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Carbon and Nutrient Inputs by Litterfall in Evergreen and Deciduous Forests in Korea

Byung Bae Park [1], Afroja Rahman [1], Si Ho Han [1], Woo Bin Youn [1], Hwa Ja Hyun [2], Jonathan Hernandez [1,3] and Ji Young An [1,4,*]

1. Department of Environment and Forest Resources, Chungnam National University, Daejeon 34134, Korea; bbpark@cnu.ac.kr (B.B.P.); afroja.r10@gmail.com (A.R.); bupleurumhan@gmail.com (S.H.H.); dbsdnqls95@naver.com (W.B.Y.)
2. Warm Temperate and Subtropical Forest Research Center, Seogwipo 63582, Korea; viola1974@korea.kr
3. Department of Forest Biological Sciences, University of the Philippines, Los Baños 4031, Philippines; johernandez2@up.edu.ph
4. Institute of Agricultural Science in College of Agriculture and Life Sciences, Chungnam National University, Daejeon 34134, Korea

* Correspondence: ajy2656@cnu.ac.kr; Tel.: +82-42-821-7837

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Abstract: Knowledge about carbon and nutrient fluxes by litterfall is important for understanding nutrient cycling in geologically unique ecosystems. However, the determination of forest litterfall production patterns is difficult due to many biophysical factors influencing the process. In this study, we (1) quantified the litterfall production and carbon and nutrient fluxes in warm-temperate evergreen forest stands in Jeju Gotjawal and (2) compared these values to those of a typical cool-temperate deciduous forest stand by forest types and climate differences. Litterfall from evergreen broadleaved forests at Cheongsu (CS) and Seonheul (SH_b), a mixed forest at Seonheul (SH_m) in Jeju Gotjawal, and a deciduous broadleaved forest at Chungnam National University Forest (CNU) was collected for a full two years using litter traps. Samples were sorted into leaves, twigs, barks, seeds, and unidentified materials, and then weighed and measured for C, N, P, K, Ca, and Mg fluxes by litterfall. Results showed that the mean annual litterfall (846.3 g m^{-2}, average of CS, SH_b, and SH_m) at Jeju Gotjawal was similar to that of CNU (885.5 g m^{-2}), but varied by site in Jeju Gotjawal: CS (933.1 g m^{-2}) was significantly higher than the average of SH_b and SH_m (802.9 g m^{-2}). Seasonal patterns of litterfall production differed by forest types; evergreen broadleaved forests showed a bimodal peak in fall and spring while deciduous broadleaved forests showed a unimodal peak in fall. Jeju Gotjawal had significantly higher total macronutrient concentrations and contents (except for K) than CNU and they also varied by site in Jeju Gotjawal: CS had higher N, P, Ca, and Mg contents than SH_b and SH_m. We conclude that litterfall production and nutrient fluxes differed by forest stand as influenced by forest types and climate. Further, our findings are important for understanding carbon and nutrient dynamics in the geologically unique ecosystem of Jeju Gotjawal and other areas with similar characteristics.

Keywords: Litter production; Nutrient flux; *Quercus acutissima* Carruth; *Quercus glauca* Thunb.; Gotjawal

1. Introduction

Litterfall indicates various ecosystem processes including biogeochemical cycles; hence, it plays a role as an important pathway of nutrient cycling [1,2]. The input–output system of litterfall production and subsequent mineralization maintains soil fertility in forest ecosystems [3–5], thereby increasing forest productivity. Litterfall is the most important source of organic matter and soil nutrients [6,7]. In forests, litterfall can transfer approximately 18 Pg C year^{-1} to the soil surface, which is about one-third of the annual C uptake [8,9]. Consequently, studies about nutrient fluxes by litterfall in forest ecosystems are deemed important for understanding nutrient cycling dynamics. However, determining the pattern of litterfall production across different forests remains a challenge for ecologists due to many physical and biological factors affecting litterfall production.

The quality and quantity of litterfall production affect the carbon and nutrient fluxes in temperate and tropical ecosystems [10,11]. Litterfall production across forest types depends on biological factors such as structure of the vegetation (e.g., density, basal area), its age, floristic composition, and characteristics of plant communities [12–14]. Many studies have shown the significant variation of litterfall on nutrient flux in different forests as influenced by climatic factors [7,15,16]. In Eurasian forests, for instance, it was reported that relative unit change in temperature (annual mean temperature change from −8 to 30 °C) had more effect on litterfall than that in precipitation (annual mean precipitation change from 350 to 4000 mm) [15]. A high interannual variation of litterfall ranging from 18 g m^{-2} to 213 g m^{-2} through the 24-year study was reported for a Scots pine (*Pinus sylvestris* L.) stand in Finland [17]. Even though the stand age was not an important determining factor for needle litterfall with no overall pattern, the average temperature in July was apparently correlated with needle litterfall, indicating that high temperature enhanced litterfall in the short term. Regression analysis also indicated that the combined effect of temperature and precipitation accounted for 30%–52% of the variation in N concentration of leaf litter across groups of conifers, broadleaves, deciduous trees, and evergreens [18]. Further, different patterns in litterfall production exist in different types of ecosystems including unimodal and bimodal [19,20], and the litter peaks could occur in several months of the year [16]. For instance, peak litterfall of temperate deciduous forests usually occurs in autumn, whereas cool-temperate evergreen forests do not show an obvious seasonal pattern [21,22].

In this study, we report for the first time the litterfall and carbon and nutrient fluxes in evergreen forests in Jeju Gotjawal in comparison to a typical broadleaf deciduous forest in Daejeon, South Korea. The Gotjawal has been the most interesting research site in Korea due to its unique biogeographic feature, characterized by its unique forest ecosystem structures formed on widely and disorderly distributed lava blocks [23]. Jeju is the largest volcanic island in South Korea where temperate and subtropical species coexist [24,25]. Jeju Gotjawal is also home to more than 1990 taxa of vascular plants, of which 90 taxa are endemic to Jeju such as *Quercus glauca* Thunb., *Euphorbia octoradiata* H.Lév.&Vaniot ex H.Lév, and *Codonopsis minima* Nakai [26]. Further, the Jeju Gotjawal area has poor soil development because the main parent material of the soils is basalt and some of the soils originated from trachyte and trachytic andesite [27], making any ecological study in the area even more important.

