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Carbon Storage in an Age-Sequence of Temperate *Quercus mongolica* Stands in Central Korea

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Abstract

This study was conducted to estimate carbon storage in *Quercus mongolica* stands based on stand age class, and to provide basic data on the carbon balance of broad-leaved forests of Korea. The research was conducted at the experimental forest of Kangwon National University, Hongcheon-gun County, Gangwon-do Province, Korea. Three plots were set up in each of three *Q. mongolica* forest stands (III, V, and VII) to estimate the amount of carbon stored in *Q. mongolica* aboveground vegetation, coarse woody debris (CWD), organic layer, mineral soil, and litterfall. The carbon storage of the aboveground vegetation increased with an increase in stand age, while the carbon storage ratio of stems decreased. The carbon storage of the organic layer, CWD, and litterfall did not show any significant differences among age classes. In addition, the carbon concentration and storage in the forest soils decreased with depth, and there were no differences among age classes for any soil horizon. Finally, the total carbon storage in the III, V, and VII stands of *Q. mongolica* were 132.2, 241.1, and 374.4 Mg C ha^{-1}, respectively. In order to predict and effectively manage forest carbon dynamics in Korea, further study on deciduous forests with other tree species in different regions will be needed.

Key Words: carbon storage, biomass, CWD, soil carbon, *Quercus mongolica*

Introduction

The forest ecosystem has the highest carbon storage per unit area among all terrestrial ecosystems (McCarl and Schneider 2001; Gower 2003), and it controls the amount of carbon accumulating in the forest ecosystem from the atmosphere by changing the CO_2 balance through photosynthesis and respiration (Pregitzer and Euskirchen 2004). The net carbon accumulation in the forest ecosystem is fundamentally related to stand age and natural disturbances (Bellamy et al. 2005), and it is known that the carbon storage of the overall ecosystem increases sharply in temperate forests according to succession stages (Pregitzer and Euskirchen 2004; Peichl and Arain 2006). In addition, second-growth forest, after disturbances such as a forest fire, harvesting, and withering, has the potential to accumulate a large quantity of carbon by rapid reproduction (Dixon et al. 1994; Davis et al. 2003; Houghton et al. 2009; Kueh et al. 2016).

Even though young stands are drawing attention because of several studies that have reported that their net primary production is higher than that of old stands (Harmon

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et al. 1990), the importance of old stands is increasing because of their function as carbon sinks (Odum 1966; Zhou et al. 2006; Luyssaert et al. 2008; Shukla and Chakravarty 2018). In addition, carbon is accumulated in four major carbon pools: vegetation, organic layers, coarse woody debris (CWD) and soil, depending on the development of the forest, and they exist simultaneously and are organically connected rather than independent (Pregitzer and Euskirchen 2004). In particular, carbon storage in both vegetation and soil makes up the largest type of storage in terrestrial ecosystems, and soil carbon dynamics have a significant influence on the carbon balance through vegetation recruitment and offset (Bellamy et al. 2005; Davidson and Janssens 2006; Houghton et al. 2009). Accordingly, it is necessary to measure all carbon pools by their stand age, even though each stand is different in site environment and genetic diversity of trees, and the most ideal approach is to consider all stand ages at the same time (Pregitzer and Euskirchen, 2004).

About 73% of the research forest (3,139 ha) of Kangwon National University is dominated by oak trees such as *Quercus mongolica*, *Q. variabilis*, and *Q. dentata*, and it is a secondary forest formed sprout forests after being exploited for firewood in the 1940s-1950s (KNU, 2018). In particular, *Q. mongolica* is the representative broadleaf species most widely spread in the secondary forest (Kim and Gil 2000), and an estimation of forest carbon storage according to ecological succession or forest practices is needed for the development of models to understand future forest carbon dynamics (Lee et al. 2015a; Lee et al. 2015b). The present study estimated carbon storage in aboveground vegetation, organic layers, CWD, and soil according to stand age (age classes III, V, and VII) using *Q. mongolica* stands, which are natural deciduous forests in the research forest of Kangwon National University.

