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Comparisons of carbon and nitrogen dynamics of litterfall components in adjacent *Pinus densiflora* and *Quercus variabilis* stands

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Abstract: This study aimed to determine the effects of the stand and month on the carbon (C) and nitrogen (N) concentrations and the inputs of the litterfall components in adjacent *Pinus densiflora* and *Quercus variabilis* stands. The monthly C concentrations of the litterfall components were significantly higher in the *P. densiflora* stand than in the *Q. variabilis* stand, whereas the monthly N concentrations of the leaf and miscellaneous litter were higher in the *Q. variabilis* stand than in the *P. densiflora* stand. The coefficient variations of the N concentrations were higher than those of C concentrations of the litterfall components. The monthly C and N inputs of the leaf litter showed a unimodal pattern in the *Q. variabilis* stand, whereas multimodal patterns in the *P. densiflora* stand could be seen. The annual total C inputs were not significantly different between the *P. densiflora* [2 691 kg(C)·ha^{-1}·yr^{-1}] and *Q. variabilis* [2 439 kg(C)·ha^{-1}·yr^{-1}] stands. However, the annual total N inputs were significantly higher in the *Q. variabilis* [44.5 kg(N)·ha^{-1}·yr^{-1}] stand than in the *P. densiflora* [38.6 kg(N)·ha^{-1}·yr^{-1}] stand. These results indicate that the C and N dynamics in the litterfall components were affected by the species and sampling months in adjacent *P. densiflora* and *Q. variabilis* stands.

Keywords: carbon; Korean red pine; litterfall components; nitrogen; oriental cork oak

Carbon (C) and nitrogen (N) in forest ecosystems are returned to the forest floor through the decomposition process of litterfall (Bray, Gorham 1964). The chemical composition of litterfall is an important factor in determining the microbial activities, decomposition, and C and N release in forest ecosystems (García-Palacios et al. 2013; Erkan et al. 2020; Jasińska et al. 2020). Thereby, the importance of a quantitative evaluation of the C and N inputs by litterfall is increasing. However, the C and N concentrations and litterfall input are determined by environmental factors, ecological factors, and forest management activities (An et al. 2017; Kim et al. 2019; Erkan et al. 2020; Jasińska et al. 2020). In particular, differences in the litterfall inputs among stands may have crucial consequences for the C and N cycling of a stand due to the differences in the leaf or non-leaf litter inputs (Bray, Gorham 1964; Erkan et al. 2020). For example, Bray and Gorham (1964) reported that the leaf and to-

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tal litter inputs were higher in coniferous stands than in broad-leaved stands. A similar result was observed with values of 5 560 kg·ha^{-1}·yr^{-1} for coniferous stands and 4 360 kg·ha^{-1}·yr^{-1} for broad-leaved stands in South Korea (An et al. 2017). In contrast, Pérez-Suárez et al. (2009) reported that the annual total input of the litterfall was higher in a *Q. potosina* (4 869 kg·ha^{-1}·yr^{-1}) stand than in a *P. cembroides* (3 023 kg·ha^{-1}·yr^{-1}) stand.

The seasonal patterns of litterfall inputs are generally unimodal, bimodal, multimodal, and irregular with different C and N concentrations depending on the species and sampling month. In temperate forests, the seasonal dynamics of broad-leaved stands show a unimodal peak in autumn, whereas coniferous stands show multimodal peaks (Zhang et al. 2014). However, coniferous stands occasionally show different seasonal patterns, with a unimodal or bimodal pattern for spruce-fir in China (Fu et al. 2017). These inconsistent results could be due to various environmental factors and site conditions, which might lead to large uncertainties in the comparison or quantification of seasonal changes of the litterfall between stand types (Hansen et al. 2009; Fu et al. 2017).

P. densiflora occupies more than 23.5% (1.5 million ha) of South Korean forests. *Q. variabilis* is also one of the most naturally distributed broad-leaved species in South Korean forests (Korea Forest Service 2020). In general, studies on the litterfall, including leaf and non-leaf litter, in *P. densiflora* and *Q. variabilis* stands have been reported in different ecosystems. However, few studies have described the effects of the stand and month on the C and N concentrations, and the inputs of each litterfall component within adjacent *P. densiflora* and *Q. variabilis* stands (Baek et al. 2022).

The objective of this study was to determine the effects of the stand and month on the dynamics of the C and N concentrations and the inputs of the litterfall components in adjacent *P. densiflora* and *Q. variabilis* stands. We hypothesised that the C and N concentrations and the inputs of the litterfall components would differ by the stand and sampling month.

MATERIAL AND METHODS

Study site and experimental design. The study was conducted in approximately 40-year-old *P. densiflora* and *Q. variabilis* stands in the Wola National Experimental Forest, Jinju-si, and the national forest in Sancheong-gun, Gyeongsangnamdo, South Korea, respectively (Figure 1). Experimental plots were located in adjacent *P. densiflora* and *Q. variabilis* natural stands that enabled one to separate the stand effects and the site effects to compare the litterfall dynamics between both stands.