Thus, the objectives of the present study were to (1) quantify carbon and nutrient fluxes through litterfall in evergreen forest stands in Jeju Gotjawal, and (2) compare these fluxes to those of a typical deciduous forest stand in terms of forest types and climate. We hypothesized that annual litterfall production does not differ between warm-temperate evergreen and cool-temperate deciduous forests while the seasonal pattern of litterfall is more distinct in cool-temperate deciduous forests than warm-temperate evergreen forests. Moreover, the second hypothesis was that carbon and nutrient fluxes through litterfall vary by forest types but not by year.

2. Materials and Methods

2.1. Study Sites and Stand Descriptions

This study was conducted in Jeju Island and Daejeon, Republic of Korea. We established two research sites in Jeju, which are Cheongsu (33°18′14.79″N, 126°16′16.67″E, 120 m a.s.l.) and Seonheul (33°30′38.82″N, 126°43′13.25″E, 110 m a.s.l.) Gotjawal, and one site in Daejeon, which is located in Chungnam National University Experimental Forest (36°22′16.0"N, 127°21′08.0"E, 105 m a. s.l.). These sites were selected based on forest functional types and climate. Cheongsu Gotjawal (hereafter, CS) is a warm-temperate broadleaf evergreen forest on lava plateau in the western part of Jeju Island, having locally distributed water holes on gentle slopes. Soil texture in CS was clay with pH 4.0, organic matter (OM) 44%, available phosphorus (AP) 70 mg kg^{-1}, total nitrogen (TN) 2.3%, and cation exchange capacity (CEC) 75 $cmol_c$ kg^{-1} [28]. Seonheul Gotjawal (hereafter, SH) is a warm-temperate broadleaf evergreen (SH_b) and mixed evergreen (SH_m) forest located in the northeastern part of the island characterized by small lava caves, wetlands, and a parasitic volcano terrain [29]. Soil texture in SH was loam with pH 4.5, OM 31%, AP 61 mg kg^{-1}, TN 1.3%, and CEC 57 $cmol_c$ kg^{-1} [28]. Lastly, Chungnam National University Experimental Forest (hereafter, CNU) is a cool-temperate broadleaf deciduous forest located in the central area of South Korea. Soil texture in CNU was sandy loam with pH 4.5, OM 4%, AP 18 mg kg^{-1}, TN 0.1%, and CEC 7.5 $cmol_c$ kg^{-1}.

The study sites in Jeju Gotjawal and CNU were naturally regenerated after severe human interferences for woods until the mid-1960s to early 1970s. Particularly, the vegetation in Jeju Gotjawal originated from the secondary coppice forests with high sprouts density [30]. Diameter at breast height (DBH) ranged from 6.1 cm to 55.8 cm in all stands and the total basal area (BA) for all tree species was the highest in SH (50.8 m^2 ha^{-1}, Table 1). CS was dominated by *Q. glauca* with a 30.3 m^2 ha^{-1} mean BA accounting for 89% of total BA. Other subcanopy species were *Actinodaphne lancifolia* (Siebold&Zucc.) Meisn., *Ficus erecta* Thunb., *Cinnamomum camphora* (L.) J. Presl, *Cinnamomum yabunikkei* H.Ohba, *Celtis sinensis* Pers., *Acer palmatum* Thunb., and *Picrasma quassioides* (D.Don) Benn. SH_b was dominated by *Q. glauca* and *Q. salicina* Blume with 50.7 m^2 ha^{-1} mean BA (88% of total BA) and 13.0 m mean height. Other canopy and subcanopy tree species were *Prunus pendula* f. ascendens (Makino) Kitam. and *Styrax japonica* Siebold&Zucc. SH_m was dominated by *Q. glauca* and *Pinus thunbergii* Parl. with 50.9 m^2 ha^{-1} mean BA. The tree height was 10.9 m for *Q. glauca* and 13.2 m for *P. thunbergii*. In this site, subcanopy species (*Camellia japonica* L., *Distylium racemosum* Siebold&Zucc., and *A. palmatum*) accounted for 8% of the total BA. Lastly, CNU was dominated by *Q. acutissima* Carruth. with 18.5 m^2 ha^{-1} mean BA and 13.8 m mean height. Other subcanopy species (*Cornus officinalis* Siebold&Zucc., *Magnolia kobus* DC., *Robinia pseudoacacia* L., and *Magnolia obovata* Thunb.) accounted for 39% of the total BA [31,32].

Table 1. Descriptions of four study stands in Jeju Island (CS, SH_b, and SH_m) and Daejeon (CNU) in Korea.

Stand	CS [1]		SH_b [2]		SH_m [3]		CNU [4]	
Forest Type	Evergreen Broadleaved		Evergreen Broadleaved		Evergreen Mixed		Deciduous Broadleaved	
All tree species								
DBH (cm)	12.5	(0.3)	19.1	(0.2)	21.6	(0.9)	20.2	(1.8)
Height (m)	9.4	(0.2)	10.7	(0.2)	10.9	(0.3)	12.5	(0.5)
BA (m^2 ha^{-1}) [5]	34.0	(0.4)	50.7	(0.6)	50.9	(0.4)	33.2	(4.4)
Density (ha^{-1})	2475	(51)	1300	(25)	1075	(35)	900	(135)
Dominant species								
Oak [6]								
DBH (cm)	12.4	(0.5)	27.3	(2.2)	20.7	(1.1)	21.4	(1.9)
Height (m)	9.5	(0.2)	13.0	(0.5)	10.9	(0.2)	13.8	(0.9)
BA (m^2 ha^{-1}) [5]	30.3	(0.2)	44.4	(0.8)	28.5	(0.3)	18.5	(3.2)
P. thunbergii								
DBH (cm)	-		-		31.4	(1.9)	-	
Height (m)	-		-		13.2	(0.9)	-	
BA (m^2 ha^{-1}) [5]	-		-		18.7	(3.2)	-	
Diversity indices								
Shannon's diversity index [7]	1.4		2.1		1.4		1.5	
Shannon's equitability	0.5		0.8		0.5		0.7	
Simpson's diversity index	2.2		5.9		2.5		3.2	
Simpson's equitability	0.1		0.4		0.2		0.4	

[1] CS, Cheongsu Gotjawal in Jeju Island; [2] SH_b, Seonheul Gotjawal in Jeju Island; [3] SH_m, Seonheul Gotjawal in Jeju Island; [4] CNU, Chugnam National University Experimental Forest in Daejeon.; [5] Sum of basal area; [6] Oak represents *Q. glauca* in CS and SH_m, *Q. glauca* and *Q. salicina* in SH_b, and *Q. acutissima* in CNU; [7] Equations for diversity indices in [33,34]; Minimum sampling DBH was 6 cm; Standard errors in parentheses (n = 4).