Materials and Methods

Research site

This study was conducted natural deciduous forests of *Q. mongolica* without any disturbances, such as afforestation, diseases, and pests, of the Experiment Forest (N37°49′ E127°50′) of the College of Forest and Environmental Sciences, Kangwon National University, located in Bukbang-myeon, Hongcheon-gun, Gangwon-do, South Korea. The 20 m×20 m survey plots were set up in a total of nine locations in *Q. mongolica* stands of age classes III, V, and VII located within 1.3 km of each other. The altitudes of these study plots are 523-665 m, and gradients were 19-37° (Table 1). The stand density per ha was 1,700-2,100 for age class III, 850-1,050 for age class V, and 325-600 for age class VII in October 2010, which indicated that the number of trees was decreased through time by competition and natural withering. The average diameters at breast height (DBH) of each age class were in the ranges of 10.6-12.1 cm, 22.6-24.1 cm, and 29.2-38.8 cm, respectively. The soil at the study site is slightly brown forest soil with sandy loam originated form granite (Korea Forestry

Table 1. Characteristics of the nine *Quercus mongoilca* stands

Stand parameter	III			V			VII		
	1	2	3	1	2	3	1	2	3
Elevation (m)	584	601	610	542	555	559	617	523	665
Aspect	NE42	SW235	SW215	SW260	SW263	NW323	NW288	NW328	SW208
Slope (°)	36	27	37	25	24	35	19	20	33
Mean DBH (cm)	12.1 (±3.7)	10.9 (±2.5)	10.6 (±2.6)	22.7 (±6.2)	22.6 (±5.5)	24.1 (±5.6)	29.5 (±10.2)	38.8 (±13.2)	29.2 (±8.5)
Tree density (trees ha^{-1})	1700	2100	1700	850	1050	900	575	325	600
Basal area (m^2 ha^{-1})	19.65	19.74	14.96	34.36	42.12	41.06	39.20	38.38	40.13

The numbers in parentheses are standard deviations.

Promotion Institute 2018). The average annual temperature for the past 30 years from 1981 to 2010 was 10.3°C, and the average annual precipitation was 1405.4 mm (Korea Meteorological Administration 2018).

Estimation of carbon storage in the forest ecosystem

Samples were collected to estimate the carbon storage of vegetation, organic layers, CWD, and soil, which are the carbon pools of the forest ecosystem. The amount of biomass stored in the aboveground part of the vegetation (leaves, branches, and stems) was estimated by applying the DBH of *Q. mongolica* to the biomass regression equations developed in the same research site (Son et al. 2007). The results of which were then multiplied by 0.45 to estimate the carbon storage (Houghton 2001). In addition, the lengths and diameters of all CWD above diameters of 10 cm were surveyed by classifying them into three stages of decay class (class 1: initial stage, class 2: middle stage, and class 3: late stage). Samples were collected at the representative locations of decay classes and measured by volume and dry weight, and the density of CWD was calculated. Carbon storage was calculated by applying carbon concentration of previous study for *Q. mongolica* by decay class (Harmon et al. 2013).

In the case of forest organic matter, three sampling locations were randomly selected in each study plot, and organic matter was collected regardless of the layer (L, F, H) using a 30 cm×30 cm collecting frame. The collected sample was then moved into the indoors, in which it was dried at 65°C for two days or longer before its dry weight was measured. Soil samples were collected at 0-10 cm, 10-20 cm, 20-30 cm, and 30-50 cm layers in the three sampling locations using a soil cylinder (400 cm^3), and rock content was measured by separating gravel with a particle size of 2 mm or greater. Samples with a particle size of less than 2 mm were dried at 75°C for one week or longer, dry weight was measured, and bulk density was calculated. Also, three litterfall traps (0.25 m^2 opening areas, 60-cm heights) were randomly installed in each stand, and litterfall was collected every three months from November 2011 to October 2012. The collected litterfall was classified by component (broadleaf, needle, 5 mm or longer branch, less than 5 mm branch, bark, others), and weighed after drying at 65°C for two days or longer. Organic layer, soil, and litter samples were analyzed using a macro elemental analyzer (vario MACRO, CN elementar Analysensysteme GmbH, Langenselbold, Germany).

Statistical analysis

Differences in the carbon concentration and carbon storage according to age class, decay class of CWD, soil depth, and litter component were tested using the general linear model, and post-hoc analysis (Duncan multiple range test, $p < 0.05$) was performed if a significant difference was found. All statistical analyses were performed using SPSS Statistics Program (Version 24.0).

