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Original article

Decomposition dynamic of fine roots in a mixed forest of *Cunninghamia lanceolata* and *Tsoongiodendron odorum* in mid-subtropics

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Abstract – Decomposition of fine roots (< 2 mm in diameter, viz. < 0.5 mm, 0.5–1.0 mm, 1.0–2.0 mm) was studied by means of litter bag in a mixed forest of Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook.) and Tsoong's tree (*Tsoongiodendron odorum* Chun) in Sanming, Fujian, China. In a 540 d period of decay, fine roots in all litter bags decomposed in a three-phase manner: (a) for the Chinese fir, an initial, relatively low rate of decay up to 90 d followed by a period of rapid weight loss until 270 d, and then by a phase of slow decay rate; (b) for the Tsoong's tree, a rapid loss period between 0–60 d followed by a relatively rapid loss period between 60–360 d, and then a slow loss period between 360–540 d occurred. The mass loss after 1 yr of decomposition ranged from 58.5% to 63.3% for the Chinese fir and 68.8% to 78.2% for the Tsoong's tree. Fine roots with a larger diameter had a lower rate of mass loss. Consistent increase in lignin concentration and decrease in absolute amount of phosphorus (P) were found for fine roots of the two tree species during decomposition. The absolute amounts of nitrogen (N) increased a little initially in the fine roots of the Chinese fir during a short duration. In contrast, the fine roots of Tsoong's tree were releasing N from the outset. The chemical composition controlled decomposition rate and it was found a change of TNC (total nonstructural carbohydrates)-regulating in the initial decomposition phase to lignin- or N-regulating in the second phase, and P- or lignin-regulating in the last phase.

fine root / decomposition / lignin / nitrogen / phosphorus / mixed forest / *Cunninghamia lanceolata* / *Tsoongiodendron odorum*

Résumé – Dynamique de la décomposition des radicelles dans une forêt mélangée de *Cunninghamia lanceolata* et *Tsoongiodendron odorum* en zone subtropicale. On a étudié la décomposition de radicelles de diamètre inférieur à 2 mm (< 0,5 mm; 0,5 à 1,0 mm; 1,0 à 2,0 mm) en utilisant des sacs enterrés dans la litière, dans une forêt mélangée de sapin de Chine (*Cunninghamia lanceolata* (Lamb.) Hook) et d'arbres de Tsoong (*Tsoongiodendron odorum* Chun) située à Sanming, Fujian, Chine. Au cours des 540 jours d'observation de la dégradation des radicelles, leur décomposition s'est déroulée selon trois phases. a) Pour le sapin de Chine, on enregistre un taux initial de dégradation relativement lent jusqu'à 90 jours, puis une perte rapide de poids au cours de la période suivante allant jusqu'à 270 jours, et ensuite un taux de dégradation lent. b) Pour l'arbre de Tsoong, on constate une perte de poids rapide au cours des 60 premiers jours, puis une perte relativement rapide jusqu'à 360 jours et enfin une perte lente entre 360 et 540 jours. La perte de poids après 1 an de décomposition est comprise entre 58,5 % et 63,3 % pour le sapin de Chine et entre 68,8 % et 78,2 % pour l'arbre de Tsoong. La perte de poids est moindre pour les radicelles les plus grosses. On note chez les deux espèces, au cours de la décomposition, une certaine augmentation du taux de lignine et une nette réduction du taux de phosphore. Pendant une courte période initiale, le taux d'azote augmente pour le sapin de Chine, alors que les radicelles de l'arbre de Tsoong libèrent de l'azote dès le début. La composition chimique commande le rythme de décomposition ; on a mis en évidence les rôles respectifs des taux de carbohydrate total non structural (TNC), lignine (ou N) et P (ou lignine) au cours des différentes phases de la décomposition.

décomposition / lignine / azote / phosphore

1. INTRODUCTION

Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook.) is one of the most important plantation tree species in China in terms of planting area, yield, and timber usage. A great deal of monoculture Chinese fir plantations are established following forest land clearcutting, slash burning and soil preparation. However yield decline and land deterioration in such a disturbed ecosystem have become serious [32, 37]. Tree species can exert some effects on soil fertility [3], and broadleaved species have been widely expected to be able to bring benefits to soil fertility in southern China [32, 36]. Thus, introduction of broadleaved trees into coniferous plantations has been recommended as a practical measure to preserve long-term site productivity [32, 37]. Several studies have reported litterfall, nutrient cycling and soil fertility in mixed stands of Chinese fir and broadleaved trees [17, 25, 32, 33, 34, 36, 37]. With the recent emphasis placed on fine roots in forests, some mixed forests have been examined in China regarding biomass, productivity, distribution and the nutrient dynamics of fine roots.