2.2. Climate Conditions

Monthly temperature and precipitation data (Figure 1) were provided by the meteorological center near each study site: (1) Seogwang Station (33°18′16.4″N and 126°18′21.6″E, 187 m a.s.l.), 3.2 km east of CS; (2) Seonheul Station (33°28′55.5″N and 126°42′32.5″E, 251 m a.s.l.), 3.4 km south of SH; and (3) Daejeon station (36°22′ N and 127° 22′ E, 70 m a.s.l), 1.8 km east of CNU. The monthly temperature in Seonheul was calibrated according to the standard temperature lapse rate because the elevation of the Seonheul weather station was 141.1 m higher than the study site in Seonheul. The mean annual temperature (MAP) of the three sites were in this order: CS (15.5 °C) > SH (14.8 °C) > CNU (13.6 °C). At all stands, the highest temperature was observed in summer (June–August, c.a. 25–26 °C). The winter temperature (December–February) at Jeju Gotjawal was warmer (c.a. 5–10 °C) than that at CNU (–5–0 °C). The mean annual precipitation of the three sites followed this descending order: SH (1883 mm) > CS (1569 mm) > CNU (1299 mm). High precipitation rate was observed during mid-summer season (July) to mid-fall (September) and the lowest was observed during winter (December–February) in all stands. In October 2016, the storm "Chaba" induced heavy rainfall and strong winds in Jeju Island.

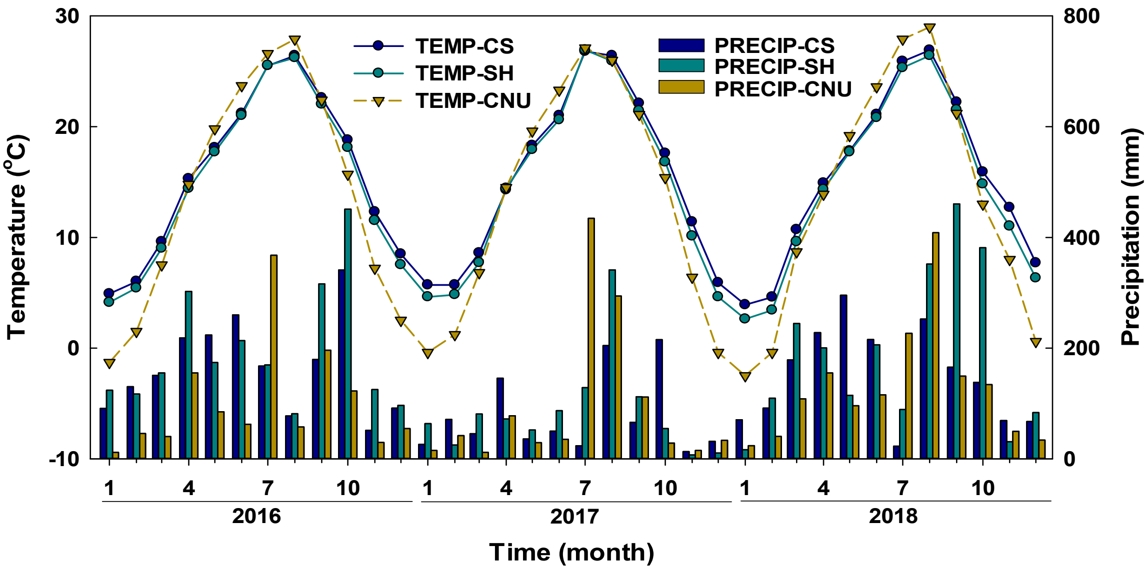

Figure 1. Monthly temperature and precipitation at Cheongsu (CS) and Seonheul (SH) Gotjawal in Jeju Island and Chungnam National University (CNU) Experimental Forest in Daejeon from 2016 to 2018.

2.3. Litterfall Collection

In each stand, we established four plots with four litter traps in each plot (>20 m distance between plots). A total of 64 traps were installed (12 m distance between traps) in a quadrangle shape manner. Litterfall was collected every three months in Jeju Gotjawal stands and CNU forest using circular litter traps (i.e., 67 cm in diameter) from August 19th, 2016 to August 21st, 2018. Litter traps were set 30 cm above the forest floor in April 2015 for Jeju Gotjawal. In August 2016, different sizes of litter traps were used for CNU forest (i.e., 56 cm in diameter) and were set 40 cm above the ground. Further, we installed a 2 mm size iron mesh and rocks were placed at the bottom of each litter trap to prevent overflow and litter loss. The litterfall samples were immediately air-dried at room temperature to prevent decomposition. After drying, samples were sorted into five litterfall components: leaves, twigs, bark, seeds, and unidentified materials. Leaf litter of dominant species was further classified into *Q. acutissima*, evergreen oak (*Q. glauca* and *Q. salicina*), and *P. thunbergii*. The sorted components were oven-dried at 65 °C for 48 h to a constant mass and then weighed. Annual litterfall production was estimated by summing up the quarterly litterfall mass during the study.

2.4. Nutrient Analysis

For nutrient concentration analysis, we used two cohort litter samples collected in November 2016 and May 2017 for CS and SH. For the CNU forest, samples from November 2016 collections were used. Samples from two plots at each collection time were composited and made two composite samples per stand. A total of 105 composite samples were analyzed for leaf, needle, and other leaf tissue.