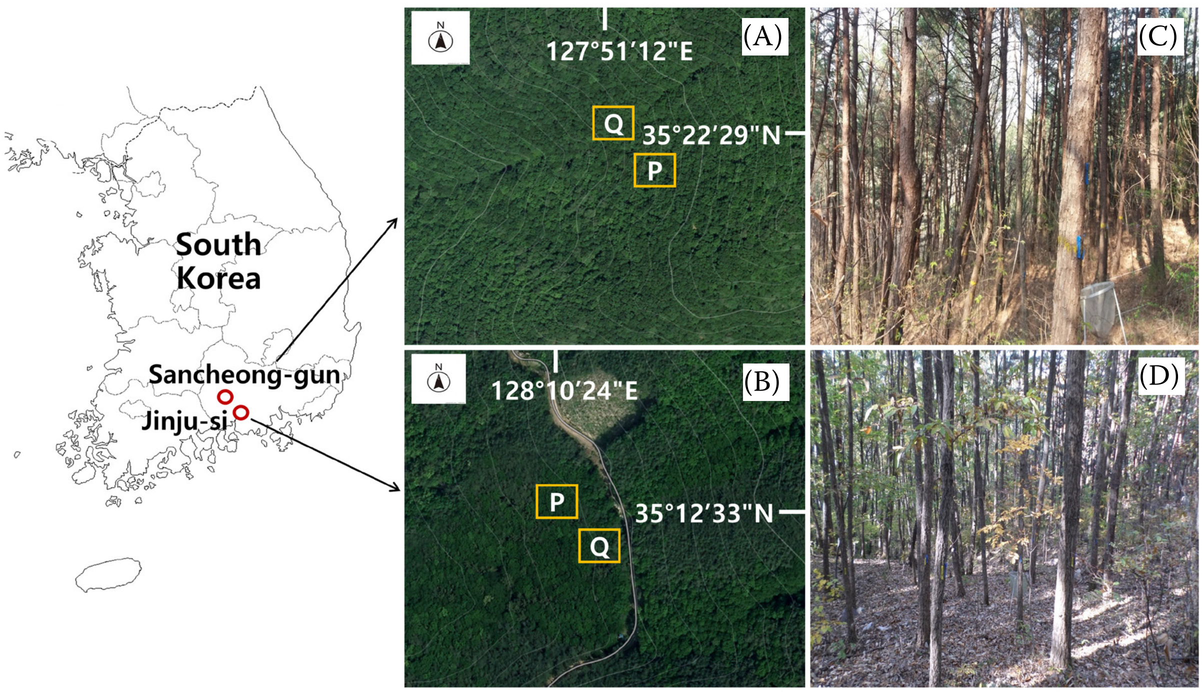

Figure 1. Location of adjacent stands in (A) Sancheong-gun and (B) Jinju-si; (C) *P. densiflora* and (D) *Q. variabilis*

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Table 1. General stand characteristics in adjacent *Pinus densiflora* and *Quercus variabilis* stands; values in parenthesis represent standard errors

Stand	Region	Location	Elevation (m a.s.l.)	Tree density (tree·ha^{-1})		DBH (cm)	Basal area (m^2·ha^{-1})
P. densiflora	Jinju	35°12'33''N 128°10'24''E	150	total	1 025	21.6 (5.8)	40.2
				P. densiflora	925	22.5	38.8
				deciduous species	100	13.0	1.4
	Sancheong	35°22'30''N 127°50'59''E	490	total	700	30.9 (7.8)	55.9
				P. densiflora	525	32.3	44.9
				deciduous species	175	26.9	11.0
	mean	–	320	–	863	26.3	48.1
Q. variabilis	Jinju	35°12'32''N 128°12'15'E	170	total	1 200	18.8 (5.8)	36.6
				Q. variabilis	1 075	19.1	33.5
				coniferous species	125	16.6	3.0
	Sancheong	35°22'29''N 127°51'12''E	470	total	950	20.7 (8.1)	37.0
				Q. variabilis	575	24.5	28.4
				coniferous species	375	15.0	7.5
	mean	–	320	–	1 075	19.8	36.8

The mean annual temperature and precipitation in the last 30 years (1991–2020) were 13.4 °C and 1 518 mm in Jinju-si, and 13.0 °C and 1 556 mm in Sancheong-gun (Korea Meteorological Administration 2021). The soil is of a slightly dry, brown forest soil type (mostly Cambisols, World Reference Base for Soil Resources) originating from sandstone or shale, with a clay loam in Jinju-si. The soil in Sancheong-gun is a moderately moist, brown forest soil originating from granite, and a sandy clay loam texture (mostly Cambisols, World Reference Base for Soil Resources). Information regarding the soils' physical and chemical properties has been presented previously in the same study sites (Choi et al. 2021).

The experimental design consisted of a split-plot with two replication regions (Jinju-si and Sancheong-gun). The replication regions were divided into two 20 m × 20 m plots under similar site conditions in adjacent *P. densiflora* and *Q. variabilis* stands (Figure 1). The general stand characteristics and climatic conditions of the study are given in Table 1 and Figure 2, respectively.

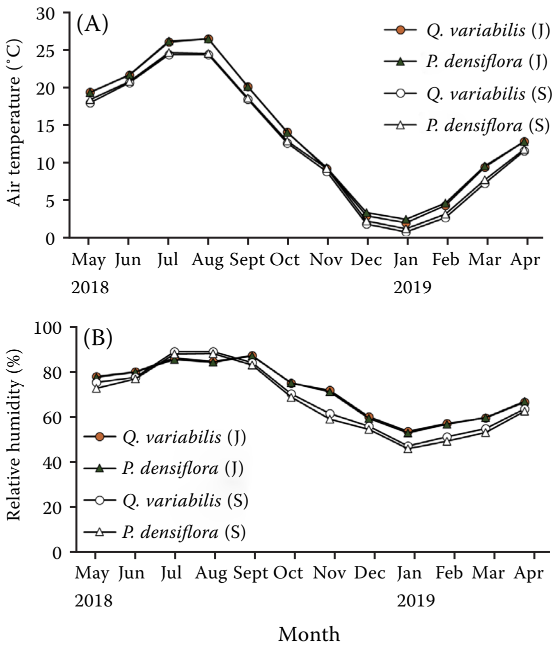

Figure 2. Monthly (A) air temperature and (B) relative humidity of study sites

J – Jinju-si; S – Sancheong-gun

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Litterfall collection. Five circular litter traps with a surface area of 0.25 m^2 were installed 60 cm above the forest floor in each plot (5 traps × 2 species × 2 regions = 20 litter traps in total) to collect litter from the *P. densiflora* and *Q. variabilis* stands at monthly intervals from May 2018 to April 2019. The litter from each trap was transported to the laboratory and oven-dried at 65 °C for 48 h. All the dried samples were separated into needle, broad-leaved, branch, reproductive organ (cones and flowers), and miscellaneous components (mainly bark and particles). We weighed all the dried litterfall components to calculate the litterfall inputs and ground some amounts of them to analyse the C and N concentrations. The C and N concentrations of the litterfall components were analysed using an elemental analyser (Vario MACRO cube, Elementar, Germany).

Statistical analyses. The data were analysed using a split-plot design based on the stands (*S*) and months (*M*). Two regions, Sancheong-gun and Jinju-si, were treated as the replication. The main (*S*, *M*) and interactive (*S* × *M*) effects on the concentration and input of the C and N in the litterfall components were tested at $P < 0.05$, using the general linear model procedure in SAS (Version 9.1, 2003). The coefficient of variation (*CV*, %) was calculated to determine the relative variability among the litterfall components.

RESULTS

Monthly C and N concentrations by litterfall components. The monthly C concentrations of all the litterfall components were significantly higher in the *P. densiflora* than in the *Q. variabilis* stand with the highest C concentrations in November, but the lowest C concentrations in March (or April) in both stands (Figure 3). For example, the C concentrations of the leaf litter were significantly higher in November (*P. densiflora*: 51.94%; *Q. variabilis*: 47.72%) and lower in March (*P. densiflora*: 47.72%; *Q. variabilis*: 44.24%) than the other months ($P < 0.05$).

The monthly N concentrations of leaf and miscellaneous litter were significantly higher, whereas the C/N ratios were lower in the *Q. variabilis* stand than in the *P. densiflora* stand. The N concentrations of the leaf and miscellaneous litter were significantly affected by the month with the lowest N concentrations seen in November, but highest N concentrations seen in March or April, whose leaf litter values were 0.46%, 1.64% in the *P. densiflora* stand, and 0.87%, 2.93% in *Q. variabilis* stand, respectively. In contrast, the N concentrations and C/N ratios of the branches and reproductive litter were not significantly different between the stands,

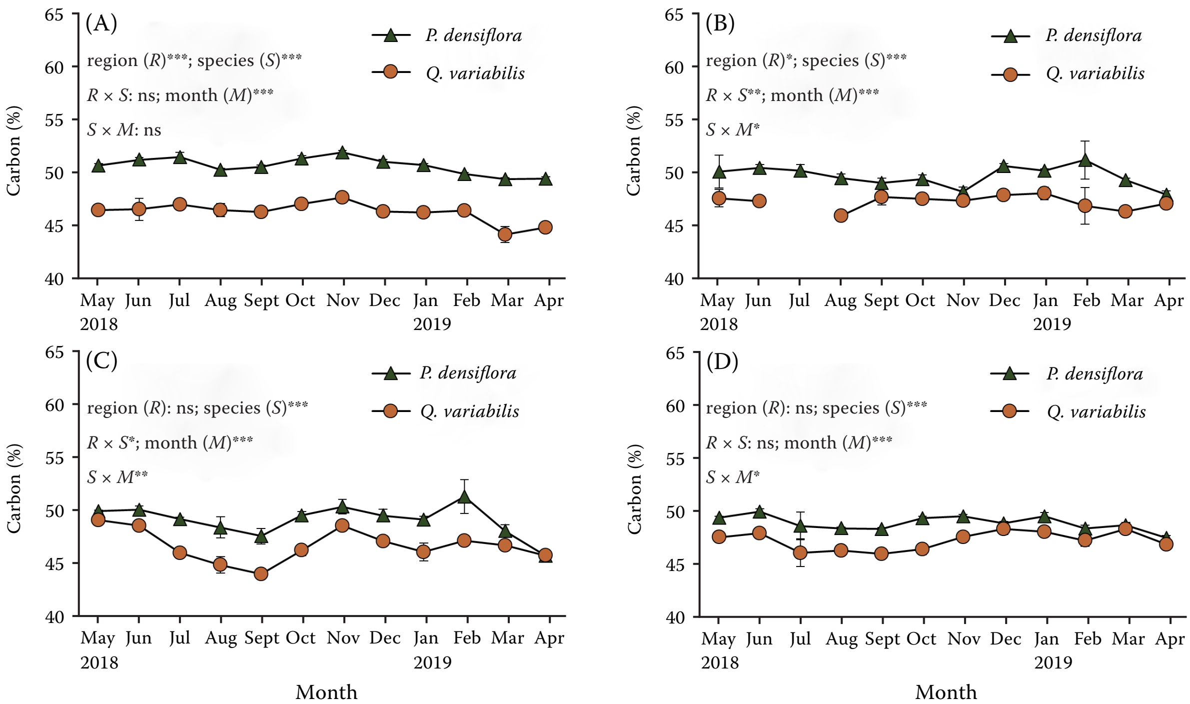

Figure 3. Monthly carbon concentration by litterfall components (A) foliage, (B) branches, (C) reproductive, (D) miscellaneous litters in adjacent *P. densiflora* and *Q. variabilis* stands

*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$; ns – non-significant; vertical bars – standard error

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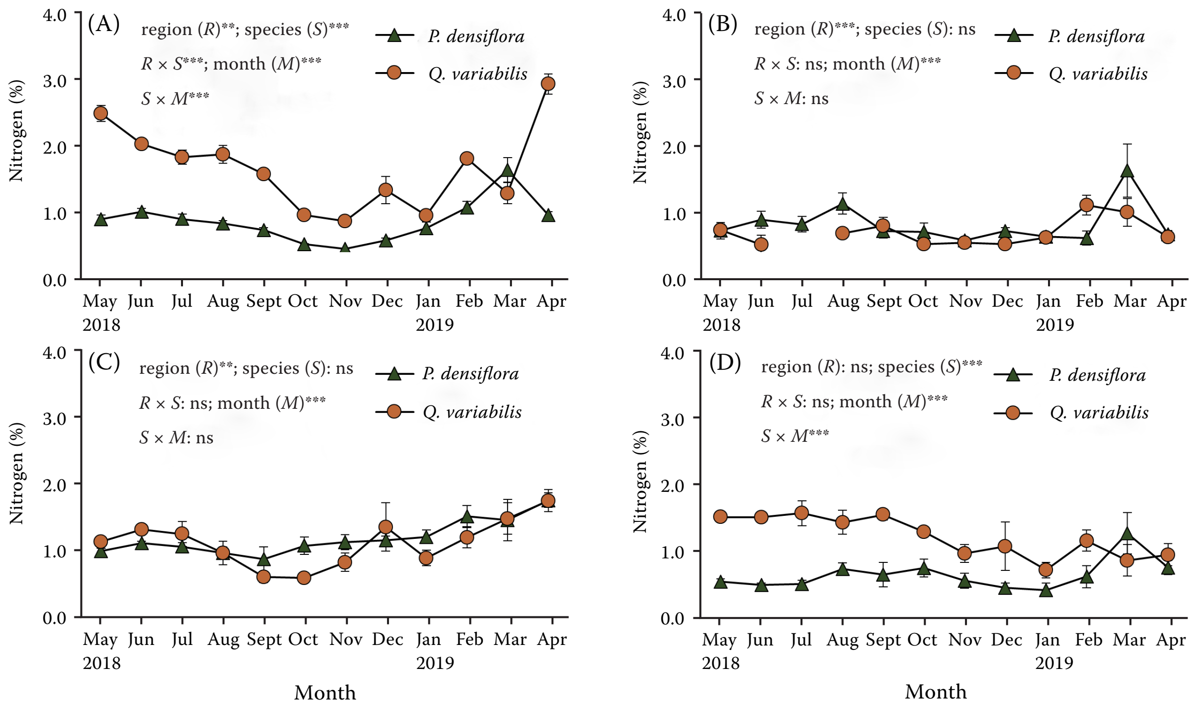

Figure 4. Monthly nitrogen concentration by litterfall components (A) foliage, (B) branches, (C) reproductive, (D) miscellaneous litters in adjacent *P. densiflora* and *Q. variabilis* stands

**P* < 0.05; ***P* < 0.01; ****P* < 0.001; ns – non-significant; vertical bars – standard error

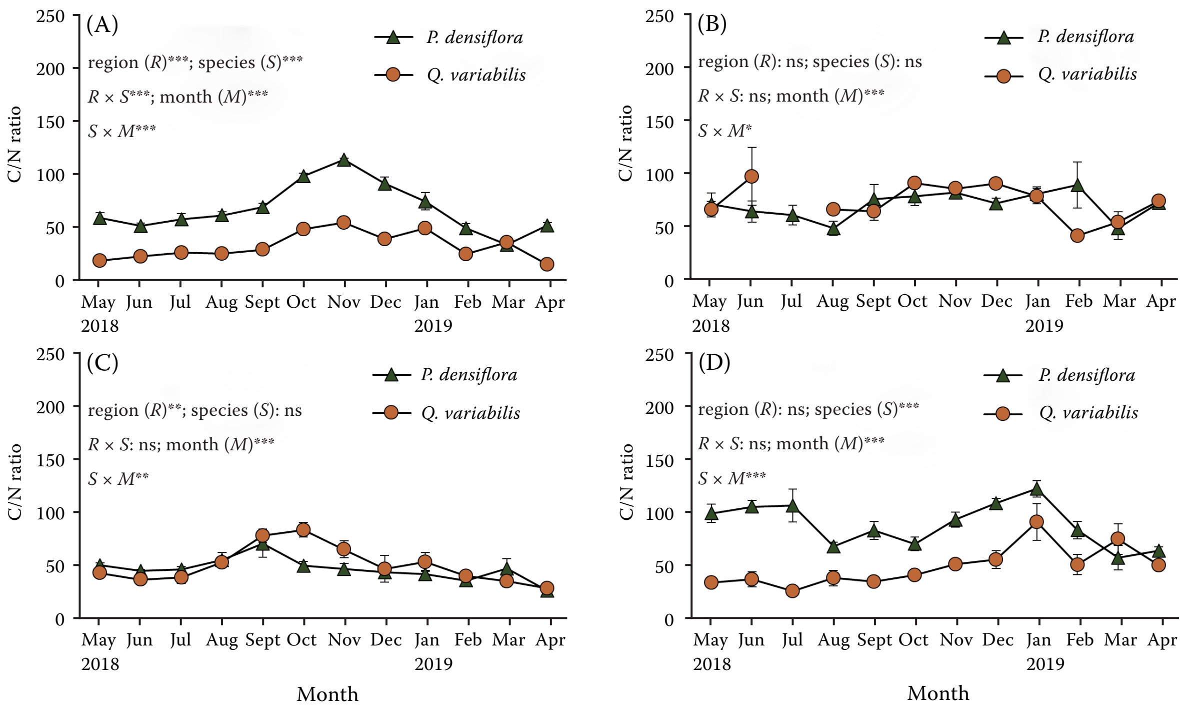

Figure 5. Monthly C/ N ratio by litterfall components (A) foliage, (B) branches, (C) reproductive, (D) miscellaneous litters in adjacent *P. densiflora* and *Q. variabilis* stands

