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Litterfall, litter decomposition, and carbon storage of *Pinus densiflora* and *Quercus variabilis* stands in South Korea

Gyeongwon Baek, Choonsig Kim*

Division of Environmental and Forest Science, Gyeongsang National University, Jinju, 52725, South Korea

Abstract

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The quantification of carbon (C) storage of different stand types is a key component for understanding forest C cycles and potential climate change. This study evaluated the effects of stand types on litterfall, litter decomposition, and forest C storage in *Pinus densiflora* S. et Z. and *Quercus variabilis* Blume stands in southern Korea. The aboveground C storage by tree biomass was not affected ($P > 0.05$) by stand types (*P. densiflora*: 79.49 Mg C ha^{-1}; *Q. variabilis*: 96.37 Mg C ha^{-1}). However, total C inputs by litterfall were significantly higher for the *P. densiflora* (4,473 kg C ha^{-1} year^{-1}) than for the *Q. variabilis* (2,633 kg C ha^{-1} year^{-1}) stands. Organic C over litter decomposition processes was more rapidly mineralized in the leaf litter of *Q. variabilis* than in needle litter of *P. densiflora*, but C storage on the forest floor was not affected by different stand types. Total soil C storage was not significantly different between the *Q. variabilis* (55.71 Mg C ha^{-1}) and *P. densiflora* (80.49 Mg C ha^{-1}), whereas the C concentrations at each soil depth were significantly higher in the *P. densiflora* than in the *Q. variabilis* stands, except for the subsurface depth (30–50 cm). These results indicate that the distribution of C storage in *P. densiflora* and *Q. variabilis* stands is less susceptible to interspecific differences, such as litterfall inputs and decomposition rates.

Keywords

carbon cycle, litter decomposition, litterfall, oak, pine, soil carbon

Introduction

Quantitative evaluation of carbon (C) storage in forests is important because of the role of global warming and sustainable forest C sink (Pugh et al., 2019). Thus, estimates of C storage in forests have been made at global (Pugh et al., 2019), national (Egusa et al., 2020; Lee et al., 2020), regional (Gao et al., 2014; Wang et al., 2019), and stand scales (Noh et al., 2013; Gao et al., 2014; Badalamenti et al., 2019). The C storage in forests is likely to be variable because variations in forest C storage are attributed to biotic and abiotic factors and forest management practices (Jandl et al., 2007; Pragasan, 2022). Thus, accurately estimating the forest C storage is difficult since multiple temporal and spatial scales due to the complexity of physical, chemical, and biological processes influence C cycling in the forests (Jandl et al., 2007; Wei et al., 2013; Lee et al., 2020).

Forest C storage varies significantly in different stand types due to changes in above- and belowground C allocation through tree growth and interspecific differences in litter production and decomposition rates (Gao et al., 2014; An et al., 2017). For example, litter from different stands decomposes at different rates because the decomposition rates of organic matter are influenced by many interacting biotic and abiotic factors, such as litter

*Corresponding author:
e-mail: ckim@gnu.ac.kr

quality, the composition of the decomposer community, and microclimate (Liu et al., 2001; Jandl et al., 2007).

Korean red pine (*Pinus densiflora* S. et Z.) and oriental cork oak (*Quercus valabili*s Blume) are the most important coniferous species and dominant oak trees in South Korea (Park et al., 2019; Baek and Kim, 2020). Although there have been many studies to evaluate C storage in forests (Noh et al., 2013; Kim et al., 2017) or national scales (Lee et al., 2018; Kim et al., 2019; Lee et al., 2020), major uncertainties remain concerning the effect of stand types on the behavior of C stocks in South Korea. This study aimed to understand how stand types such as coniferous and broadleaved forests affect the biomass, forest floor, and soil C distribution. The objectives of this study were to determine 1) the change in organic C storage (aboveground biomass, forest floor, and 50 cm of soil depth); 2) the dynamics in organic C inputs (litterfall) and losses (litter decomposition rates) in *P. densiflora* and *Q. variabilis* stands.