Samples for chemical analysis were ground and homogenized following a standard protocol in tissue nutrient analysis. Total nitrogen (TN) was determined by using the micro-Kjeldahl digestion method. Ca, Mg, and K were measured by atomic absorption spectrophotometry, and P by the ascorbic acid method [35]. Nutrient contents were calculated by annual total litterfall multiplied by average nutrient concentrations by each tissue.

2.5. Statistical Analysis

Two-way analysis of variance (ANOVA) was performed to detect statistical differences in litterfall mass, nutrient concentration, and nutrient contents across different forest stands. Multiple comparisons of means were completed using Duncan's multiple range test at $\alpha = 0.05$. All statistical analyses were performed using SAS 9.4 software (SAS Institute, Cary, NC, USA).

3. Results

3.1. Litterfall Variation

The first year's total litterfall was significantly greater than the second year of production in all stands, except for the CNU forest, in which it increased significantly in 2018 (Figure 2a). Between deciduous and evergreen forests, the mean annual litterfall at Jeju Gotjawal (i.e., 846.3 g m^{-2}, average of CS, SH_b, and SH_m) did not differ significantly from that at CNU (i.e., 884.5 g m^{-2}), but varied by stand in Jeju Gotjawal, such that CS (933.1 g m^{-2}) was significantly higher than the average of SH_b and SH_m (802.9 g m^{-2}). Mean annual litterfall at SH_b was lower (i.e., 782.5 g m^{-2}) than that at SH_m (i.e., 823.3 g m^{-2}). Further, annual leaf litterfall comprised 60%–69% of the total litterfall in all sites, of which SH_m had the highest leaf litterfall across the stands ($p < 0.05$, Figure 2b) in the first study period. This result did not vary significantly in the second study period. The other litterfall components comprised 30%–35% of the total litterfall across the sites in the first year; nearly the same pattern was observed in the following year (Figure 2b).

Total and each litter component were significantly different across stands and seasons (Table 2). Seasonal patterns of total litterfall production differed between evergreen and deciduous forests; total litterfall in CS and SH_b was the greatest in fall and spring seasons, that is, it showed a bimodal pattern, while CNU showed a unimodal total litterfall production (i.e., peaked only in the fall season) (Figure 3). However, a bimodal pattern of litter production in the Jeju Gotjawal sites was inconspicuous in the second year (Figure 3a,c,d). Summer and winter had the lowest litterfall across the sites and study periods. Leaf and twig litters in Jeju Gotjawal stands peaked in the season of fall 2016, and we did not observe the same pattern the following year.

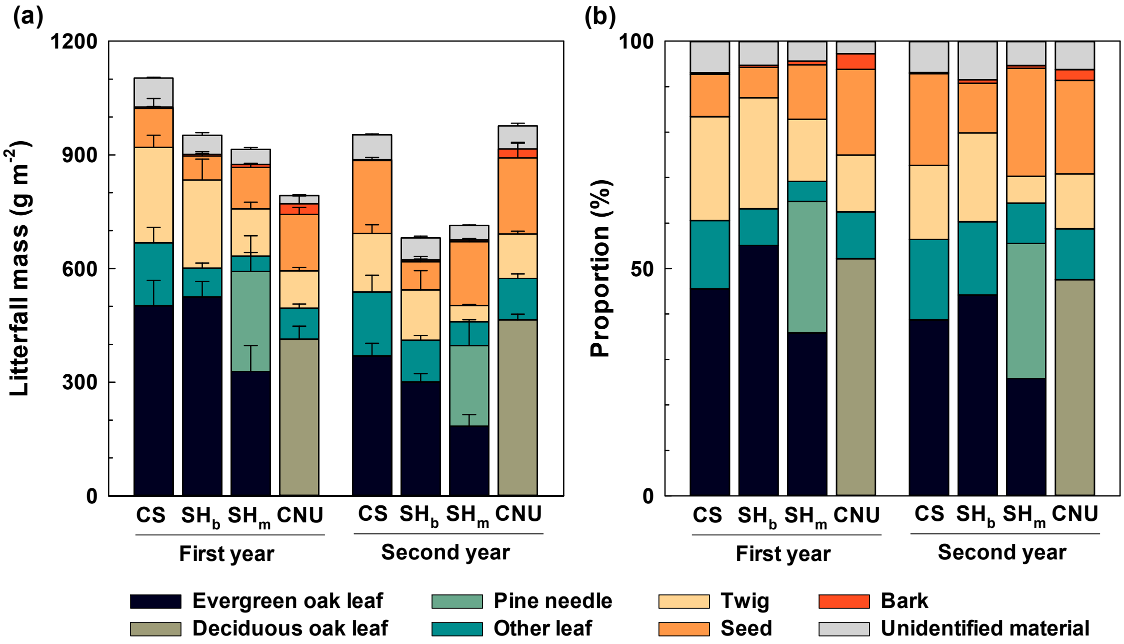

Figure 2. Annual litterfall (**a**) mass and (**b**) proportion of each litter component in evergreen broadleaved forest at Cheongsu (CS), evergreen broadleaved forest at Seonheul (SH_b), mixed forest at Seonheul (SH_m), and deciduous broadleaved forest at Chungnam National University (CNU) from August 2016 to August 2018. First and second year indicate the period from August 19, 2016 to August 23, 2017 and from August 24, 2017 to August 21, 2018, respectively. Evergreen oak leaf includes *Quercus glauca* and *Q. salicina* in CS, SH_b, and SH_m. Pine needle in SH_m represents needle litter of *Pinus thunbergii*. Deciduous oak leaf in CNU represents leaf litter of *Q. acutissima*.

Table 2. P values estimated by two-way analysis of variance (ANOVA) for seasonal litterfall variation across stands in Jeju Island and Daejeon of South Korea.