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However, there is scant information on fine root decomposition [15, 16, 23, 35].

Fine roots represent a large and dynamic entity of the below-ground biomass and nutrient capital, and a significant part of the net primary production of forest ecosystems [19, 30]. According to existing models, fine root mortality transfers significant amounts of organic matter and nutrients into the soil and is important in forest nutrient cycles [30]. Therefore, root decomposition is a key process in nutrient, mass and energy dynamics of forest ecosystems [2, 20]. Fine roots contributed 25%–80% to the total soil carbon stock annually and 18%~58% greater input of N to soil than aboveground leaf litter [19, 30]; its turnover may be five times as much as that of aboveground litter is [1, 13]. Thus, more studies on fine roots, combined with aboveground litter, are needed to have a better understanding of nutrient dynamics in forest ecosystems. The primary aims of this study were to (i) examine the pattern and rate of dry weight loss and nutrient release from decomposing fine roots of the Chinese fir and the Tsoong's tree, (ii) determine the relationship between decomposition rate and chemical composition during the three decay phases.

2. MATERIALS AND METHODS

2.1. Site description

The study was carried out from 1999 to 2000 in the 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). This area borders Daiyun Mountain on the southeast, with Wuyi Mountain on the northwest. The region has a middle subtropical monsoonal climate, with a mean annual temperature of 19.1 °C and a relative humidity of 81%. The mean annual precipitation is 1 749 mm, mainly occurs from March to August. Mean annual evapotranspiration is 1 585 mm. The growing season is relatively long with an annual frost-free period of around 300 d.

The sites have a northeast orientation and a 35° slope; the forest studied is a mixed forest of Chinese fir and Tsoong's tree. The soil type is red soil derived from sandy Paleozoic shale, and its thickness exceeds 1.0 m. Surface soil (0–20 cm depth) has organic matter (OM) content of 26.74 $g\cdot kg^{-1}$, total N of 1.180 $g\cdot kg^{-1}$, total P of 0.252 $g\cdot kg^{-1}$, humic carbon content of 8.595 $g\cdot kg^{-1}$, C/N of 17.24 and C/P of 81 [18]. In 1973, the mixed forest was planted with an initial planting density of 3 000 $stems\cdot ha^{-1}$. The mixed pattern is on strips, with three rows of Chinese fir and then one row of Tsoong's tree. At the time of survey (at age 27 a), the mixed stand had a density of 907 $stems\cdot ha^{-1}$ for Chinese fir and 450 $stems\cdot ha^{-1}$ for Tsoong's tree. The mean tree height and diameter at breast height (DBH) were 20.88 m and 25.1 cm for Chinese fir, and 17.81 m and 17.0 cm for Tsoong's tree, respectively. The canopy cover was 95% and the understory cover was 80%.

2.2. Fine root collection

Fine roots (< 2 mm in diameter) of Chinese fir and Tsoong's tree were collected in the mixed forest by sieving from the upper 0–20 cm soil layer in May 1999, gently washed in tap water to remove adherent soil particles, and spread on a laboratory table to dry for 24 h [20]. Dead fine roots were discarded, and live fine roots of Chinese fir and Tsoong's tree were picked out, separated and further sorted into three size classes: < 0.5 mm, 0.5–1 mm, and 1–2 mm.

2.3. Fine root decomposition

The 18 cm × 18 cm, 0.25–mm mesh size nylon bags were used to quantify the decomposition rate of fine roots. Fine root samples were air dried at room temperate to constant mass. Each bag was filled in a known amount of air-dried fine roots (5 g). Sub-samples of fine roots were retained for the determination of moisture content and initial chemical composition. For each size class and tree species, 60 bags were prepared and incubated in the soil at a depth of 10 cm in May 1999; 6 bags were retrieved randomly after 30, 60, 90, 150, 210, 270, 360, 450, and 540 d of sample placement, and transported to the laboratory. The adherent soil and plant detritus were excluded, and the samples were then oven-dried at 60 °C to constant weight for the determination of remaining weight. Sub-samples of each date were retained for the analysis of their chemical composition.

2.4. Chemical analyses

All sub-samples were oven-dried, ground and passed through a 0.25-mm mesh screen. For the determination of C, the root samples were digested in a $K_2Cr_2O_7$-H_2SO_4 solution (1:1) by oil-bath (175 ± 5 °C) and then the C concentration was determined by titration [10]. For determination of N and P, the samples were digested in a solution of H_2SO_4-$HClO_4$ (10:1), and then N concentration was determined by the micro-Kjeldahl technique, and P concentration was determined colorimetrically by forming chloro-phosphoric molybdate (blue colour) [10]. TNC were measured using a takadiastase digestion of non-extracted subsamples followed by a titrametric determination of reducing power [20]. Solutes, acid soluble fiber (largely holocellulose), acid insoluble fiber (largely lignin and suberin) and lignin were determined by proximate chemical analysis [31]. All results are presented on an ash-free dry matter basis.

