processes; thus, soil fertility was improved[11, 12].

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