Table 1. General description of the study site in *Pinus densiflora* and *Quercus variabilis* stands

Stand	Region	Location	Altitude (m asl)	Slope (°)	Aspect (°)	Stand age (years)	Stand density (tree ha^{-1})	Mean DBH (cm)	Basal area (m^2 ha^{-1})
Pinus densiflora	Sancheong-gun	35°22’26”N 127°51’13”E	484	20	240	57	625	34.9	59.7
	Sancheong-gun	35°24’10”N 127°48’46”E	350	22	80	30	600	30.0	42.2
	Jinju-si	35°12’45”N 28°10’06”E	190	10	240	52	1,075	25.9	55.0
	Jinju-si	35°12’30”N 128°10’27”E	196	28	270	35	400	31.6	31.4
	Goseong-gun	35°04’43”N 128°15’47”E	246	8	330	60	575	37.1	24.9
	Hadong-gun	35°12’26”N 127°43’12”E	524	20	280	60	675	28.3	22.4
	Hadong-gun	35°12’256’N 127°43’11”E	519	25	180	45	2,225	27.5	29.9
	Uiryeong-gun	35°22’14’N 128°10’37”E	401	28	90	30	550	24.9	30.6
	Uiryeong-gun	35°12’32’N 127°42’52”E	497	23	180	35	1,775	20.6	29.6
	Mean	–	378 (46)	20 (2)	210 (28)	41 (4)	1,125 (248)	27.3 (2.3)	39.2 (5.4)
Quercus variabilis	Sancheong-gun	35°21’23”N 127°48’49”E	317	30	270	70	875	41.4	41.0
	Sancheong-gun	35°22’26”N 127°51’10”E	450	31	270	45	275	21.7	10.8
	Sancheong-gun	35°22’27”N 127°51’15”E	497	35	160	35	900	18.5	25.7
	Sacheon-si	35°04’07”N 127°57’07”E	31	5	270	60	500	26.4	32.1
	Jinju-si	35°12’29”N 128°10’27”E	177	15	260	40	825	17.9	23.0
	Jinju-si	35°12’32”N 128°10’26”E	179	10	240	50	1,625	14.3	28.5
	Uiryeong-gu	35°22’45”N 128°06’21”E	116	30	270	45	1,000	11.8	20.8
	Uiryeong-gu	35°22’46”N 128°06’21”E	120	30	270	45	425	24.1	24.4
	Goseong-gun	35°04’56”N 128°15’46”E	170	20	260	60	475	27.6	44.8
	Mean	–	228 (52)	23 (4)	252 (12.0)	50 (4)	767 (136)	21.1 (3.3)	27.9 (3.4)

The values in parenthesis represent standard error.

Materials and methods

Study site

The study was conducted in six regions (Goseong-gun, Hadong-gun, Jinju-si, Sacheon-si, Sancheong-gun, and Uiryeong-gun) in Gyeongsangnam-do, southern Korea (Table 1). Annual mean precipitation and temperature for 30 years in the study area are 1,556 mm yr^{-1}, 12.8°C for Sancheong-gun, 1,493 mm yr^{-1} and 13.5°C for Jinju-si, 1,436 mm yr^{-1} and 13.6°C for Uiryeong-gun, respectively (Korea Meterological Administration, 2019). The soils are a well-drained, slightly wet or dry, brown forest soil (mostly Cambisols) originating from granite for Hadong, Sacheon-si, Sancheong-gun, and Uiryeong-gun, with a loamy texture and a slightly dry dark reddish-brown forest soil (mostly Cambisols) originating from sandstone or shale in Jinju-si. The experimental design consisted of eighteen 20 m × 20 m plots (nine plots of *P. densiflora* and nine plots of *Q. variabilis* stands), respectively. The tree density in *P. densiflora* stands ranged from 400 trees ha^{-1} to 2,225 trees ha^{-1}, whereas tree density in *Q. variabilis* stands ranged from 275 trees ha^{-1} to 1,625 trees ha^{-1}. The mean basal area was higher in the *P. densiflora* than in *Q. variabilis* stands (Table 1). All plots measured the diameter at breast height (DBH) over three years from 2010 to 2012.

Aboveground biomass carbon

The C contents of tree components of all plots were calculated by the allometric equations developed for each of the tree components (stem, branches, leaf) in *P. densiflora* (Kim et al., 2017) and *Q. variabilis* (Kim, 2019) in these regions in South Korea.