2.5. Statistical analysis

Statistical analyses were performed with the Statistical Program for Social Science (SPSS) software for analysis of variance (ANOVA), and Newman-Keuls tests for comparisons of mean values (significance for $P < 0.05$). The model for constant potential weight loss is represented by the following equation: $x/x_0 = \exp(-kt)$, where x is the weight remaining at time t, x_0 is the initial weight, the constant k is the decompostion coefficient, and t is the time. Linear regressions between mass loss as dependent variable, lignin, N, P, TNC, lignin/N ratio and lignin/P ratio as independent variables were performed for three successive periods as presented below and the whole study period.

3. RESULTS

3.1. Dry weight loss

Fine roots decomposed in a three-phase manner in a 540-d period: for the Chinese fir, an initial relatively low rate of decay up to 90 d, was followed by a period of rapid weight loss until 270 d, and then by a phase of low decay rate; and for the Tsoong's tree, a rapid weight loss period up to 60 d followed by a relatively rapid weight loss period between 60–360 d, and a slow rate of decay period from 360 d (Fig. 1).

Percentages of mass lost after 1 year of decomposition from litter bags ranged from 58.5% to 63.3% for the Chinese fir and 68.8% to 78.2% for the Tsoong's tree (Tab. I). Fine roots with a thicker diameter had a lower rate of mass loss ($P < 0.05$). The

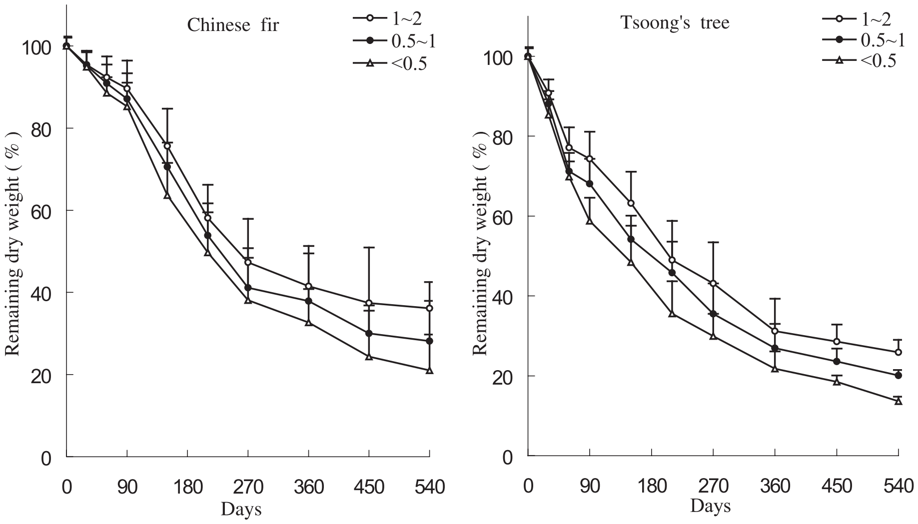

Figure 1. Percentage of dry-matter remaining over time in decomposing fine roots of Chinese fir and Tsoong's tree. Bars indicate standard error.

Table I. Weight loss rate and decay constant (k) of fine roots after one year decay. Values followed by different letters on the same column indicate significant differences at $P < 0.05$.

Tree species	Diameter class (mm)	Decay constant (k)		Correlation coefficient (r)	Expected rate of weight loss (%)	Observed rate of weight loss (%)	Mean half-time (day)	Time of total decomposition (day)
		day-based	year-based					
Tsoong's tree	1–2	0.0028	1.01	–0.9616	63.5	68.8a	248	1070
	0.5–1	0.0033	1.19	–0.9629	69.5	73.1b	210	908
	< 0.5	0.0040	1.44	–0.9553	76.3	78.2c	173	749
Chinese fir	1–2	0.0022	0.79	–0.9333	54.7	58.5a	315	1362
	0.5–1	0.0026	0.94	–0.9298	60.8	62.1b	267	1152
	< 0.5	0.0031	1.12	–0.9431	67.2	63.3b	224	966

negative exponential decay model showed a good fit for the decay pattern of the fine roots of both species and regressions were highly significant ($r^2 > 0.9$, $P < 0.05$) (Tab. I). The time of total decomposition (95% decay) was 749–1 070 d for Tsoong's tree and 966–1 362 d for the Chinese fir.