**P* < 0.05; ***P* < 0.01; ****P* < 0.001; ns – non-significant; vertical bars – standard error

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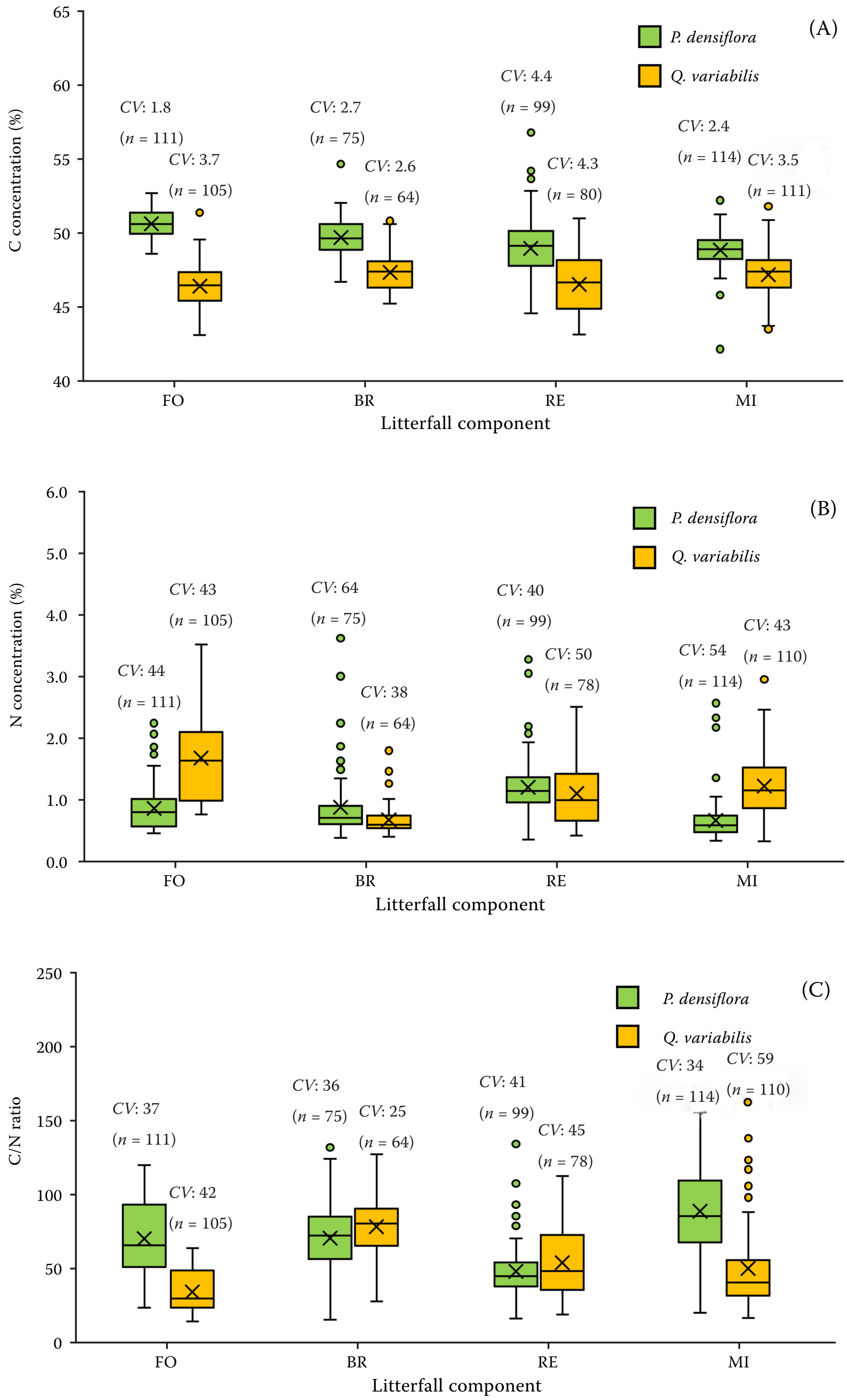

Figure 6. Box plots of (A) C and (B) N concentration and (C) C/N ratio in litterfall components in adjacent *P. densiflora* and *Q. variabilis* stands; the solid lines extend to 1.5 of the interquartile range and the values outside this range are indicated by a circle

FO – foliage; BR – branches; RE – reproductive; MI – miscellaneous litters; the box – median and the 25th and 75th percentiles; × – the arithmetic mean; *CV* – coefficient variation; *n* – number of observations

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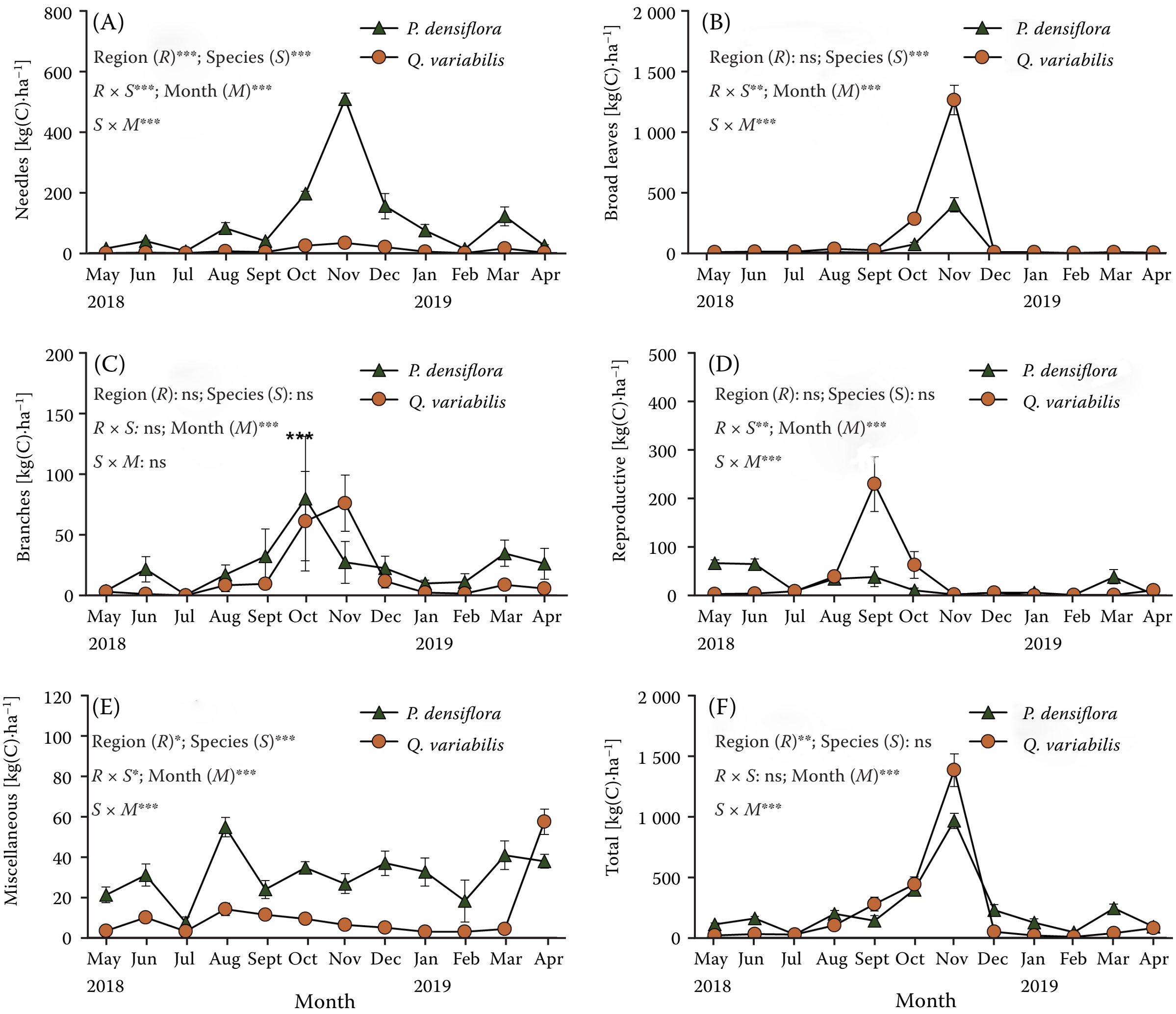