		Stand	Season	Stand×Season
Litter components	df	3	7	21
Leaf litterfall				
Oak[1]		<0.0001	<0.0001	<0.0001
Pine[2]		<0.0001	0.0263	0.0026
Other species		<0.0001	<0.0001	<0.0001
Total leaf		0.0476	<0.0001	<0.0001
Other litterfall				
Twig		<0.0001	<0.0001	<0.0001
Seed		<0.0001	<0.0001	<0.0001
Bark		<0.0001	0.0087	**0.5218**[3]
Unidentified material		<0.0001	<0.0001	<0.0001
Total litterfall		0.0002	0.0002	<0.0001

[1] Oak denotes leaf litter of *Q. glauca* and *Q. salicina* in Cheongsu and Seonheul, and *Q. acutissima* in Chungnam National University; [2] Pine denotes needle litter of *Pinus thunbergii*; [3] P value in bold indicates statistically nonsignificant (<0.05).

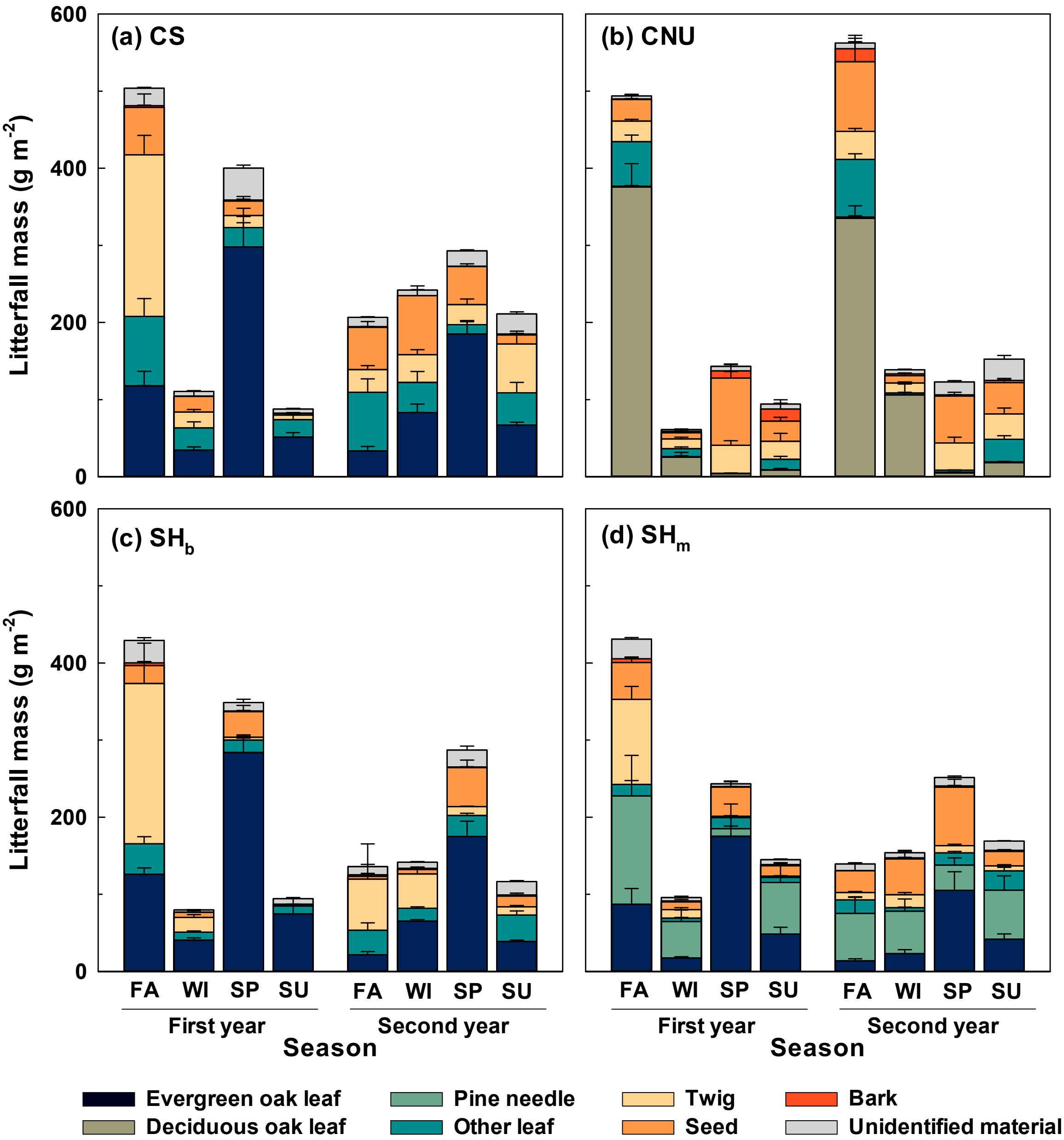

Figure 3. Seasonal variation of litterfall mass in (**a**) evergreen broadleaved forest at Cheongsu (CS), (**b**) deciduous broadleaved forest at Chungnam National University (CNU), (**c**) evergreen broadleaved forest at Seonheul (SH_b), and (**d**) mixed forest at Seonheul (SH_m) from August 2016 to August 2018. FA, WI, SP, and SU indicate the seasons of fall, winter, spring, and summer, respectively. First and second year indicate the period from August 19, 2016 to August 23, 2017 and from August 24, 2017 to August 21, 2018, respectively. Evergreen oak leaf includes *Quercus glauca* and *Q. salicina* in CS, SH_b, and SH_m. Pine needle in SH_m represents needle litter of *Pinus thunbergii*. Deciduous oak leaf in CNU represents leaf litter of *Q. acutissima*.

3.2. Carbon and Nutrient Concentrations of Litterfall

Litterfall concentrations in Jeju Gotjawal stands ranged from 46.15% to 51.01%, showing the highest value in pine needle at SH_m (Table 3) and they were not different from CNU. Similarly, there was not much difference between CS and SH and between SH_b and SH_m. Generally, CNU had lower total macronutrient concentrations (except for K) than those stands in Jeju Gotjawal (Table 3). The annual K concentration was found highest at CNU but CNU had the lowest P and Mg concentrations across the stands. In terms of leaf litterfall macronutrient concentrations, CNU had lower N, P, Ca, and Mg concentrations compared to those stands in Jeju Gotjawal. Within Jeju, macronutrient concentrations at CS were higher than SH_b and SH_m. There was also not much difference for the C and macronutrient concentrations in the nonleaf components (twig, seed, bark, and other tissues) across the sites.

Table 3. Carbon and nutrient (nitrogen, phosphorus, potassium, calcium, and magnesium) concentrations of each litter component at four stands in Jeju Island (CS, SH_b, and SH_m) and Daejeon (CNU) of South Korea.

Stand	Litter Component	Carbon (%)	Nitrogen (%)	Phosphorus (%)	Potassium (%)	Calcium (%)	Magnesium (%)
CS[1]	EO[5] leaf	47.48 (0.21)	1.58 (0.05)	0.07 (0.00)	0.13 (0.01)	0.69 (0.04)	0.27 (0.01)
	Other leaf	46.98 (0.37)	1.60 (0.10)	0.10 (0.00)	0.14 (0.02)	1.02 (0.07)	0.30 (0.04)
	Twig	48.08 (0.19)	0.98 (0.10)	0.05 (0.00)	0.08 (0.01)	0.81 (0.08)	0.18 (0.01)
	Seed	47.25 (1.27)	1.11 (0.19)	0.09 (0.01)	0.24 (0.04)	0.34 (0.05)	0.20 (0.04)
	Bark	47.11 (0.24)	1.72 (0.09)	0.11 (0.01)	0.12 (0.00)	1.07 (0.13)	0.29 (0.02)
SH_b[2]	EO leaf	48.76 (0.28)	1.39(0.05)	0.06 (0.01)	0.12 (0.01)	0.54 (0.03)	0.26 (0.03)
	Other leaf	47.65 (0.29)	1.57 (0.07)	0.09 (0.00)	0.13 (0.01)	0.63 (0.07)	0.30 (0.02)
	Twig	48.12 (0.25)	0.86 (0.05)	0.05 (0.00)	0.07 (0.01)	0.52 (0.03)	0.19 (0.02)
	Seed	47.19 (0.08)	1.07 (0.09)	0.08 (0.01)	0.25 (0.06)	0.22 (0.00)	0.21 (0.04)
	Bark	47.49 (0.22)	1.73 (0.11)	0.11 (0.01)	0.11 (0.01)	0.65 (0.04)	0.25 (0.02)
SH_m[3]	EO leaf	48.13 (0.11)	1.32 (0.04)	0.06 (0.00)	0.12 (0.01)	0.46 (0.02)	0.26 (0.01)
	Pine[6] needle	51.01 (0.09)	0.60 (0.03)	0.04 (0.00)	0.04 (0.00)	0.34 (0.02)	0.14 (0.01)
	Other leaf	46.15 (0.63)	1.37 (0.11)	0.08 (0.01)	0.12 (0.02)	0.50 (0.07)	0.38 (0.02)
	Twig	50.30 (0.73)	0.61 (0.07)	0.05 (0.00)	0.04 (0.00)	0.55 (0.06)	0.14 (0.02)
	Seed	48.74 (0.89)	0.89 (0.10)	0.07 (0.00)	0.13 (0.01)	0.15 (0.03)	0.15 (0.01)
	Bark	48.68 (0.61)	1.32 (0.25)	0.08 (0.01)	0.05 (0.01)	0.44 (0.05)	0.21 (0.03)
CNU[4]	DO[7] leaf	49.11 (0.46)	0.97(0.09)	0.03 (0.00)	0.18 (0.01)	0.46 (0.01)	0.13 (0.01)
	Other leaf	47.69 (0.34)	1.52 (0.06)	0.05 (0.00)	0.32 (0.02)	0.81 (0.14)	0.21 (0.02)
	Twig	48.69 (0.22)	0.73 (0.04)	0.04 (0.00)	0.23 (0.01)	0.53 (0.01)	0.17 (0.02)
	Seed	48.50 (0.19)	0.93 (0.12)	0.06 (0.00)	0.28 (0.05)	0.22 (0.05)	0.15 (0.01)
	Bark	44.29 (1.69)	1.55 (0.19)	0.09 (0.01)	0.20 (0.03)	0.53 (0.14)	0.17 (0.01)

[1] CS, Cheongsu Gotjawal in Jeju Island; [2] SH_b, Seonheul Gotjawal in Jeju Island; [3] SH_m, Seonheul Gotjawal in Jeju Island; [4] CNU, Chugnam National University Experimental Forest in Daejeon; [5] EO denotes evergreen oak trees, which are *Quercuss glauca* and *Q. salicina* in Cheongsu and Seounheul; [6] Pine denotes *Pinus thunbergii*; [7] DO denotes deciduous oak tree, which is *Q. acutissima* in CNU; Standard errors in parentheses (n = 4).

3.3. Carbon and Nutrient Inputs by Litterfall

Across the stands, litter carbon content did not show considerable difference across the stands (Figure 4). However, carbon content decreased in the second year in Jeju Gotjawal stands; CNU showed a reverse trend (Figure 4a). Jeju Gotjawal stands had higher nutrient contents (except for K) than CNU. Nutrient contents all decreased in the second year across the sites, except K at CNU which increased significantly. The K content was found highest at CNU across the stands (Figure 4d). Lastly, CS had higher N, P, Ca, and Mg contents than SH_b and SH_m.