3.2. Nutrient release

Changes in N and P concentrations in fine roots during decomposition differed between species and diameters: for Chinese fir, N concentrations increased followed by a decline in all size classes; and the duration of increase ranges from 210 d for fine roots < 0.5 mm to 360 d for fine roots 1–2 mm (Fig. 2). For Tsoong's tree, N concentration increased slightly initially in fine roots 0.5–1mm and 1–2 mm. P concentrations in fine roots of Tsoong's tree showed consistent decrease, while they remained stable or relatively increased slightly in those of the Chinese fir (Fig. 2). Generally, both C and TNC concentrations decreased, and concentrations of lignin relatively increased during fine root decomposition for the two tree species (Tab. II).

The absolute amounts of N increased initially in fine roots of the Chinese fir with a low magnitude and a short duration (Fig. 3). In contrast, fine roots of the Tsoong's tree were releasing N from the start of the experiment. The absolute amounts of P decreased in fine roots of the two tree species during decomposition (Fig. 3). Fine roots of Tsoong's tree released N and P at a faster rate than those of Chinese fir ($P < 0.05$). After 540 d, the rates of N and P release relative to dry mass loss can be arranged in the sequence of: dry mass > P > N for the Chinese fir; and P > dry mass = N for the Tsoong's tree (Figs. 1 and 3). Our estimates of nutrient release from fine roots can also be combined with the exponential model to describe changes in absolute amounts of nutrients during the decomposition ($r^2 > 0.9$, $P < 0.05$), with the exception of N in all size classes of the Chinese fir.

4. DISCUSSION

4.1. Dry weight loss

Mass losses from litter bags during the study period appeared in three consecutive phases as often reported in many studies in which the root decomposed at least two phases [6, 20]. Early losses of mass from fresh root litter may be due to leaching and microbial or root respiration of readily soluble compounds [20]. During the initial decay stage, the losses of

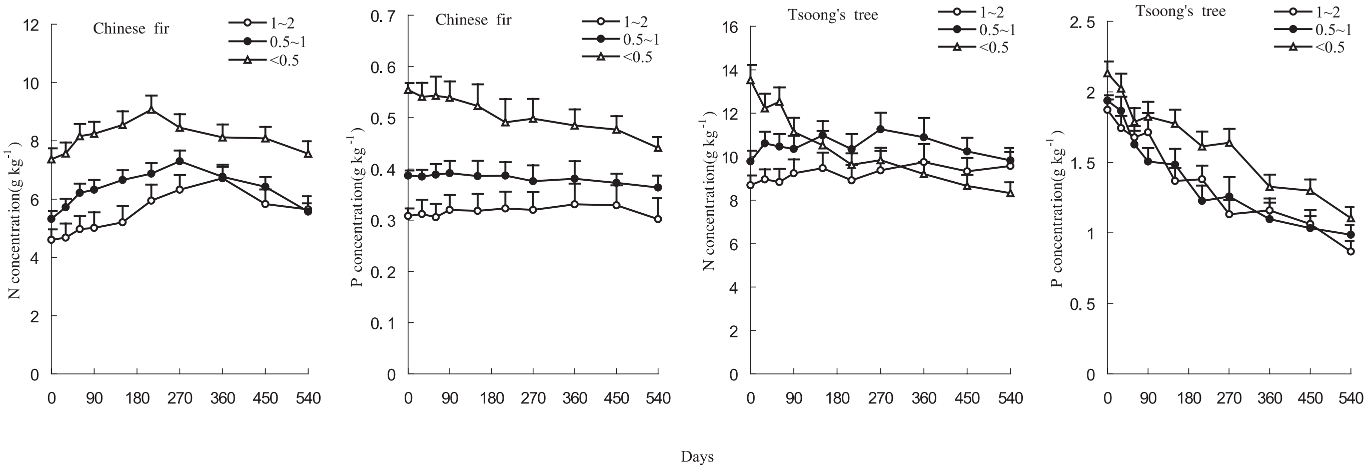

Figure 2. Changes in N and P concentrations over time in decomposing fine roots of Chinese fir and Tsoong's tree. Bars indicate standard error.

soluble compounds contributed half or more of the initial dry mass losses (Tab. II). The next phase of weight loss was presumably due to active consumption of readily available energy sources by microbes (mainly holocellulose). Also, lignin (acid-insoluble) is degraded in this phase with a lower extent relative to acid-solubles (Tab. II). A remarkable reduction in the decay rate during the third phase might be related to the relatively higher percentage of recalcitrant fractions like lignin (acid-insoluble) in the decaying root tissue (Tab. II). These materials were known to control decomposition rate through their own resistance to enzymatic attack and by physically interfering with the decay of other chemical fractions of the cell wall [5, 9].

Fine roots with a smaller diameter had a higher rate of mass loss in this study (Tab. I), which agrees with the common findings in other studies [5, 9, 27], but differs from the observation of McClaugherty et al. (1984) who found slower root decomposition for small roots [20]. The decrease in the rate of decomposition with increasing root diameter as observed in the present study might be due to the initial N concentration that was related to root diameter (Tab. I). Smaller roots having higher N concentration decomposed at somewhat faster rate compared to thicker roots. However, it seems that there is no consistent pattern between the rate of root decomposition and N concentration [9]. Camiré et al. [9] explained that when roots have a high N concentration, their rate of decomposition may be lowest in roots with the highest initial N concentration, and when low in N, the rate of decomposition may be highest in the roots with the highest initial N concentration [9]. In view of the significantly higher root N concentrations in the Chinese fir and the Tsoong's tree as compared to other studies, our results did not hold for the hypothesis of Camiré et al. [9].

The external factors, including temperature, water content, and chemical characteristics of the soil may also control the decay rate of fine roots [22]. Similar mass losses have been reported for fine roots of the Chinese fir (61.3%) after 1 year of decomposition in Huitong north of our research site [15], while much lower values of 12% to 25% were obtained for red pine, Scots pine, Douglas fir, and mixed hardwood in temperate zones [4, 11, 19]. The values of annual decay constant (k, year-based) for the fine roots of the Chinese fir and the Tsoong's tree (Tab. I) fall in the range of the values reported for the forests of the world (0.03–1.74) [2, 8, 11, 15, 23, 26, 29], and were comparable with the values for the subtropical forest ecosystems (0.6–1.74) [2, 8, 15].

Although coarser mesh litter bags (0.5 mm) were used in the experiments of the aboveground litter decomposition, which may have some effects on decaying rate, the rates of fine root decomposition are in the vicinity of those for the corresponding above-ground tissue (56.31% for the needles of Chinese fir and 74.54% for the leaves of Tsoong's tree after 1 year of decay) in the same study [33]. This, however, was not true in the studies of McClaugherty et al. [19] and Usman et al. [27], where the mass loss rates of aboveground litters were much higher than those in fine roots [19, 27].

4.2. Nutrient release

The initial increase of N concentration in fine roots of the Chinese fir was largely due to microbial immobilization (Fig. 2). The tendency for P concentration to decrease or remain relatively constant indicated that there was little P immobilization (Fig. 2). The differences in changes of N and P concentrations between fine roots of the two species might be due to the different N and P availability for microorganisms in the fine roots. A bi-phasic pattern for nutrient release from decomposing fine roots of the two species (Fig. 3), characterized by an initial rapid and a subsequent slow release phase, was different from the generalized tri-phasic model proposed by Berg and Staaf [4]. Compared with other studies, there only occurred for N in the fine roots of Chinese fir an initial microbiological immobilization with a low magnitude and a short duration, and release of P began from the outset for both species without a period of net immobilization (Fig. 3), indicating that the N and P availability for microorganisms in the site were relatively high [2, 5, 8]. Of the initial amount of P in fine roots of Tsoong's tree, 30.9–41.5% was lost from decomposing root litter during the first 60 days compared with a weight loss of 22.9–30.2% (Figs. 1 and 3); this indicated initial leaching loss of P. It has also been emphasized that the importance

Table II. The chemical composition and weight loss rates during the three decay phases. Values within parentheses indicate standard errors.