Figure 7. Monthly C inputs by litterfall components (A) needle, (B) broad leaves, (C) branches, (D) reproductive, (E) miscellaneous, (F) total litterfall in adjacent *P. densiflora* and *Q. variabilis* stands

*P < 0.05; **P < 0.01; ***P < 0.001; ns – non-significant; vertical bars – standard error

but were significantly affected by the months. Significant interactions ($S \times M$) were observed in the C, N, and C/N ratios of the litterfall components, with some exceptions (Figures 3–5). Meanwhile, the *CV* of the C concentrations was lower than that of the N concentrations and C/N ratios (Figure 6).

Monthly C and N inputs by litterfall components. The monthly patterns of the C and N inputs of the litterfall components differed between the two stands. The broad–leaved litter in the *Q. variabilis* stands exhibited a unimodal pattern, with the highest peak in November. In contrast, the needle litter in the *P. densiflora* stands showed multimodal patterns, including a high input in October, November, December, and March (with the input of some green-leaf litter). The branch litter showed irregular monthly C and N input patterns. The reproductive litter of *P. densiflora* fell in May, June, September, and March, whereas that of *Q. variabilis* was observed in September, in which acorns were the major components accounting for 83% and 64% of the total C and N inputs in September. The monthly patterns of the total C and N input were similar to the patterns of the leaf litter because the C and N inputs by the needle and broad-leaved litter were the major components (Figures 7 and 8).

Annual C and N inputs by litterfall components. The annual C input by the leaves (sum of the needle and broad-leaved litter) and total litter were not significantly different between the *P. densiflora* [foliage: 1 773 kg(C)·ha^{-1}·yr^{-1}; total: 2 691 kg(C)·ha^{-1}·yr^{-1}] and *Q. variabilis* [foliage: 1 763 kg(C)·ha^{-1}·yr^{-1};

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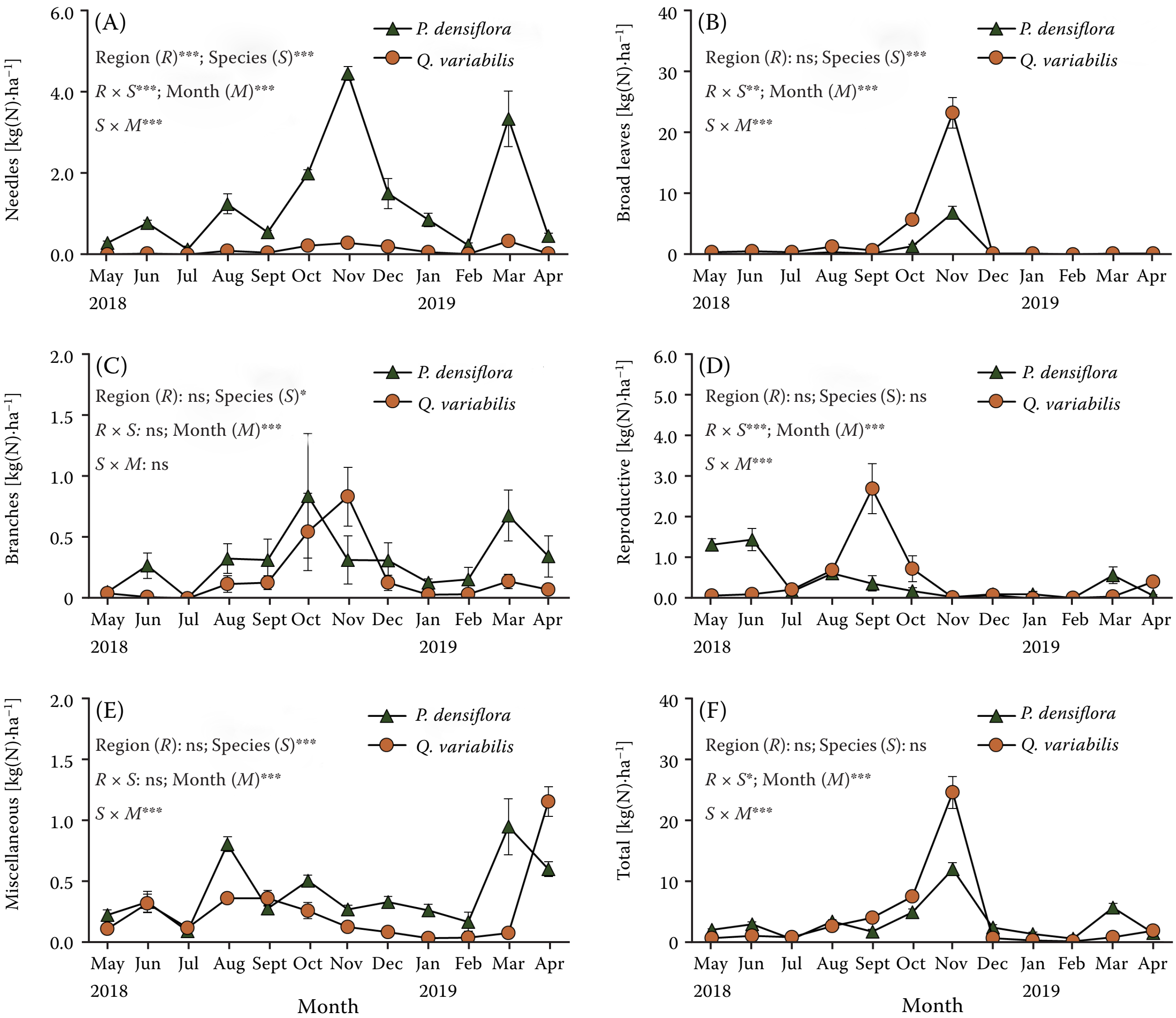