Litterfall and litter decomposition

Three circular litter traps with a surface area of 0.25 m^2 were installed 60 cm above the forest floor at each plot on 30 November 2010 to measure litterfall inputs. Litter was collected at three-month intervals between March 2011 and December 2012 (17 March, 21 June, 26 October, 15 December 2011, 27 March, 18 June, 18 October, 11 December 2012). The litter from each trap transported to a laboratory was oven-dried at 65 °C for 48 h. All dried litter samples were separated into needles, broadleaved leaves, branches, and miscellaneous litter, and each portion was weighed.

The needle or leaf litter decomposition rates were measured using the litterbag technique (Krishna and Mohan, 2017). Fresh needle or leaf litter from each plot was collected from the forest floor in late November 2010. After collection, the litter was air-dried at room temperature for 14 days, and a sample of approximately 10 g was placed in a 30 cm × 30 cm nylon net bag (mesh size of 0.1 mm). Subsample from the air-dried litter was oven-dried at 65 °C for 48 h to get moisture factors. Litterbags were randomly placed on the forest floor of each plot on 15 December 2010 and collected eight times (17 March, 21 June, 26 October, 15 December 2011, 27 March, 18 June, 18 October, and 11 December 2012). Each litterbag sample after the collection was oven-dried at 65 °C for 48 h to determine the mass loss rates. The decay coefficient of needle and leaf decomposition (2 years after incubation) was calculated using a single exponential decay model (Olson, 1963):

$$W_t / W_0 = e^{-k \cdot t},$$

where W_0 is the original mass (g) of needle or leaf litter, W_t is the remaining mass (g) after incubation time t, and k is the decay coefficient ($year^{-1}$), e is the base of the natural logarithm.

Litter samples collected from the litter trap and bags were ground in a mill. The organic C concentration from the subsample for ground litter was determined using an elemental analyzer (Vario Macro cube, Langenselbold, Germany).

Carbon storage of forest floor and mineral soils

Forest floor samples were collected from three random points of each plot using a 900 cm^2 template in August 2010. The forest floor samples were oven-dried at 65 °C, ground with a mill, and passed through a 40-mesh (0.425 mm) stainless sieve. The C concentration of the forest floor was determined using an elemental analyzer (Vario Macro cube, Langenselbold, Germany).

Three soil pits of 80 cm × 80 cm from three randomly selected points in each plot were established to collect soil samples at three surface depths (0–10 cm, 10–20 cm, 20–30 cm) and a subsurface depth (30–50 cm) in June 2011. Soil samples were collected at each soil depth using 400 cm^3 steel core cans (7.2 cm in diameter, 10 cm in length) to determine bulk density and coarse fragments of > 2 mm. The collected soil samples were passed through a 40-mesh sieve and measured C concentration using an elemental analyzer (Vario Macro cube, Langenselbold, Germany). Soil C storages at each soil depth were calculated using the following formula (Eq. 1).

$$CS = \sum CDi \times BDi \times Di \times (1 - Fi/100), \quad \text{(Eq. 1)}$$

where CS is C storage of each soil depth (Di), CDi is the C concentration in each soil depth, BDi is bulk density (Mg m^{-3}) of each soil depth, Di is each soil depth (cm), and Fi is volumetric coarse fragments (%) of each soil depth.

Data analysis

All data distributions were tested for normality with the Shapiro–Wilk test. A Student's t-test was performed to compare both stand types using the Proc t-test procedure of SAS (SAS Institute Inc., 2003) for significant differences at $P < 0.05$.

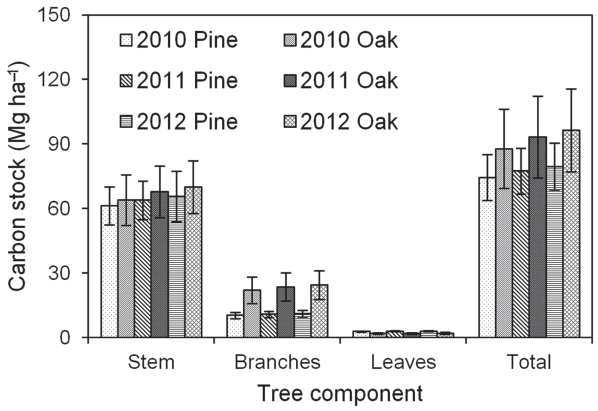

Fig. 1. Carbon stocks of aboveground tree components in *Pinus densiflora* (Pine) and *Quercus variabilis* (Oak) stands. Vertical bars represent standard errors.

Results

Carbon storage of aboveground biomass

The estimated C storage of aboveground biomass was not significantly different ($P > 0.05$) between *P. densiflora* (79.49 Mg C ha^{-1}) and *Q. variabilis* (96.37 Mg C ha^{-1}) stands (Fig. 1). There was a common tendency for both stand types that C storage of stem biomass is a large proportion of C storage of total biomass. The C storage of stem biomass represents 82.4% in *P. densiflora* and 72.5% in *Q. variabilis* of the C storage of total biomass. In contrast, C storage of branch biomass was lower in *P. densiflora* (13.5%) than in *Q. variabilis* (25.3%) stands. The C storage of leaf biomass was 3.6% for *P. densiflora*, and 2.0% for *Q. variabilis* stands, respectively.

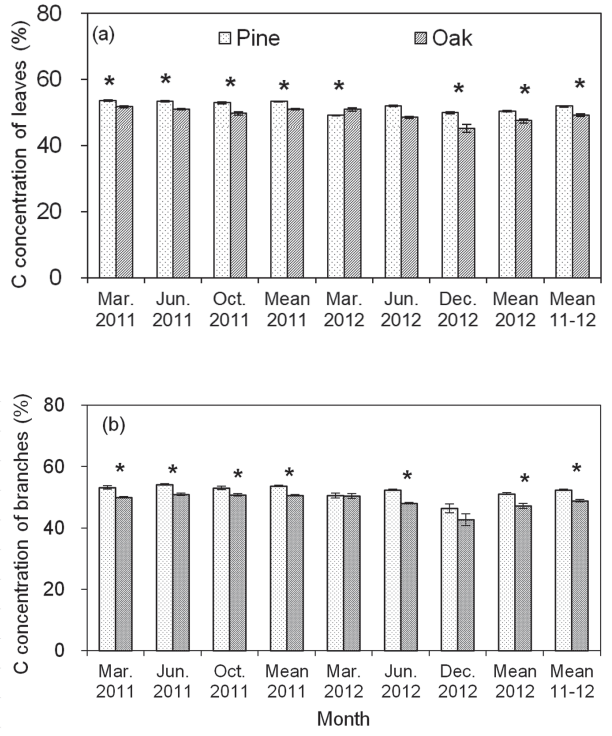

Fig. 2. Carbon concentration of litterfall components (a: leaf; b: branches) in *Pinus densiflora* (Pine) and *Quercus variabilis* (Oak). Vertical bars represent standard errors. Asterisks indicate a significant difference between *Pinus densiflora* and *Quercus variabilis* stands at $P < 0.05$.

Litterfall and decomposition rates

The C concentration of leaves or branches litter was consistently higher in *P. densiflora* than in *Q. variabilis* during the study period (Fig. 2). Thus, mean C concentration was significantly higher in the needle (51.9%) or branch (52.4%) litter of *P. densiflora* than in those (leaf: 49.19%; branches: 48.91%) of *Q. variabilis*. Organic C inputs by litterfall components over two years were significantly higher in *P. densiflora* than in *Q. variabilis* stands ($P < 0.05$). Mean total C inputs by litterfall were 4,473 kg C ha^{-1} yr^{-1} for *P. densiflora* and 2,633 kg C ha^{-1} yr^{-1} for *Q. variabilis* stands (Fig. 3).

Carbon concentration over litter decomposition processes was significantly higher in needle litter of the *P. densiflora* than in leaf litter of the *Q. variabilis.* Carbon concentration in the leaf litter of *Q. variabilis* was decreased with increased decomposition period, whereas C concentration in needle litter in *P. densiflora* was not changed during decomposition processes (Fig. 4). Needle litter decomposition rates in *P. densiflora* stands were significantly lower than leaf litter in the *Q. variabilis* stands during the study period (Fig. 4). Thus, the decay coefficient of leaf litter was higher in the leaf litter of the *Q. variabilis* (k = 0.56) than in needle litter of *P. densiflora* (k = 0.53) stands.

Forest floor and mineral soils

Carbon concentration of forest floor was significantly higher in the *P. densiflora* (48.04%) than in the *Q. variabilis* (44.75%) stands (Fig. 5). In contrast, C storage on the forest floor was not significantly different between the *P. densiflora* (6.37 Mg C ha^{-1}) and the *Q. variabilis* (5.49 Mg C ha^{-1}) stands. Bulk densities at all soil depths and the coarse fragment content of 0–20 cm depth were significantly lower in the *P. densiflora* than in the *Q. variabilis* stands, wheseas the mean C concentrations at each soil depth were significantly higher in the *P. densiflora* than in the *Q. variabilis* stands (Fig. 5), except for the subsurface depth (30–50 cm). Total soil C storage was not significantly different between the *Q. variabilis* (55.71 Mg C ha^{-1}) and in the *P. densiflora* (80.49 Mg C ha^{-1}), except for 0–10 cm depth.

Discussion

Aboveground biomass carbon storage

The C accumulation of live tree biomass in this study was

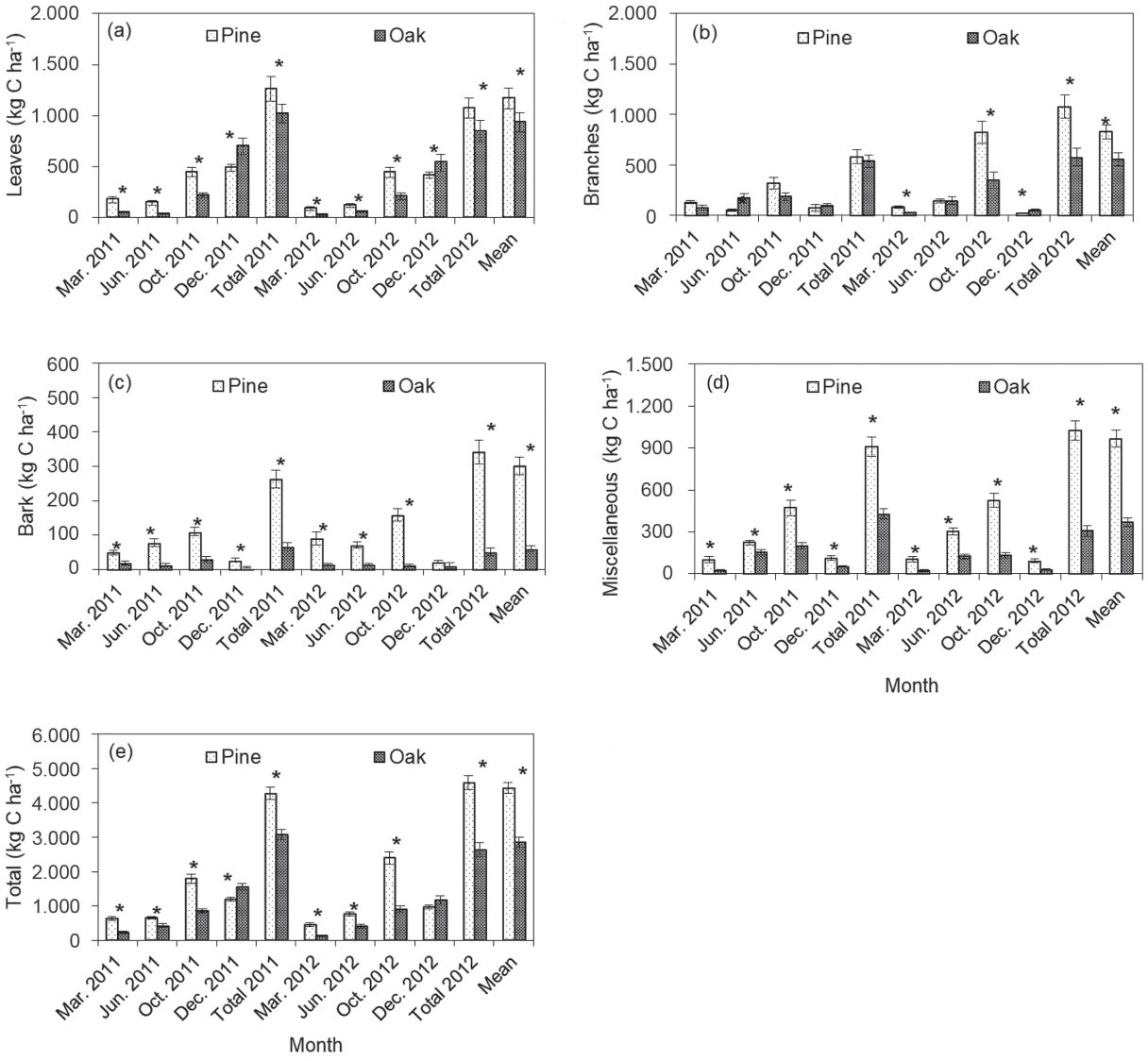

Fig. 3. Carbon inputs of litterfall components (a: leaf litter; b: branches; c: bark; d: miscellaneous; e: total) in *Pinus densiflora* (Pine) and *Quercus variabilis* (Oak) stands. Vertical bars represent standard errors. Asterisks indicate a significant difference between *Pinus densiflora* and *Quercus variabilis* stands at $P < 0.05$.

less affected by stand types. Other studies reported that inherent variations in growth rates mainly caused the interspecific differences in tree biomass C under a similar site condition, stand density, altitude, basal area, wood density, genetic differences, and biomass allocation among tree species (Egusa et al., 2020; Lukina et al., 2020; Yang et al., 2019). In this study, no significant difference in C storage of aboveground biomass in both stand types despite the difference in stand characteristic (stand density; basal area) could be attributed to wood density. For example, the basic wood density reported in this region was 0.34 Mg m^{-3} in *P. densiflora* (Kim et al., 2011) and 0.63 Mg m^{-3} in *Q. variabilis* (Kim et al., 2019). Previous studies reported that biomass C storage was affected by wood density at similar wood volume (Jandl et al., 2007; Kim et al., 2020). The C storage of tree biomass in *P. densiflora* and *Q. variabilis* stands was higher than the mean C storage of both tree biomass (*P. densiflora*: 60 Mg C ha^{-1}; *Q. variabilis*: 83 Mg C ha^{-1}) observed in a national scale in South Korea (Lee et al., 2018).

Carbon inputs from litterfall and decomposing needle and leaf litter

The variation of C concentration in litterfall components is mainly determined by factors such as tree species, site condition, stand characteristics, and forest management practices (Lavadinović et al., 2015; Park et al., 2020). High C concentration in litterfall components of coniferous forests compared with the deciduous hardwood tree species was observed in other studies (Park et al., 2019), which was negatively correlated with the nitrogen (N) concentration of litter components. The values in this study are comparable to the C concentration of 51.8% for *P. densiflora* needle litter and 49.1% for *Q. variabilis* leaf litter reported by Park et al. (2019). Significant difference in C inputs by litterfall (4,473 kg C ha^{-1} yr^{-1} for *P. densiflora* and 2,633 kg C ha^{-1} yr^{-1} for *Q. variabilis*) could be due to a considerable difference in the stand basal area and the stand density with the difference of C concentration

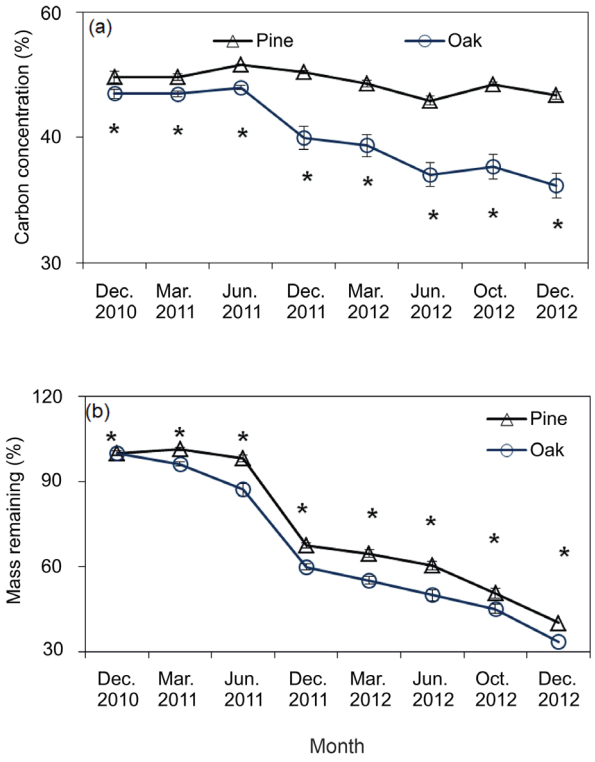

Fig. 4. Carbon concentration (a) and mass remaining (b) during leaf litter decomposition in *Pinus densiflora* (Pine) and *Quercus variabilis* (Oak) stands. Vertical bars represent standard errors. Asterisks indicate a significant difference between *Pinus densiflora* and *Quercus variabilis* stands at $P < 0.05$.

in litterfall components. Total C inputs of litterfall in this study are higher than in a *P. densiflora* (2,021 kg C ha^{-1} yr^{-1}) stand with a basal area of 22.37 m^{-2} ha^{-1} (Park et al., 2019) and is similar to a *Q. variabilis* (2,653 kg C ha^{-1} yr^{-1}) stand reported by Won et al. (2011) in South Korea.

Litter decomposition can be affected by biotic and abiotic factors with the difference in substrate quality. Rapid C loss in the leaf litter of *Q. variabilis* may be attributed to the high leaching loss of soluble labile C components and rapid C mineralization throughout the decomposition process. In contrast to leaf litter of *Q. variabilis*, the slow decay rate of needle litter of *P. densiflora* could be influenced by the chemical composition, such as the high C/N ratio and lignin concentration (Berg and Laskowski, 2006; Lukina et al., 2020). Many studies have reported that litter with high N concentrations and low C/N ratio in the oak litter was more rapidly decomposed than those with low N concentrations and high C/N ratio in pine needle litter (Berg and Laskowski, 2006; Krishna and Mohan, 2017). In addition, *Q. variabilis* stands in this study were located at a lower mean altitude (228 m) where the tree was higher temperature to accelerate the litter decomposition compared with *P. densiflora* stands (378 m).

Carbon storage of forest floor and mineral soils

Although variables such as litterfall inputs and litter decomposition are important to controlling the C storage of forest, there was no significant difference in the C storage of the forest floor in both stand types. These discrepancies between

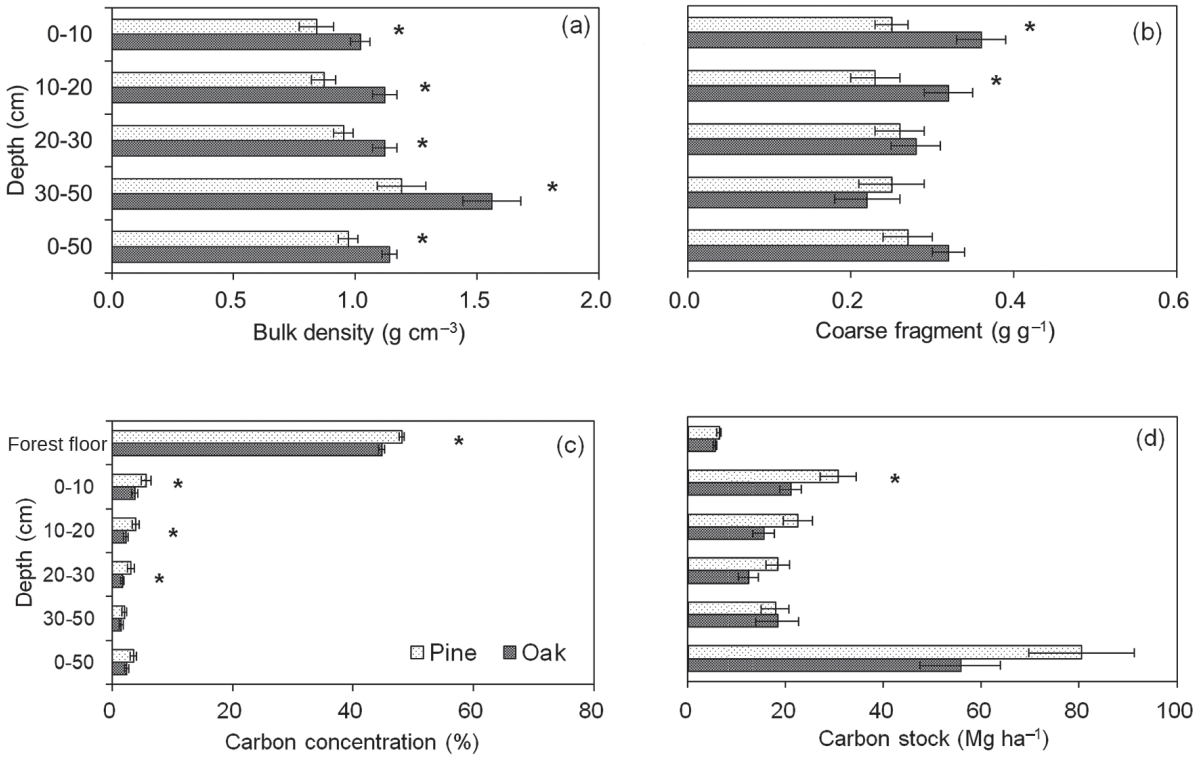

Fig. 5. Bulk density (a), coarse fragment (b), carbon concentration (c), and carbon stocks (d) at forest floor and soil depth in *Pinus densiflora* (Pine) and *Quercus variabilis* (Oak) stands. Vertical bars represent standard errors. Asterisks indicate a significant difference between *Pinus densiflora* and *Quercus variabilis* stands at $P < 0.05$.

the C storage of forest floor and litterfall inputs are probably related to high variability between stand types at short distances (Domke et al., 2016). In addition, other factors such as climate, stand age, altitude, and forest management practices play an important role in determining the C storage of the forest floor in both stand types.

The C storage of forest floor in this study is slightly higher than the 4.63 Mg C ha^{-1} for coniferous and 3.28 Mg C ha^{-1} for deciduous forests on a national scale in South Korea reported by Lee et al. (2020).

The significant difference in soil C concentration and storage at 0–10 cm of soil depth of the *Q. variabilis* (3.76%) and *P. densiflora* (5.65%) stands might be due to less litterfall input and higher decomposition processes (Fig. 3, 4) compared with *P. densiflora* stands. In addition, Baek and Kim (2020) reported that annual mean soil respiration was significantly higher in *Q. variabilis* (3.00 umol m^{-2} s^{-1}) than in *P. densiflora* (1.59 umol m^{-2} s^{-1}) stands, indicating rapid C mineralization in *Q. variabilis* stands. Previous studies found that the C concentration and storage of the surface soil depth might reflect the difference in the litterfall inputs, and litter decomposition dynamics, which are principal pathways for the return and loss of C to the soil (Jandl et al., 2007; Noh et al., 2013).

Although organic C concentration at the 10–30 cm depth was significantly higher in the *P. densiflora* than in the *Q. variabilis* stands, no significant differences in soil C storage between both stand types could be due to the site factors such as bulk density or coarse fragments. In addition, the rooting depth and density in both tree species can be relevant for soil C concentration and storage because root growth is the most effective way to introduce C to soils (An et al., 2017). However, Jandl et al. (2007) suggest that coniferous species with shallow roots generally tended to accumulate less C in soils, while deciduous hardwood trees presented deeper rooting patterns than the conifer trees. The result of this study was not in agreement with the previous finding that *P. densiflora* forests (37.83 Mg C ha^{-1}) have low soil C storage compared with *Q. variabil*s forests (57.09 Mg C ha^{-1}) in a national scale reported by Lee et al. (2018).

Conclusions

Although litter inputs and litter decomposition rates varied considerably by different stand types, C storage for the tree, forest floor, and soil components was less affected by stand types, except for surface soil depth (0–10 cm). A significant difference at surface soil depth might be due to the difference in temperature induced by the altitude because *Q. variabilis* forests are confined to low-altitude sites. This study emphasizes the importance of site factors to evaluate the C storage in different stand types.

Acknowledgements

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