Tree species	Root diameter (mm)	Periods	Concentration					Percentage of weight loss (%)			
			N (g·kg^{-1})	P (g·kg^{-1})	C (%)	Lignin (%)	TNC (%)	Dry-mass	Solute	Acid-soluble	Acid-insoluble
Chinese fir	< 0.5	0–90	7.37	0.55	43.6	32.8	8.1	14.8	7.07	4.66	3.08
			(0.37)	(0.01)	(2.22)	(1.3)	(0.3)	(1.5)	(0.7)	(0.4)	(0.3)
		90–270	8.24	0.54	44.52	35.4	4.9	47.13	5.76	26.91	14.46
			(0.41)	(0.03)	(2.4)	(0.9)	(0.2)	(4.6)	(0.5)	(2.5)	(1.5)
		270–540	8.45	0.50	42.47	39.9	3.9	17.09	1.96	8.84	6.29
			(0.46)	(0.04)	(2.25)	(1.1)	(0.2)	(3.0)	(0.3)	(1.4)	(1.1)
	0.5–1	0–90	5.32	0.39	49.45	33.5	7.8	12.9	6.3	3.7	2.9
			(0.27)	(0.01)	(2.49)	(0.8)	(0.3)	(1.2)	(0.5)	(0.3)	(0.3)
		90–270	6.32	0.39	50.94	35.1	5.4	45.97	5.54	26.85	13.58
			(0.33)	(0.02)	(2.72)	(1.3)	(0.2)	(5.3)	(0.6)	(2.9)	(1.6)
		270–540	7.30	0.38	45.4	40.7	4.8	13	1.53	6.73	4.75
			(0.37)	(0.03)	(2.6)	(1.5)	(0.2)	(3.3)	(0.4)	(1.6)	(1.2)
	1–2	0–90	4.60	0.31	55.2	35.5	6.9	10.4	5.7	2.3	2.4
			(0.36)	(0.02)	(2.78)	(1.2)	(0.4)	(0.8)	(0.4)	(0.2)	(0.2)
		90–270	5.01	0.32	50.87	36.9	4.7	42.29	5.1	23.59	13.6
			(0.53)	(0.03)	(2.82)	(1.4)	(0.3)	(4.7)	(0.5)	(2.4)	(1.5)
		270–540	6.32	0.32	45.33	41.2	3.8	11.19	1.11	5.91	4.17
			(0.51)	(0.04)	(2.58)	(1.6)	(0.3)	(3.3)	(0.3)	(1.6)	(1.3)
Tsoong's tree	< 0.5	0–60	13.52	2.13	43.3	18.1	14.9	30.2	18.9	9.11	2.19
			(0.70)	(0.08)	(2.17)	(0.7)	(0.6)	(2.2)	(1.3)	(0.6)	(0.2)
		60–360	12.53	1.79	45.18	20.3	8.6	48.04	6.32	32.03	9.7
			(0.65)	(0.11)	(2.28)	(0.7)	(0.4)	(7.4)	(0.9)	(4.6)	(1.5)
		360–540	9.20	1.33	34.52	23.3	8.2	8.2	3.94	2.45	1.81
			(0.58)	(0.10)	(1.86)	(0.8)	(0.3)	(1.1)	(0.5)	(0.3)	(0.3)
	0.5–1	0–60	9.78	1.94	45.18	21.6	13.7	28.8	16.61	10.1	2.09
			(0.49)	(0.04)	(2.27)	(0.7)	(0.5)	(2.3)	(1.2)	(0.8)	(0.2)
		60–36	10.47	1.63	41.52	23.1	8.3	44.31	6.5	27.52	10.29
			(0.60)	(0.10)	(2.1)	(0.8)	(0.4)	(7.3)	(1.0)	(4.3)	(1.8)
		360–540	10.89	1.10	34.1	26.3	7.6	7.8	2.58	3.33	1.89
			(0.76)	(0.14)	(1.97)	(0.9)	(0.3)	(1.8)	(0.5)	(0.7)	(0.4)
	1–2	0–60	8.69	1.87	49.2	24.8	12.8	22.9	11.77	9.21	1.92
			(0.44)	(0.08)	(2.47)	(0.8)	(0.5)	(1.4)	(0.7)	(0.5)	(0.1)
		60–360	8.83	1.68	36.84	26.8	8.4	32	6.25	15.6	10.15
			(0.64)	(0.14)	(1.86)	(1.0)	(0.3)	(7.1)	(1.3)	(3.2)	(2.3)
		360–540	9.75	1.16	35.15	28.2	8.1	6.31	2.31	1.96	2.04
			(0.89)	(0.10)	(2.8)	(1.2)	(0.3)	(1.9)	(0.6)	(0.5)	(0.6)

of the initial ratios of C to nutrients in determining nutrient mineralization [29]. In this study the values of C/N were 59–120 for roots of the Chinese fir and 32–57 for roots of the Tsoong's tree, and the corresponding values of C/P were 793–1781 and 203–263, respectively (Tab. II). The higher release rate of both N and P in fine roots of Tsoong's tree could be contributed to the lower initial values of C/N and C/P.

4.3. Control of decomposition

In most studies of litter decomposition, the decay rates were often related to litter quality of a pool of different species that included both intraspecific and interspecific differences [5, 6, 9, 24, 28]. In this study, roots of different diameter classes of the same species were pooled together to create a range of substance qualities, thus, the interspecific interferences were excluded and only the intraspecific difference were included in the predictions of the mass loss rate (Tab. III).