Figure 8. Monthly N inputs by litterfall components (A) needle, (B) broad leaves, (C) branches, (D) reproductive, (E) miscellaneous, (F) total litterfall in adjacent *P. densiflora* and *Q. variabilis* stands

*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$; ns – non-significant; vertical bars – standard error

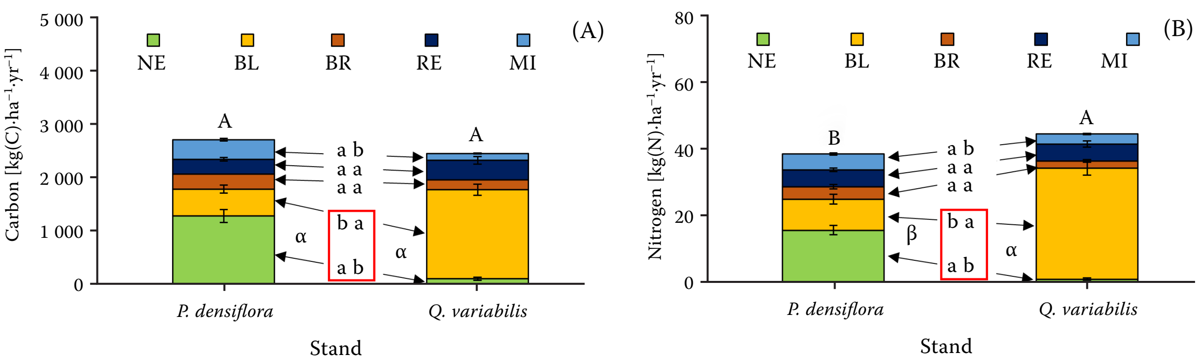

Figure 9. Total carbon (A) and nitrogen (B) inputs of litterfall components in adjacent *P. densiflora* and *Q. variabilis* stands

NE – needle; BL – broad leaves; BR – branches; RE – reproductive; MI – miscellaneous; vertical bars – standard error; different letters – significant difference at $P < 0.05$

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total: 2 439 kg(C)·ha^{-1}·yr^{-1}] stands ($P > 0.05$). However, the N input by the leaf and total litter was significantly higher in the *Q. variabilis* [foliage: 34.4 kg(N)·ha^{-1}·yr^{-1}; total: 44.5 kg(N)·ha^{-1}·yr^{-1})] than in *P. densiflora* [foliage: 25.1 kg(N)·ha^{-1}·yr^{-1}; total: 38.6 kg(N)·ha^{-1}·yr^{-1}] stands ($P < 0.05$). The annual C and N inputs of the non–leaf litter were not significantly different between the two stands ($P > 0.05$), except for that of the miscellaneous litter (Figure 9).

DISCUSSION

C and N concentrations of litterfall components. The variations in the C and N concentrations of the litterfall components are mainly determined by the species and sampling months (Thomas, Martin 2012; Kim et al. 2019; See et al. 2019; Erkan et al. 2020). Many studies have reported that the C concentration of the litterfall is negatively correlated with the N and positively correlated with the lignin concentration (Macinnis–Ng, Schwendenmann 2015; Kim et al. 2017; See et al. 2019). In this study, the higher C concentration of the leaf litter in the *P. densiflora* than in the *Q. variabilis* stands could be due to the difference in the lignin and N concentrations determined by the genetic factors between the tree species (Thomas, Martin, 2012; See et al. 2019). For example, Park et al. (2018) reported that the leaf litter of *P. densiflora* showed a higher lignin concentration (40.7%) than *Q. variabilis* (32.6%). In addition, a significantly higher N concentration in this study was observed in the leaf litter of the *Q. variabilis* compared to *the P. densiflora* stands (Figure 4).

In this study, the peak C concentration of the litterfall components in November (autumn) could be attributed to the N resorption before the litter abscission (Macinnis–Ng, Schwendenmann 2015; See et al. 2019). Baek et al. (2018) reported that the C concentration of needle litter relatively increased from July to November because of the N resorption in *P. densiflora* stands. The decrease in the C concentration from November until March can be explained by the C re-translocation to produce new organs in the spring season (Macinnis–Ng, Schwendenmann 2015; Baek et al. 2018; See et al. 2019).

The significant interactions ($S \times M$) in the C, N, and C/N ratios of the litterfall components were due to the different C and N concentrations of the litterfall components between the stands during the sampling months. This result was explained by the differences in the green litter inputs and the resorption rate between the stands. In addition, a relatively higher *CV* was observed in the N concentrations and C/N ratios of the litterfall components than in the C concentrations of the litterfall components, indicating large monthly fluctuations. The C and N concentrations of the litterfall components collected in the heavy litterfall season (November), or in 3–4 month intervals might result in a considerable bias, especially for the N inputs of the litterfall components.

The C concentrations of the litterfall components were similar to other study results, in which the leaf litter was approximately 50% in *P. densiflora* stands in South Korea (Kim et al. 2019) and 47.5% in *Q. variabilis* stands in China (Du et al. 2017), but lower than those of *P. brutia* stands (51.24 %) in Turkey (Erkan et al. 2020). The mean N concentrations of the leaf, branch, reproductive, and miscellaneous litter in this study are comparable to other studies in *Q. variabilis* in China (Du et al. 2017) and in *P. brutia* stands in Turkey (Erkan et al. 2020).

C and N inputs by litterfall components. The annual total C input in this study falls within the global mean value of coniferous and broad–leaved forests [approximately 2 500 kg(C)·ha^{-1}·yr^{-1}] in a warm–temperate climate (Bray, Gorham, 1964) and unthinned *P. densiflora* [2 569 kg(C)·ha^{-1}·yr^{-1}] and *Q. variabilis* [2 998 kg(C)·ha^{-1}·yr^{-1}] stands in South Korea (Baek et al. 2022).

The similarity in the C inputs of the leaf and total litter between adjacent stands could be attributed to the similar litterfall inputs by the canopy closure in our mature forests (Bray, Gorham 1964), as the C concentration of the leaf litter differed only 2%. Other results have reported similar litterfall inputs in adjacent stands, including coniferous and broadleaf species in South Korea (Kim et al. 2010), Japan (Kato et al. 2021), Greece (Michopoulos et al. 2020), and Denmark (Hansen et al. 2009). However, a higher N input by the leaf and total litter in the *Q. variabilis* than in the *P. densiflora* stands could be due to the two-fold higher N concentration in the *Q. variabilis* than in the *P. densiflora* stands.

The highest C and N inputs of the litterfall in November (autumn; heavy litterfall season) in both stands were expected because of the natural senescence in temperate forests (Zhang et al. 2014). The seasonal patterns of the litterfall inputs were similar to the global results with a unimodal peak

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in autumn in broad-leaved stands, and multimodal patterns in coniferous stands (Zhang et al. 2014). Meanwhile, our results proved that the reproductive organs in *Q. variabilis* stands were the major component of the total C and N inputs in September, in which acorns could be an important source of C and N inputs in the months before the heavy litterfall season. The patterns of the branch litter input were irregular in both stands because the inputs of the branch litter are mainly determined by abiotic conditions such as rainfall and wind (Cheng et al. 2020). The higher C and N inputs by miscellaneous litter in the *P. densiflora* than in the *Q. variabilis* stands could be due to the input from the bark, which was classified as miscellaneous litter in this study.

Many litterfall studies are limited to the leaf or total litterfall because of the small contributions to the C and N inputs of the non-leaf litter into the forest soil (Erkan et al. 2020; Jasińska et al. 2020). Although the C and N inputs of each non-leaf litter in this study accounted for approximately 10% of the total C and N inputs, the sum of the non-leaf litters accounted for more than 30% of the total C and N inputs (Figure 9). The ranges of the C and N inputs by the non-leaf litter are 271–363 $kg(C)\cdot ha^{-1}\cdot yr^{-1}$ and 3.7–5.0 $kg(N)\cdot ha^{-1}\cdot yr^{-1}$ in the *P. densiflora* stands and 128–360 $kg(C)\cdot ha^{-1}\cdot yr^{-1}$ and 2.1–5.0 $kg(N)\cdot ha^{-1}\cdot yr^{-1}$ in the *Q. variabilis* stands, respectively. The values of the non-leaf litter at our study sites fall within the range established for other pine and oak stands in Japan (Kato et al. 2021).

Previous studies on the estimation of the C and N inputs of the litterfall have used a general approach of using composite concentrations, annual mean concentrations, or those collected in the heavy litterfall season, and then multiplying by the mass rather than using monthly concentrations (Hansen et al. 2009; Erkan et al. 2020). However, an annual interval estimation should be cautiously used for N inputs, unlike just the estimation of the litter inputs. It is because the N concentration of the litterfall components might be increased unless the litterfall components are collected immediately after the heavy litterfall season. This result could be due to the input of rainfall, dust, and immobilisation by microorganisms, and fungi adhering to the litterfall components (Berg, Laskowski 2006; Kim et al. 2019). Although most of the leaf inputs in the *Q. variabilis* stands were observed in November, information on the monthly C and N inputs by the litterfall components might be needed because of the variable input patterns of the other components. In addition, the monthly estimation of the N inputs in *P. densiflora* stands might be needed considering that the input patterns and N concentrations of the leaf litter were highly variable with the month. For example, the needle litter in March, as well as in November, was also an important source of N because of the multimodal patterns and the higher N concentration in March compared to the other months (Figure 4).

CONCLUSION

Our findings suggested that the C and N concentrations and the inputs of the litterfall components were affected by the stands and months in adjacent *P. densiflora* and *Q. variabilis* stands under similar site conditions. In addition, the leaf litter showed the highest C and N inputs in November in both stands with different input patterns. These results indicate that information on the monthly C and N inputs by the litterfall components is needed to evaluate the C and N cycles in forest ecosystems. Although the annual total C input was not significantly different between the adjacent stands, the annual total N inputs were significantly higher in the *Q. variabilis* stand than in the *P. densiflora* stand due to the differences in the N concentrations. Our results contribute to the advanced understanding of C and N dynamics of litterfall components in adjacent *P. densiflora* and *Q. variabilis* stands.

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