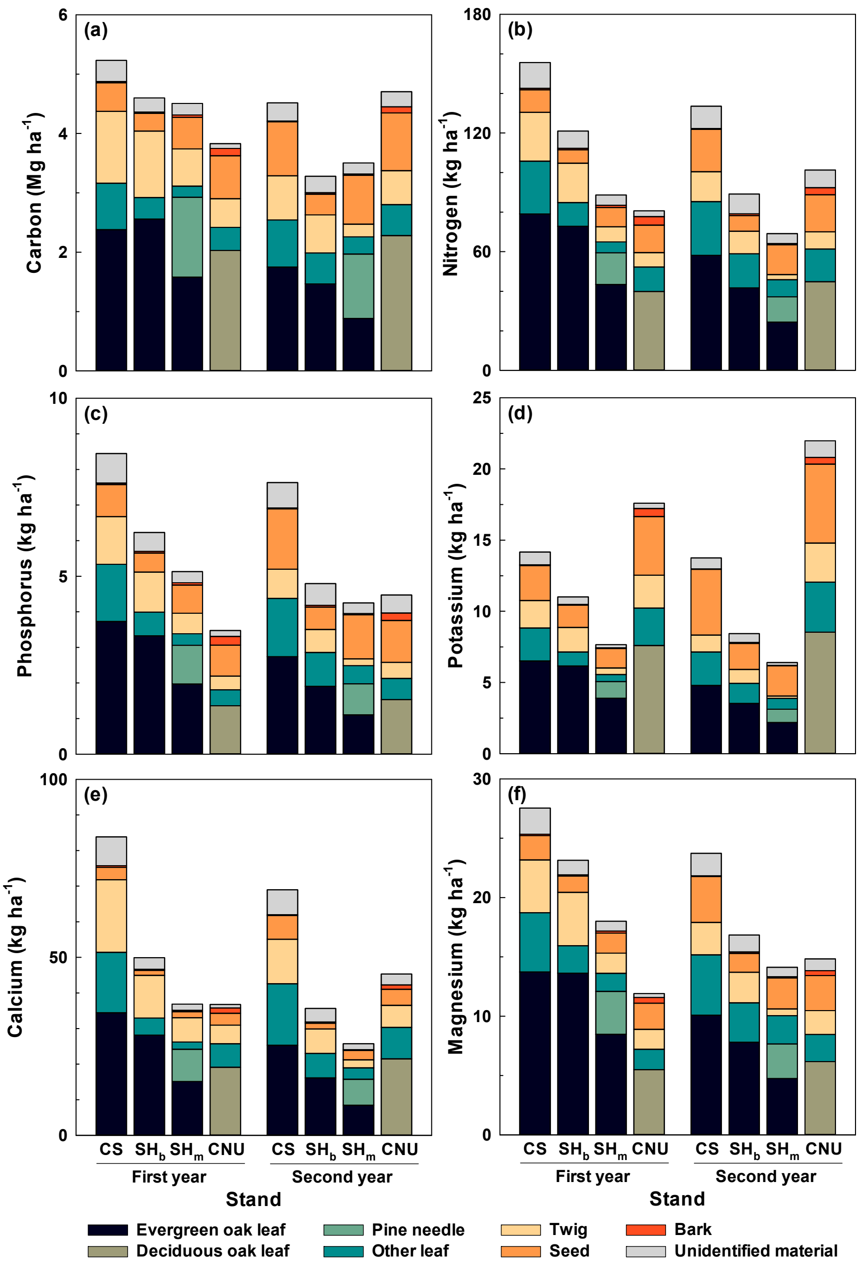

Figure 4. Annual (**a**) carbon, (**b**) nitrogen, (**c**) phosphorus, (**d**) potassium, (**e**) calcium, and (**f**) magnesium content of litterfall in evergreen broadleaved forest at Cheongsu (CS), evergreen broadleaved forest at Seonheul (SH_b), mixed forest at Seonheul (SH_m), and deciduous broadleaved forest at Chungnam National University (CNU) from August 2016 to August 2018. First and second year indicate the period from August 19, 2016 to August 23, 2017 and from August 24, 2017 to August 21, 2018, respectively. Evergreen oak leaf includes *Quercus glauca* and *Q. salicina* in CS, SH_b, and SH_m. Pine needle in SH_m represents needle litter of *Pinus thunbergii*. Deciduous oak leaf in CNU represents leaf litter of *Q. acutissima*.

4. Discussion

4.1. Litterfall Production in Different Forests

Annual litterfall production at evergreen broadleaved stands in Jeju Gotjawal did not vary significantly from that of a deciduous stand at CNU. This result confirmed a previous study [36] conducted in the same region, in which annual litterfall production in deciduous broadleaved forests (i.e., 560.6 g m^{-2}) was nearly similar to that of evergreen broadleaved forests (i.e., 544.8 g m^{-2}). Such a pattern of litterfall production, however, contrasts with the global pattern of litterfall between evergreen and deciduous stands [37]. The possible reason for the inconsistency in the result may include the difference in the diversity of species and stand structures. Although the forest functional type of Jeju Gotjawal (i.e., evergreen) is very distinct from that of CNU (i.e., deciduous), the variation in the diversity of tree species and the stand structure may have not differed significantly across the stands to cause significant litterfall variation. In this study, we found that all the stands at Jeju Gotjawal and CNU fall in the same category of diversity index (i.e., very low to low) based on the classification scheme of the Shannon–Wiener diversity index [38]. Significant difference in litterfall production may exist in different ecosystem types which are partly dependent on plant community composition and species abundance [39]. Some diversity-related studies have reported that more diverse tree species produce more litter [40,41] by changing the diversity of litter quality [40]. According to a previous study, higher mean annual litterfall production was found in evergreen mixed forests than in evergreen broadleaved forests [42]. For example, the mean annual litter production in the evergreen mixed forest was significantly higher by 24% than the evergreen broadleaved stand in a subtropical region in China [43].

However, we found that litterfall production varied by stand within Jeju Gotjawal, such that litterfall at CS was significantly higher than that at SH_b. This observation can be explained by the difference in stand structure; DBH, height, and BA are higher in SH_b than CS, indicating that SH_b is probably older than CS. Several studies have long documented a rapid increase in annual litterfall production during the stand development until canopy closure; it then remains nearly stable as the stand becomes older [44,45]. Moreover, [46] found higher litterfall production in pioneer forests. The difference between the two stands may also be explained by a mechanism called competitive production principle [47]. The forest stand at CS had higher MAT and lower MAP than at SH, which may have induced its net primary production. In some studies, litterfall correlated positively with temperature, which controlled nearly half of the variation [15,48]. Further, actions of herbivores influencing the leaf senescence and decay were also positively related to temperature [49].