Results and Discussion

Aboveground carbon storage of vegetation

The aboveground carbon storage (Mg C ha^{-1}) of *Q. mongolica* increased significantly by age class ($p < 0.001$) (Table 2), from 52.26±8.66 for age class III, to 181.97±13.54 for age class V, and 256.23±8.71 for age class VII. The aboveground carbon storage of 30-year-old *Q. mon-*

Table 2. Carbon storage of different tree components in the nine *Quercus mongoilca* stands

Age-classes	Carbon storage (Mg C ha^{-1})				Carbon storage fraction (%)			
	Foliage	Branch	Stem	Total	Foliage	Branch	Stem	Total
III	0.61a (±0.11)	2.49a (±0.93)	49.16a (±7.70)	52.26a (±8.66)	1.16a (±0.02)	4.62a (±1.04)	94.21c (±1.06)	100.00
V	2.30b (±0.18)	31.78b (±2.13)	147.88b (±11.65)	181.97b (±13.54)	1.26b (±0.00)	17.49b (±0.72)	81.24b (±0.71)	100.00
VII	3.01c (±0.07)	80.07c (±12.34)	173.15c (±6.60)	256.23c (±8.71)	1.18a (±0.04)	31.14c (±3.94)	67.68a (±3.91)	100.00

The numbers in parentheses are standard errors.
Different alphabet letters indicate statistically significant differences among age-classes in each component by the Duncan test ($p = 0.05$).

golica stands in Gwangju, Gyeonggi-do were 30.10 Mg C ha^{-1}, less than that of age class III in this study (Son et al. 2002). This is due to smaller average DBH (9.06 cm) despite similar altitude (644 m) and lower stand density (1,425 trees per ha^{-1}). In addition, the aboveground carbon storage of age class V was also very high compared to those of 44-year-old *Q. mongolica* forest in the Hoeng-seong area (101.48 Mg C ha^{-1}) (Lee et al. 2009). Compared to our study, where the density of the stands is similar (1,000 trees per ha^{-1}), the reason for the small average DBH (13.7 cm) of Hoeng-seong is that the elevation (833 m) is high. Even though direct comparisons are difficult because of insufficient research estimating the total carbon storage of *Quercus* species stands, the carbon storage of this study site appears to be higher than results of previous studies reported in Korea. These differences in tree productivity by region are due to factors such as forest site productivity (Oren et al. 2001), and higher carbon storage in the present study site appears to be due to the greater development of stand stage based on high forest site productivity.

Aboveground carbon storage was the highest in stems, followed by branches and then leaves, and the amount of carbon storage in each component increased as age class increased. The carbon storage ratio of leaves was higher for age-class V (1.26%) than VII (1.16%) ($p < 0.05$), and that of stems decreased as age class increased from 94.21% for age class III, 81.24% for age class V, and 67.68% for age class VII ($p < 0.001$). The carbon storage ratio of branches increased from 4.62% for age class III to 31.14% for age class VII. The stem ratio of age class III was much higher than the 75.5% for 30-year old *Q. mongolica* reported by Son et al. (2002), and it was also higher than the 80% for 30-year old *Q. mongolica* of Mt. Mudeung reported by Lee et al. (2015c). The stem ratio of age class VII, however, was lower than 83.9% but similar to the 69.6% stem ratios of 70-year old *Q. mongolica* stands on the south- and the north-facing slopes, respectively, reported in the study by Kwon and Lee (2006). Since the sites of this study were located on the north-facing slope where the light was insufficient, it was a result of increasing the productivity by the photosynthesis by increasing the ratio of leaves and branches.

Carbon storage of organic layers, CWD, and soil

The dry weight (Mg ha^{-1}) of organic layer was the highest to age class V with 12.91, followed by age classes VII with 11.60 and III with 9.36. There was no significant difference in carbon concentration, which was the highest for age class III with 46.46%, followed by age classes VII and V with 44.10% and 44.03%, respectively (Table 3). The average carbon concentration of organic layer was 44.86% in all age classes, which was higher than the 38.2% reported for *Q. mongolica* stands in Hoengseong by Lee et al. (2009) and the 35.4% reported for pine stands in the Gyeongsangnam-do by Kim et al. (2009). Also, this result was similar to the 43.33-47.24% for Q. variabilis stands in the western region of Gyeongsangnam-do (Ju et al. 2015), but lower than 47.84-51.37% for pine stands in Gangneung (Ko et al. 2014). Therefore, the carbon storage of the organic layer was 4.42-5.74 Mg C ha^{-1} (Fig. 1), which was

Table 3. