Research paper

Effects of Thinning Treatments on Nutrient Release from Decomposing Needle Litter of Sugi (*Cryptomeria japonica* D. Don) in Northeastern Taiwan

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【Summary】

Nutrient release processes associated with needle litter decomposition were monitored for 2 yr after thinning in a 50-yr-old Sugi (*Cryptomeria japonica* D. Don) plantation in northeastern Taiwan. Three thinning intensities [unthinned (T0), low (T28), and moderately low (T36)] were applied. Litterbags were used to measure the Sugi needle litter decomposition. Results of decomposition for 2 yr illustrated that the current thinning intensities in this study gave clear effects on nutrient release and return of Sugi needle litter. C release from the litter was the fastest. In addition to C, this study categorized nutrient dynamics of the decomposition litter into 3 types based on the quantity correlation of nutrient loss and changes in the weight remaining and concentration of nutrients: (1) N and P, (2) Ca and Mg, and (3) K. The overall relative mobilities of the nutrients examined after 2 yr were as follows: C > (P, K) > Ca > Mg > N. In this study, only the relative mobility of K and P changed with the different thinning intensities. The annual return of all nutrients showed no significant difference between treatments T0 and T28. Significantly lower nutrient return rates existed with treatment T36, and these may have contributed to the significantly lower input of Sugi leaf litterfall. The quantities of C and other nutrients returned through litterfall decreased with an increasing thinning intensity. Amounts of bioelements of Sugi needle litter that were returned to the soil were as follows: C > Ca > N > K > P > Mg for the 3 thinning intensities in this study. It is possible that the current thinning level was not high enough to produce very significant changes in needle litter decomposition, nutrient release, or nutrient availability. For future studies, we suggested that both higher thinning intensity treatment and long-term decomposition studies of changes in temperate and moist environmental conditions are necessary.

Key words: Sugi (*Cryptomeria japonica* D. Don), forest thinning, nutrient release, nutrient return, litter decomposition.

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研究報告

台灣東北部不同疏伐強度下柳杉針葉凋落物分解之養分釋出變化

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摘　要

本研究主要的目的在於探討台灣東北部50年生之柳杉(*Cryptomeria japonica* D. Don)人工林經疏伐後，兩年的監測期間柳杉針葉凋落物分解後養分的釋出變化。研究區疏伐的強度有三種，包括未疏伐(T0)、低度疏伐(T28)與中低度疏伐(T36)。本研究利用分解袋法來瞭解柳杉針葉凋落物的分解情形。兩年的凋落物分解試驗研究結果發現：本研究當前的疏伐強度對於柳杉針葉凋落物的養分釋放與養分回歸，有明顯的影響。凋落物分解後，碳的釋放速率最快；除了碳之外，本研究可將凋落物分解的養分動態變化，依據分解試驗期間養分損失量的相關性分析、養分重量留存量與養分含量的變化，歸類為三種類型：(1)氮與磷、(2)鈣與鎂、以及(3)鉀。另外，三種疏伐強度下養分的總體相對移動性的順序大致為：碳＞(磷、鉀)＞鈣＞鎂＞氮，本研究中不同疏伐強度的處理只有改變鉀與磷的相對移動性。另外，養分的年回歸量在T0與T28疏伐處理間沒有顯著差異，T36疏伐處理有顯著較低的養分回歸量，推測此結果可能因為在T36疏伐處理區有明顯較低的柳杉針葉凋落物的收集量。隨著疏伐強度的提高，凋落物分解後釋出的碳與其它養分的回歸量均有減少的趨勢。在本研究所有三種疏伐強度下，柳杉針葉凋落物中的生物元素回歸到土壤中的數量多寡有以下的順序：碳＞鈣＞氮＞鉀＞磷＞鎂。本研究疏伐的強度可能不夠高，因此無法導致針葉凋落物分解、養分的釋放與養分的有效性等有顯著的改變。本研究建議在未來的研究中，能針對溫帶與潮濕環境下，進行較高的疏伐強度處理下的養分分解長期變動研究。

關鍵詞：柳杉(*Cryptomeria japonica* D. Don)、森林疏伐、養分釋放、養分回歸、凋落物分解。

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INTRODUCTION

Sugi (*Cryptomeria japonica* D. Don) is an evergreen conifer and a major plantation species for timber production in Taiwan (Forestry Bureau 1995). The inventory of the third forest resources survey in Taiwan showed that the area of Sugi plantations among a total area of 295,500 ha in public man-made forests was approximately 39,100 ha with the growing stock of about 9.33 x 10^6 m^3. Sugi plantations are the most common forest type in middle-elevation areas in Taiwan. In the past, more than 3000 trees ha^{-1} were usually planted in mono-specific stands. Thinning of Sugi is not only a regular component of the management program for this species, but also a major problem. Sugi needs thinning to reach timber dimensions sufficiently fast, but thinning introduces potential risks of wind throw and surface erosion to forest ecosystems in Taiwan, because precipitation is very high and mountain slopes are very steep (Forestry Bureau 1995). Sustainable forest practices must currently aim to maintain long-term forest ecosystem structure and function, as well as develop the socioeconomic value of forests (Blanco et al. 2005, 2008).

Thinning is widely used in forest management, and is a prerequisite activity adopted in plantation management. Slodicak et al. (2005) indicated that thinning is generally considered beneficial for a stand's microclimate, litter decomposition, and biogeochemical cycling of nutrients in temperate forests, in contrast to possible negative effects or increased production risks. Thinning is also a key variable in managing the accumulation of organic matter and rates of nutrient cycling (Roig et al. 2005). The intensity of thinning affects needle litter production because of decreased canopy closure (Bray and Gorham 1964), reduced stand biomass, nutrient contents, and litterfall (Klemmedson et al. 1990, Harington and Edwards 1999), and altered decomposition rates (Piene and Van Cleve 1978). Decomposition of detritus provides more than 70% of nutrients annually needed for forest growth (Vogt et al. 1986), and it is particularly important in the nutrient budget of tropical and subtropical forest ecosystems based on nutrient-poor soils, where vegetation depends on the recycling of nutrients from plant detritus (Sundarapandian and Swamy 1999, Liao et al. 2006). The role of litter decomposition in nutrient cycling becomes even more important when considering degradation of forest vegetation (Roig et al. 2005). Decomposition is considered an emergent property of ecosystems (Odum 1983), and thus is sensitive to changes in ecosystem function. Variations in land management practices change most of the factors that influence decomposition. Therefore, changes in the rates of decomposition can be used to evaluate the effects of different intensities of land management on ecosystem function, and it thus may be a good indicator of sustainable practices (assuming that sustainable land-use practices should simulate natural functions of ecosystems) (Mesquita et al. 1998).

In order to be consistent with current forest ecosystem management policies in Taiwan, determining how to apply thinning practices to existing Sugi plantations to enhance the heterogeneity of the stand composition and structure to meet the goals of biodiversity conservation, land productivity promotion, and stability of ecosystems has become quite an important issue for sustainable forest management. Only a few studies have been conducted in relation to the forest thinning effects in Sugi plantations in Taiwan, for example, on soil nitrogen mineralization and nitrification (Zhuang et al. 2005) and microclimatic responses (Weng et al. 2007). However, no published study was found regarding the effects of thinning on the decomposition and nutrient release from Sugi needle litter. For better management of such thinning practices in Sugi plantations in Taiwan, it is important to evaluate the influence of litter characteristics on decomposition and nutrient release. This would provide plantation managers with baseline data on the mass of nutrients recycled to the soil through litterfall and create a foundation on which to build a general understanding of nutrient cycling in Sugi plantations. Therefore, the aims of this study were (1) to investigate nutrient release dynamics and (2) to examine nutrient return changes from litter decomposition under different thinning intensities.

MATERIALS AND METHODS

Site description

The study was carried out at a Sugi plantation in the Taiping Mt. area, northeastern Taiwan. Its aspect is southwest; the elevation ranges 1800~1900 m, and the mean slope is 25°. The average annual air temperature

(1995~2005) is about 12.5℃. The highest average monthly temperature is 17.6℃ in July, and the lowest is 6℃ in January. The climate of the study area is temperate and humid with prevailing northeasterly monsoon winds from October to March. However, the annual rainfall (1995~2005) of the study area ranges 2400~5500 (average, 4000) mm, and most of it falls from June to October. Typhoons passing through the study area between June and September usually bring heavy rains. Annual rainfall was 5450 mm with a mean temperature of 12.3℃ (Fig. 1), and 4 typhoons occurred during the study period. Additionally, the soil moisture regime is udic (perudic), and the soil temperature regime is mesic. The dominant soil parent materials are slate and metamorphic sandstone (Ho 1988). The soils are classified as Typic Dystrudepts and Typic Hapludults (Chang et al. 2006).

The dominant species in the study area are Sugi (*Cry. japonica*) and Formosa red cypress (*Chamaecyparis formosensis* Matsum.) with a relatively high density and dominance values of 64 and 22%, respectively. The broadleaf trees occupy approximately 14% of the stand and consist of *Sassafras randaiense* (Hay.) Rehder, *Illicium anisatum* L., *Eurya glaberrima* Hayata, *Viburnum foetidem* Wall. var. *rectangulatum* (Graebner) Rehder, *Barthea formosana* Hayata, *Eur. loquaiana* Dunn, *Cyclobalanopsis morii* (Hayata) Schottky, *Neolitsea aciculata* (Bl.) Koidz. var. *variabillima* (Hayata) J. C. Liao, *Neo. acuminatissima* (Hayata) Kanehira & Sasaki, and *Eur. crenatifolia* (Yamamoto) Kobuski.

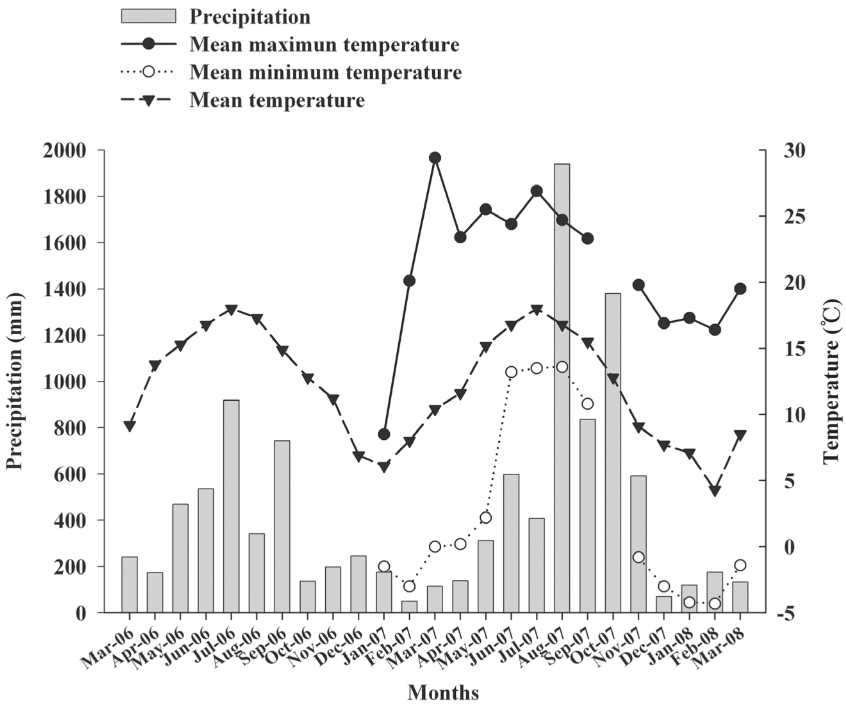

Fig. 1. Changes in monthly rainfall (mm), mean, and the mean maximum and minimum temperatures (℃) during the course of the study. No data (missing values) for mean maximum and minimum temperatures existed in March~December 2006 or in October 2007.

Experimental design

The Sugi plantation at Taiping Mt., northeastern Taiwan, is an even-aged stand resulting from clear cutting by the government, carried out during the early 1950s. The tree density was about 1060 trees ha^{-1}, with a mean height of 17 m, a mean diameter at breast height (dbh) of 28.3 cm, and a mean basal area of 76.2 m^2 ha^{-1}. Sugi is the dominant tree with a mean dbh of 31.2 cm and a mean basal area of 56.5 m^2 ha^{-1}. Nine experimental rectangular plots (20×25 m) were established (Lin 2008). To avoid edge effects, the silvicultural treatment corresponding to each plot was also applied to a strip of 5~10 m surrounding the plot. Thinning was carried out on Taiping Mt. in September and October 2004. To prevent damage from the prevailing northeasterly monsoon winds and frequent typhoons, the maximum thinning intensity removed < 40% of the total individual stems (or 20% of the basal area). Three treatments with 3 replicates were conducted: (1) T0, no thinning; (2) T28, low thinning (28% of total individuals or 14% of the basal area removed) with a selection of crop trees, mainly by removing suppressed trees and some dominant or codominant trees with malformed trunks; and (3) T36, moderately low thinning (36% of total individuals or 18% of the basal area removed) with a selection of crop trees, removing suppressed and some intermediate trees, as well as some dominant or codominant trees with malformed trunks. Logs and most of the branches from the felled trees were left outside of the plot limits.

Leaf litter decomposition

The rate of weight loss of needle litter was measured using the litterbag technique, in which known weighed samples were enclosed in a mesh bag and incubated on site. Sugi needles were examined and investigated in this study. Fresh Sugi needles were collected and air-dried. Equivalent amounts of air-dried leaf litter (20 g) were placed inside 20×20-cm plastic bags with a 2-mm mesh, and 216 bags in total were prepared. On March 3, 2006, the bags were randomly placed on the ground at each site. The bags were secured to the forest floor by metal pins to prevent movement and to ensure contact between the bags and litter layer. Every month, 1 bag containing decomposing litter was collected per plot. All samples in the litterbags were brushed clear of external soil and litter. Litterbags were handled with great care during removal, and each bag was carefully transported in a separate plastic bag to minimize the loss of small litter fragments from the litterbags. All leaves were oven-dried at 70℃ for 2 d and weighed. Mass loss was calculated as the difference between the initial dry mass and the actual dry mass of leaves on each sampling date. Litterfall production was measured by Lin (2008) for the 24-month period from February 2005 to January 2007.

Chemical analysis of the litter

Oven-dried samples of fresh and decomposing litter were ground and sieved through a 1-mm mesh sieve prior to the analyses of C, N, P, Ca, Mg, and K. C was measured by the dry combustion method (Nelson and Sommers 1982). Total N was extracted by digesting 0.5 g of a dried and powdered sample with concentrated H_2SO_4 in a Kjeldahl flask using K_2SO_4, $CuSO_4$, and Se powder as catalysts. The total N concentration was determined by the micro-Kjeldahl method (Keeney and Nelson 1982). To measure P, samples were digested in a muffle furnace after mixing with a saturated solution of Mg acetate at 480℃ for 1 h, and then cooled. Total P was determined with digested samples colorimetrically using the ammonium molybdate stannous chloride method (Olsen and Sommers 1982). Regarding the measurement of K, Na, Ca, and Mg, the sample was digested with $HClO_4$-HNO_3 (Jones and Case 1990), and then the elements were determined with a flame atomic absorption spectrophotometer (FAAS) (Hitachi Z-8100, Hitachi Ltd., Tokyo, Japan).

Statistical analysis

Litter chemistry data are expressed as the percentage of total leaf dry mass. The remaining mass (relative decomposition rate, RDR) for each period of time (X_t) was determined and compared to the initial mass values (X_o) in accordance with this formula: $\%MR = (X_t/X_o) \times 100$. Nutrient release in percent (%) was calculated as $(C_0 \times M_0)/(C_t \times M_t) \times 100$; where M_t is the dry mass of the decomposed leaf litter at sampling time t, M_0 is the initial dry mass of the litter, C_0 is the initial concentration of the nutrient, and C_t is the concentration of the nutrient at sampling time t. Data were analyzed using analysis of variance (ANOVA) for a completely random design. Means were compared using Ducan's new multiple-range tests (SAS Institute 1982). Statistical significance was defined as $p < 0.05$. If not stated otherwise, means and standard errors of 3 plots per thinning treatment were calculated.

RESULTS AND DISCUSSION

Nutrient release

Leaching, comminution, and catabolism are the 3 major processes of decomposition, and can be temporally separated or superimposed (Swift et al. 1979). Nutrient release during decomposition generally follows a pattern where water-soluble compounds are rapidly released, followed by a pattern of immobilization and finally net release (Bubb et al. 1998, Liao et al. 2006). In this study, losses of C, N, P, and K during days 0~100 and Ca and Mg during days 0~50 occurred very rapidly (Fig. 2), especially the loss of K (with about 70~80% of the initial weight lost). Similar results were presented by Ribeiro et al. (2002) after 643 d of decay in *Eucalyptus* plantations in Portugal, indicating that N, P, S, Mg, and K losses mostly occurred during the first 133 d of decomposition, and that the loss of K accounted for 85~89% of the initial weight. Additionally, significant ($p < 0.05$) differences in needle litter nutrient loss and nutrient concentrations of C, N, P, Ca, Mg, and K appeared several times between thinning intensities in the current study period. That is, the current thinning intensities had clear effects on nutrient release of Sugi needle litter. Wollum and Schubert (1975) found no changes in foliar nutrient concentrations in ponderosa pine, and Möller et al. (1991) reported slight differences between thinned and unthinned stands in foliar N, P, and K concentrations after thinning of diverse species. Moreover, Berg (2000) suggested that fresh litter greatly differs from older, partially decomposed litter from a chemical point of view, thus influencing rate-regulating factors and the microbial community.

The rapid loss of C observed during the first 100 d or during days 350~500 was likely due to leaching of water-soluble organic substances from the litter during spring and summer which are warm and wet. In eastern Maine, USA, Rustad and Cronan (1989) and Rustad (1994) both observed rapid loss of C from red spruce (*Picea rubens* Sarg.) litter during the first 6 mo of decay and during the wet winter and early spring months. After excluding C, Osono and Takeda (2001) categorized nutrient dynamics of the decomposition litter into 2 types according to changes in the weight remaining and concentrations of nutrients during decomposition: (1) N and P and (2) K, Ca, and Mg. In this study, a close correlation was found between N and P losses (r^2 = 0.48~0.57, p < 0.005), and between Ca