In this study, seasonal litterfall production varied between Jeju Gotjawal and CNU. CNU is located in the cool-temperate region while Jeju Gotjawal is located in the warm-temperate/subtropical region of South Korea. Studies have already shown that warm-temperate and cool-temperate forests have strong seasonal variability that influences the seasonal patterns of litterfall [7] as a function of climate and plant functional types [45,46]. The litterfall peak patterns (i.e., spring and fall) observed in CS and SH_b stands may be due to two factors, namely, (1) the influence of temperature on leaf phenology of the species, and (2) the disturbance effect of typhoons. First, it was reported that the enhanced annual litterfall production was positively related to temperature due to the advancement of leaf expansion and increased forest productivity during the spring season [50–53]. The litterfall peaks we observed are also consistent with the pattern reported for a subtropical evergreen forest in China [54], which was associated with physiological leaf senescence as cited in similar studies [55,56]. Second, litterfall in CS and SH_b stands also peaked in the fall season during the first study period, causing high annual litterfall fluctuation. This can be in part a consequence of the disturbance effects of the storm Chaba that hit forests in Jeju Gotjawal in October 2016 (i.e., fall season), as it is evident that twig and leaf litterfall was huge in the first study period and was not consistent the following year. Similar findings were reported in [20], who observed higher branch litterfall production during typhoon and rainy months. In addition, litterfall was found significantly higher in years with typhoons than in years without typhoons in a subtropical forest in Taiwan, in which 82% of the litterfall variation was attributed to the number of strong typhoons [57]. Consequently, the disturbance effect of the storm in this study may remain a speculation that needs to be investigated in future studies using longer study duration.

4.2. Carbon and Nutrient Fluxes through Litterfall

In this study, the litter carbon concentration and contents did not vary significantly across the forest stands. This is consistent with the study on carbon and energy fluxes between deciduous and evergreen oak woodlands reported in [58]. In a cretaceous polar forest, similar annual carbon fluxes were reported between deciduous and evergreen species, despite incurring carbon losses of deciduous species through annual leaf shedding [59]. The result can represent different strategies of dominant species in Jeju Gotjawal (*Q. glauca*, evergreen) and CNU (*Q. acutissima*, deciduous) for coping with the environmental conditions. Evergreens can minimize the rate of C return via litterfall through a "conservative" leaf strategy. Through this strategy, evergreens produce leaves with longer life span and lower photosynthetic capacity than deciduous leaves [60–62]. However, evergreens can compensate for the lower photosynthetic capacity by assimilating carbon over a longer growing season [63–65], whereas deciduous trees compensate for the shorter growing season by producing shorter-lived leaves that have higher photosynthetic rates and low carbon cost [66].

In the present work, we report for the first time the nutrient fluxes via litterfall in Jeju Gotjawal, one of the important forest ecosystems and groundwater aquifers in Korea. In this study, the nutrient concentrations and contents differed significantly between CNU (deciduous) and Jeju Gotjawal (evergreen) and between evergreen forests in CS (lower precipitation) and SH (higher precipitation). This result is consistent with the pattern reported in [10]. Even though annual litterfall production did not significantly vary between Jeju Gotjawal and CNU stands, Jeju stands were shown to have higher total nutrient contents (N, P, Ca, Mg) compared to CNU, which can be due to its higher nutrient concentration. These high litterfall nutrient concentrations (except K) can be attributed to the unique properties of volcanic ash soil (i.e., allophanic and Al-humus Andisols) on the island [67]. Andisols possess many unique properties that are rarely found in other types of soil [68]. This soil is formed from basalt-based volcanic materials such as ash, resulting in minerals in the soil that have an unusually high nutrient-holding capacity [67,69], but may have limited K and some micronutrients. Other unique physicochemical properties of Andisol soils include a large amount of humus accumulation, high water retention, phosphate retention, friability, and affinity for multivalent cations such as Ca^{2+} and Mg^{2+}, making the soil productive and fertile [70]. The soil in Jeju Gotjawal is also rich in silicon (Si) [61], which affects the absorption, uptake, distribution, and functionality of several nutrients (e.g., N, P, Mg, and Ca) in plants [71,72]. Increased concentrations of some elements such as N, P, Ca, and Mg in soil and plant tissues after Si amendments were already recognized in some studies [73,74].

The variations can also be attributed to the difference in temperature and precipitation between CNU and Jeju Gotjawal stands. Jeju has a higher MAP and MAT than CNU, which makes it more favorable for plant growth. Warmer temperatures along with higher water availability could enhance nutrient uptake [63]. Similarly, stands at SH had lower nutrient concentrations and contents of leaf and total litterfall than CS, and this can be due to its higher MAP [75] and nutrient resorption efficiency [76].

The effect of the typhoon Chaba on the patterns of litterfall production in Jeju Gotjawal may further explain the observed pattern of nutrient inputs between Jeju Gotjawal and CNU. Catastrophic events, such as typhoons, influence the timing and amount of litterfall, therefore altering the cycling rate of certain nutrients, particularly N and P cycles [77]. In a study of the effect of typhoon disturbance on litterfall in subtropical forests in Okinawa Island, Japan, results revealed that the highest concentrations of N and P were recorded in typhoon season; in that, N and P concentrations were 34% and 106% greater, respectively, in the green leaves that fell during typhoon season than in senescent leaves [11]. Further, K is highly mobile and is easily leached from senescent and typhoon-caused leaf litter [78], and this phenomenon can partly explain the lower K concentration and input in Jeju Gotjawal stands than in those at CNU.

5. Conclusions

Litterfall production and nutrient fluxes differed by stand as influenced by forest type and climate in this study. Annual litterfall production was not different by forest types but the seasonal pattern was different between evergreen and deciduous oak-dominated forests, showing bimodal peaks (spring and fall) in evergreen forests and unimodal peaks (fall) in deciduous forests. However, bimodal peaks in evergreen forests were not observed in the second year, suggesting a more distinct seasonal pattern in cool-temperate deciduous forests. The amount of nutrient input by litterfall was higher in evergreen forests of Jeju than in deciduous forests of Daejeon except for K, and it was also higher in Cheognsu Gotjawal than in Seonheul Gotjawal with high precipitation. Moreover, the differences in carbon and nutrient input between stands were more remarkable than yearly changes. These variations may be attributed to species composition of each stand and abiotic factors induced by precipitation and temperature. The information provided in the present study will contribute to understanding carbon and nutrient dynamics in various forest ecosystems and further research on the litter decomposition process in a geologically unique ecosystem such as Jeju Gotjawal will benefit from the results in this study to broaden our knowledge.

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