The mass loss rate was found to have only significant correlation with initial TNC for both species in the first phase of decay, indicating that decomposition rates were regulated by TNC (Tab. III). The significant correlations between mass loss and N concentration, and lignin/N ratio, and the lack of significant correlations between mass loss and lignin/P ratio for the Chinese fir in the second decomposition phase indicated that mass losses for the Chinese fir roots were regulated by N concentration, and that N was relatively less available than P for microorganisms during this decay stage (Tab. III). During

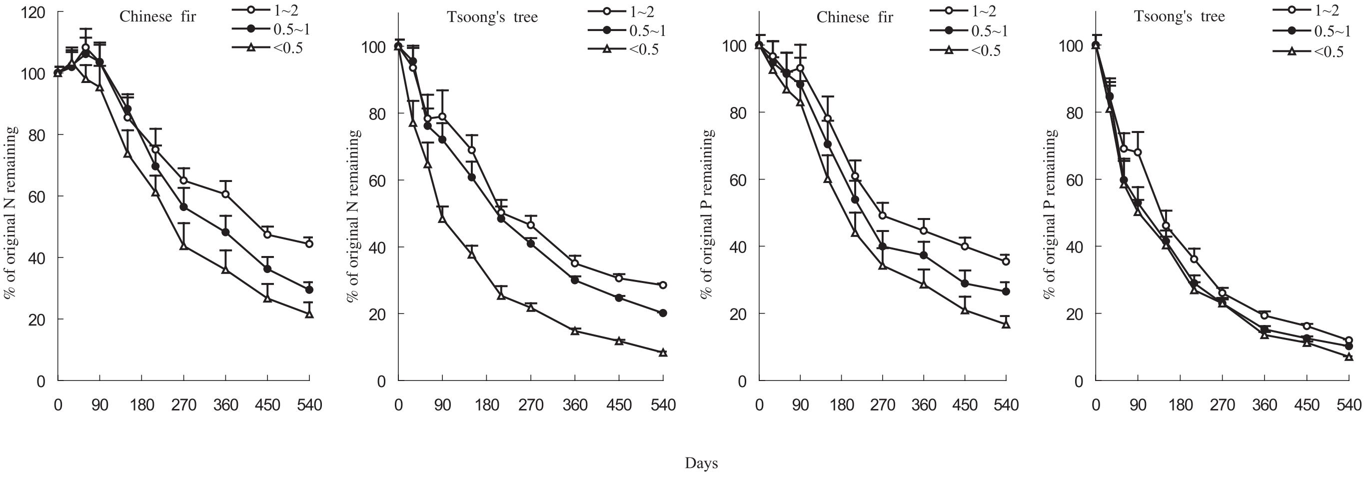

Figure 3. Percentage of nutrient remaining over time in decomposing fine roots of Chinese fir and Tsoong's tree. Bars indicate standard error.

Table III. Correlations between rates of dry matter loss with % N, % P, % lignin, % TNC, and the ratios of % lignin/% N and % lignin/% P during the three decay phases. Probabilities of observing larger correlations are given in parentheses ($n = 18$; $^*P < 0.05$; $^{**}P < 0.01$).

Tree species	Periods	N	P	Lignin	TNC	Lignin/N	Lignin/P
Chinese fir	0–90	0.746	0.602	–0.657	0.905*	–0.703	–0.614
		(0.084)	(0.234)	(0.103)	(0.011)	(0.091)	(0.173)
	90–270	0. 92*	0.679	–0.856*	0.692	–0.91*	–0.703
		(0.026)	(0.111)	(0.030)	(0.115)	(0.015)	(0.094)
	270–540	0.73	0.891	–0.856	–0.514	0.715	0.931*
		(0.102)	(0.026)	(0.033)	(0.211)	(0.21)	(0.011)
	0–540	0.806*	0.790	–0.807*	0.603	–0.915**	–0.842*
		(0.048)	(0.076)	(0.043)	(0.382)	(0.009)	(0.031)
Tsoong's tree	0–60	0.801	0.644	–0.695	0.93*	–0.69	–0.635
		(0.126)	(0.252)	(0.127)	(0.013)	(0.141)	(0.151)
	60–360	0.719	0.682	–0.89*	0.72	–0.763	–0.617
		(0.081)	(0.207)	(0.031)	(0.133)	(0.073)	(0.242)
	360–540	–0.687	0.575	0.873*	0.367	0.756	0.693
		(0.143)	(0.302)	(0.035)	(0.543)	(0.161)	(0.178)
	0–540	0.701	0.568	–0.76*	0.71	–0.52	–0.46
		(0.139)	(0.260)	(0.044)	(0.25)	(0.34)	(0.58)

the second phase, only the correlation between mass loss rate and % lignin were found significant for roots of the Tsoong's tree (Tab. III). Our results are consistent with the earlier works which showed that as lignin concentrations increase during litter decomposition the decay rates are suppressed [14, 21], and the decomposition rate of remaining litter would thus be ruled by the lignin degradation rate as the cellulose in the remaining parts would be shielded by lignin [7].

During the last phase, significant correlation between mass loss and lignin/P ratio and no significant correlation between mass loss and lignin/N ratio were found for the Chinese fir roots (Tab. III). It seems to indicate that mass losses became increasingly dependent on the lignin/P ratio. This is consistent with the hypothesis given by Gallardo and Merino [12] that difference in the biochemistry of N as opposed to P may be important in order to explain the availability of these nutrients to decomposers and the role of N and P in determining the litter mass loss [12]. Detrital N is mostly carbon-bonded (C-N) and often in structural or complexed forms, while detrital P is mostly PO_4^{3-}-aminon hydrolyzed by esterextracellular phosphatases that cleave the ester phosphate bond. In contrast, multiple enzyme systems are involved in the breakdown of structural or phenolic N-containing organic compounds before any N can be released into available forms. Consequently, N may be relatively less available than P in initial litter. As decomposition proceeds, P may become less available than N for decomposers and, at this stage, P content may be the main nutrient controlling the decomposition process [12].

For roots of the Tsoong's tree during the last decomposition phase, mass losses were found significantly and positively correlated with % lignin (Tab. III). Our results seem to confirm the findings of Berg (1986) that high initial N can be associated with low rate of root decomposition and low initial levels of lignin could have resulted in lower rates of decomposition after the initial rapid mass loss [6]. The control of mass loss by lignin at the condition of high N concentration in the late stage may result from the lignin-nitrogen interactions (Tab. III). Berg et al. (1984) found that the N-lignin derivative compounds, which are more resistant substances such as humic substance, are formed in N-rich roots [5]. Thus, the higher N content, the more lignin was combined into the high-resistant secondary compounds; and the increase in relative importance of lignin as a predictor of mass loss in the later phase may indicate that C is increasingly limiting microbial biomass in litter. It seemed that high N concentrations enhanced the decomposition of the water-soluble compounds and non-lignified cellulose and repressed the formation of lignolytic enzymes.

In this study, the chemical constituents (N, P, lignin and TNC) affect decomposition of fine roots differently during different decay phases and between litter species (Tab. III). TNC contribute largely to the initial mass loss through leaching. During the second phase of decomposition, % lignin and % N would affect root decomposition greatly (Tab. III). N is likely to be responsible for determining the amount of microbial biomass in litter, which in turn determines the amount of new recalcitrant material formed in litter, and the mineralization of P. Meanwhile lignin, known as recalcitrant material, keeps the cell wall from degradation. If roots are low in N or high in lignin such as for the Chinese fir in this study, the rate of root decomposition during this phase may be regulated by both the % N and % lignin. As the release of P and the consumption of readily available energy sources proceeds, litter P instead of litter N becomes less available for microorganisms [12], and lignin becomes more important as an energy source for microorganisms. If the fine roots are low in P (as in the Chinese fir) or low in lignin (as in the Tsoong's tree), the decay rate then would be regulated by P or lignin (Tab. III).

Even though single chemical characteristics of roots may have a limited potential for predicting the rate of decomposition, they could be reliable predictors for a limited range [20]. During the study period of decay (540 d), N concentration, lignin content, ratio of lignin/N and ratio of lignin/P of the initial material were the best predictors of mass loss for roots of the Chinese fir; and initial lignin concentration was the best predictor of decomposition rate for roots of the Tsoong's tree (Tab. III). These results are in agreement with the findings of other authors who found the lignin, N and the lignin/nutrient ratio to be the best predictors of litter decomposition rate in a wide range of ecosystems [12, 20].

5. CONCLUSION

Decomposition of fine roots is an important process of nutrient releasing and intimately linked to soil fertility. In order to give an overall evaluation of the potential of mixed forests of Chinese fir and broadleaved trees to preserve long-term site productivity, a mixed forest of Chinese fir and Tsoong's tree was chosen to study the decomposition dynamic of fine roots. The result showed that the decomposition of fine roots of both Chinese fir and Tsoong's tree appeared in a three-phase manner. After 1 year of decomposition, 58.5–63.3% and 68.8–78.2% of dry mass were lost for Chinese fir and Tsoong's tree, respectively. Mass loss of fine roots decreased with increasing root diameter. Pattern of change of N and P concentrations differed with diameter and tree species. An initial net immobilization of N occurred in fine roots of Chinese fir. Release of P was found from the outset of experiment for both species. The successive control of decomposition rate by the TNC, lignin (or N) and P (or lignin) was found during the different decomposition stage.

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