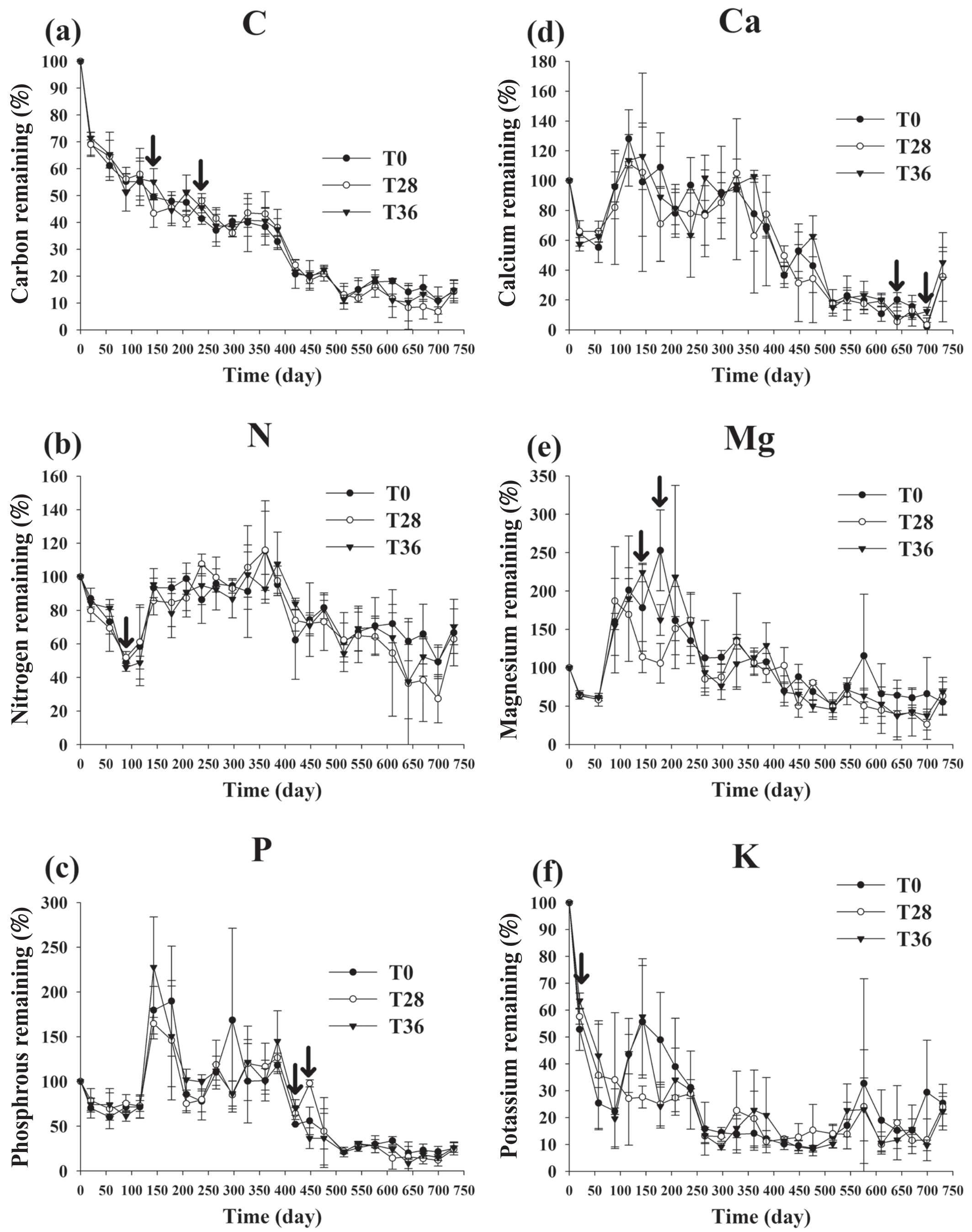

Fig. 2. Nutrient remaining (%) in needle litter (mean ± S.D., *n* = 3) at various time intervals. Arrows indicate differences among treatments with Duncan's new multiple-range test at *p* ≤ 5% level.

and Mg losses (r^2 = 0.57~0.66, p < 0.005) in decomposing litter for the 3 thinning intensities. The loss of K showed a lower correlation with Ca loss (r = 0.40~0.42, p < 0.05) for all treatments, and with Mg (r = 0.53~0.57, p < 0.005) for treatments T0 and T36. According to the correlation of nutrient loss and changes in weight remaining with concentrations of nutrients during decomposition, we categorized nutrient dynamics of the decomposition of litter into 3 types: (1) N and P, (2) Ca and Mg, and (3) K.

Changes in the weights of N and P in this work were characterized by 3 phases: (1) first mobilization in the early stage (days 0~100), (2) immobilization in the early-middle stage (days 100~380); and (3) second mobilization in the middle-late stage (days 380~730). Osono and Takeda (2001) indicated that the net immobilization phase of N and P occurred in the first 21 months and was characterized by an absolute increase of N and P weights due to their incorporation into the litter from the environment. In addition, microbial immobilization, nutrient inputs from atmospheric precipitation and N_2 fixation (Pandey et al. 2007), and increased fungal biomass were probably accompanied by increases in N and P concentrations in the decomposition study (Berg and Söderström 1979, Coûteaux et al. 1998). N and P concentrations increased with time during the immobilization phase and were constant during the mobilization phase (Osono and Takeda 2001), but these time-dependent patterns of N and P levels were not observed in this study. As shown in Fig. 3b and 3c, N and P concentrations increased during the first mobilization phase, and showed a considerable increase in quantities during the immobilization phase. In the second mobilization phase, the N concentration still showed a gradual increase, but the P concentration appeared to decrease and was constant after 500 days.

The second type of nutrient dynamics of the decomposition litter included Ca and Mg. Throughout the study period, patterns of the weight and concentration of Ca were similar to those of Mg irregardless of the thinning intensities. At the end of the study period, the weights of Ca and Mg were lower, but concentrations were higher than the initial level. The mobility of Ca was low during the first year of the study period and indicated that its release was more dependent on biotic activity than on leaching. Ribeiro et al. (2002) suggested that this is consistent with the importance of Ca as a structural component in cell walls of leaves.

The third type only included K. The pattern of weight remaining of K was unlike the pattern of the concentration, but both proved to be variable throughout the study period for the 3 thinning intensities. At the end of the study period, the weight of K remaining was lower, but the K concentration was higher than the initial level. The low portion of K remaining early in the study period was consistent with the high mobility of K due to the lack of incorporation of this element into the organic structure (Ribeiro et al. 2002). Immobilization and mineralization processes regulated the patterns of N and P release in this study, whereas K was released continuously. Isaak and Nair (2005) and Pandey et al. (2007) reported similar patterns of nutrient dynamics to those in this study. However, different decomposer communities developing in the litter in different ecosystems could have resulted in different nutrient release patterns (Pandey et al. 2007).

The overall relative mobilities of the nutrients and mass examined after 730 days are listed as follows: C > P ≈ K ≈ Ca > Mg > N with treatment T0, C > K ≈ P > Ca > Mg > N with treatment T28, and C > K > P > Ca > Mg

> N with treatment T36. Different thinning intensities only changed the relative mobilities of K and P in this study. In other studies, Bubb et al. (1998) suggested that the order of

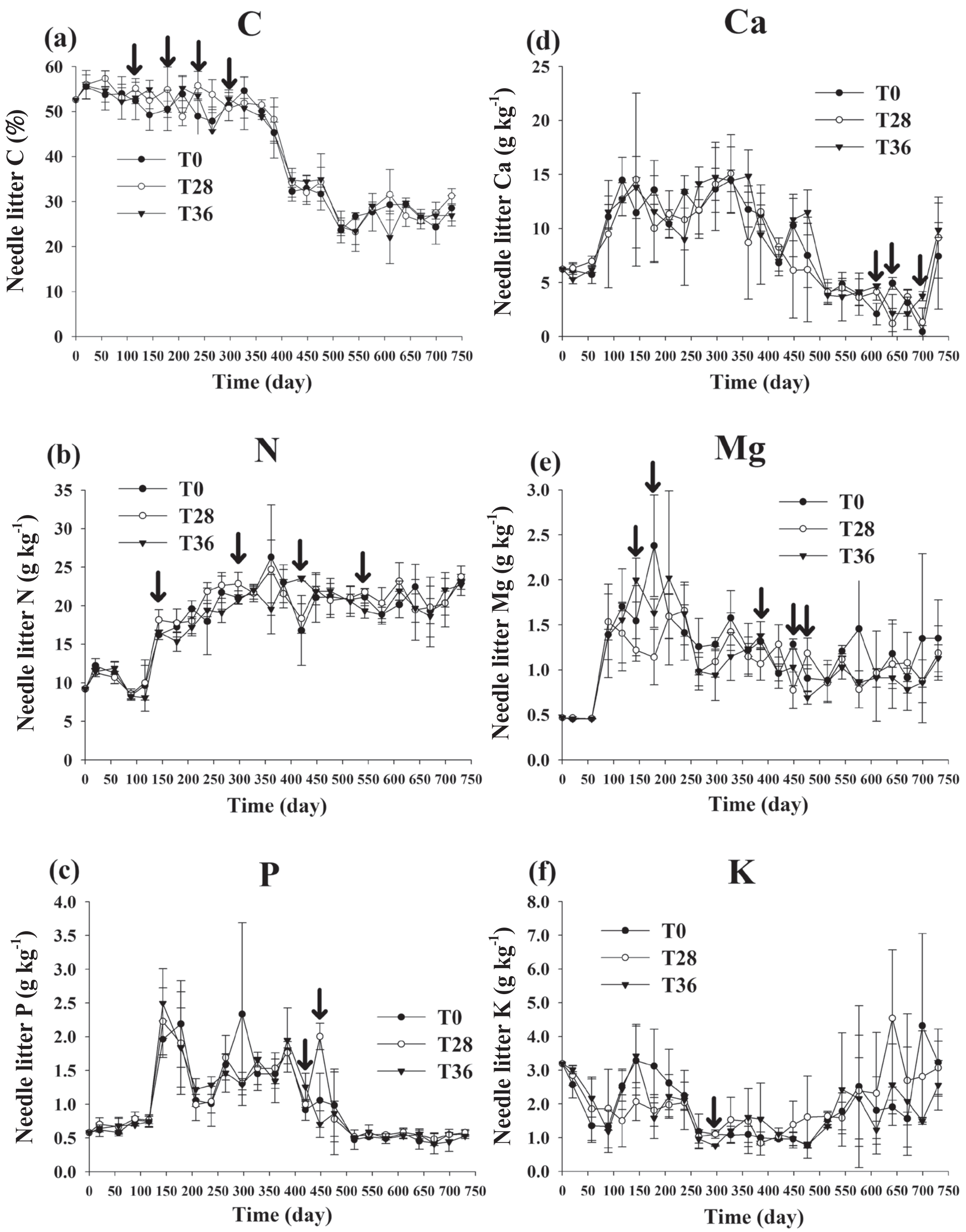

Fig. 3. Nutrient concentrations (g kg^{-1}) in needle litter (mean±S.D., *n* = 3) at various time intervals. Arrows indicate differences among treatments with Duncan's new multiple-range test at the $p \leq 5\%$ level.

element release from hoop pine litter was K > Na > C > Mg > P during the 15-mo period in southeastern Queensland, Australia. Will et al. (1983) reported K > P > dry weight loss > Mg = Ca = Mn > N from *Pinus radiata* litter; and Kavvadias et al. (2001) reported the sequence as Na > K > P > Mg > Ca > N for maritime pine, K > P > Mg > Na > N > Ca for black pine, and K > Ca > P > N > Na > Mg for fir. After excluding C, K was the most mobile nutrient consistently released most rapidly in this study and in the literature. O'Connell (1988) suggested that the rapid loss of K was associated with its leaching in advance of microbial decay. An increase in gaps by thinning caused accelerated leaching of K.

Nutrient return

Element input via litterfall is important to nutrient management in forest ecosystems. In the results reported by Lin (2008), the weights of annual litterfall under treatments T0, T28, and T36 were 5116, 3076, and 2740 kg ha^{-1}, respectively (average of 2 yr). No significant difference was found among thinning treatments (Table 1). The annual weights of needle litterfall of Sugi were 1347, 1095, and 747 kg ha^{-1} yr^{-1}, respectively (2-yr average), which comprised about 26, 36, and 27% of the annual total litterfall for treatments T0, T28, and T36, respectively. No significant difference in annual needle litterfall was found between treatments T0 and T28; however, the litterfall for T36 was clearly lower than the others.

The C return of Sugi leaf litter for all thinning intensities ranged 335 kg ha^{-1} yr^{-1} with T36 to 608 kg ha^{-1} yr^{-1} with T0 (Table 2). C was the highest element in amount returned to the forest floor, followed by Ca with a range of 2.55~5.43 kg ha^{-1} yr^{-1}. The annual return of Ca slightly exceeded that of N. The annual input of N was highest in treatment T0 (4.13 kg ha^{-1} yr^{-1}) and lowest in treatment T36 (2.05 kg ha^{-1} yr^{-1}). The mean annual return of K was slightly lower than that of N. Quantities of P and Mg returned to the soil through needle leaf litter and their stocks in the forest-floor litter mass were considerably lower than those of N. The annual return of all nutrients showed no significant difference between treatments T0 and T28. However, significantly lower nutrient return in treatment T36 was attributed to the lowest input of Sugi leaf litterfall.

About 70~90% of nutrients annually needed for forest growth are provided by decomposition of organic detritus (Vogt et al. 1986). In other words, during these processes, nutrient conservation mechanisms, like strong nutrient retranslocation efficiency and immobilization of nutrients, operate in the ecosystem to maintain productivity (Pandey et al. 2007). The accumulated amounts of C, N, and P in the forest floor reflect differences between litter production rates and decompo-

Table 1. Litterfall production with the 3 thinning treatments in the study area

Treatment	Litterfall (1st yr)	Litterfall (2nd yr)	Litterfall (2-yr average)	Sugi needle litterfall (2-yr average)
	kg ha^{-1}	kg ha^{-1}	kg ha^{-1} yr^{-1}	kg ha^{-1} yr^{-1}
T0	6685±2010a[1)]	3546±670a	5116±2176a	1347±157a
T28	3681±1150ab	2471±582a	3076±1063a	1095±157a
T36	3120±638b	2361±591a	2740±699a	747±87b

[1)] Values followed by different letters within the same column significantly differ at $p \leq 5\%$ according to the Duncan's new multiple-range test [Data source: Lin (2008)].

Table 2. Quantities and nutrient return of needle leaf litter with the 3 thinning treatments in the study area

Treatment	C	N	P	Ca	Mg	K
Initial concentration (g kg^{-1})						
	526±39.1	9.20±1.13	0.58±0.06	6.22±0.95	0.47±0.002	3.19±0.19
Nutrient return (kg ha^{-1} yr^{-1})						
T0	608±71a[1)]	4.13±0.48a	0.58±0.07a	5.43±0.63a	0.28±0.03a	3.21±0.37a
T28	493±71a	3.74±0.54a	0.48±0.07a	4.38±0.63a	0.19±0.03b	2.66±0.38a
T36	335±39b	2.05±0.24b	0.32±0.04b	2.55±0.30b	0.11±0.01c	1.85±0.22b

[1)] Values followed by different letters within the same column significantly differ at $p \leq 5\%$ according to the Duncan's new multiple-range test.

sition rates (Olson 1963). Thinning seems to affect nutrient returns mainly by reducing the aboveground biomass and litterfall production rather than through changes in nutrient concentrations (Blanco et al. 2008). Needle litter production with T0 was similar to that with T28 in this study, whereas T36 was significantly lower than T0 and T28 (Table 1). Needle litter addition may be affected by the thinning intensity because of decreased canopy closure (Bray and Gorham 1964). With afforestation of Mediterranean pine *Pin. pinaster* in central Spain, Roig et al. (2005) indicated that time, treatments, and their interaction had significant effects on litterfall, decreasing the quantity of litterfall with an increased thinning intensity.

The composition and concentration of plant nutrients in litter are important to the decomposition of litter (Jensen 1974). Initial concentrations of N, P, Ca, Mg, and K in Sugi needles were relatively low compared to C (Table 2). Quantities of C and other nutrients returned through litterfall decreased with an increase in the thinning intensity (Table 2). In 32- and 37-yr-old *Pin. sylvestris* L. forests in the western Pyrenees, Blanco et al. (2006) proposed that thinning significantly decreased all nutrient pools with 2 thinning intensities (P20 and P30, with 20 and 30% of the basal area removed, respectively) relative to an unthinned plot (P0) on Garde and Aspurz, but no significant difference was found between P20 and P30, due to the low statistical power. Even when thinning does not seem to accelerate nutrient turnover to the soil, it is an effective tool to avoid litter accumulation in the soil (Roig et al. 2005).

Moreover, quantities of C and other nutrient returned in this study were much lower than those of Norway spruce (*Picea abies* (L.) Karst.) (Slodicak et al. 2005) and *Cunninghamia lanceolata* (Wang et al. 2008). As shown in Tables 1 and 2, both the litterfall amount and concentrations of nutrients in Sugi needles were quite low and would result in lower quantities of nutrient return from Sugi needle decomposition in this study. In addition, the amounts of bioelements in Sugi needle litter returned to the soils are listed as follows: C > Ca > N > K > P > Mg with the 3 thinning intensities in this study. Edmonds and Murray (2002) reported the sequence as Ca > N > K > Mg > P > Na in a temperate ecosystem covered by western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) in Washington state, USA. Slodicak et al. (2005) found the sequence was Ca > N > K > P = Mg in a Czech thinning experiment of Norway spruce (*Pic. abies*). Wang et al. (2007, 2008) reported the sequences to be Ca > N > Mg > K > P and C > N > Ca > Mg > K > P, respectively, on a *Cunninghamia lanceolata* plantation in South China. As indicated by O'Connell (1988), different sequences of bioelements with leaf litter returned to the soil in different forest ecosystems could be due to the initial concentrations of nutrients in the leaf litter, microclimate conditions, mineralization, leaching, the import and export of nutrients through animal activity, translocation in fungal hyphae, and abiotic processes.

Litter decomposition and nutrient cycling in terrestrial ecosystems involve complex long-term processes and cannot be quantified by short-term studies (Anderson et al. 1983, Guo and Sims 2001). However, it is possible that the current thinning level was not high enough to produce changes in needle litter decomposition, nutrient release, and nutrient availability, as was supported by many reports (Vesterdal et al. 1995, Prescott 1997, McJannet et al. 2001, Son et al. 2004). The data presented in this study underscore the need for higher thinning intensity treatments and longer-term decomposition studies of changes in temperate and moist environmental conditions.

CONCLUSIONS

The results of 2-yr monitoring of Sugi needle litter decomposition illustrated that the current thinning intensities had clear effects on nutrient release of Sugi needle litter. During spring and summer, rapid C loss was attributed to the leaching of water-soluble organic substances from the litter. With the exclusion of C, 3 types of nutrient dynamics of decomposing litter in this work were categorized according to the correlation of nutrient loss and changes in the weight remaining and concentration of nutrients during decomposition: (1) N and P, (2) Ca and Mg, and (3) K. Changes in N and P weight loss in this study were characterized into 3 phases, including mobilization in the initial period, immobilization in the middle period, and mobilization in the later period during the 2-yr study. The overall relative mobilities of nutrients examined after 730 days are listed as follows: C > P ≈ K ≈ Ca > Mg > N with treatment T0, C > K ≈ P > Ca > Mg > N with treatment T28, and C > K > P > Ca > Mg > N with treatment T36. In this study, only the relative mobilities of K and P changed with different thinning intensities. K was the most mobile nutrient consistently released most rapidly in this study, except for C.

Gaps increased after thinning and could have resulted in high leaching of K in this study. The annual Sugi needle litterfall showed no significant difference between treatments T0 and T28, but both were higher than treatment T36. The annual return of all nutrients showed no significant difference between treatments T0 and T28. Significantly lower nutrient return existed in treatment T36, and this could be attributed to the lowest input of Sugi needle litterfall. Quantities of C and other nutrients returned through litterfall decreased with an increased thinning intensity. Amounts of bioelements in Sugi needle litter returned to the soils are listed as follows: C > Ca > N > K > P > Mg for the 3 thinning intensities in this study. The above sequence of nutrients returned from needle litter differs from the quantity sequence of the relative mobilities of these nutrients. The current thinning level was not high enough to produce very significant changes in needle litter decomposition, nutrient release, or nutrient availability. However, the present study provides a basis for comparing decomposition processes in a Sugi plantation with different thinning treatments, and also provides a better understanding of the decomposition processes at the ecosystem level.

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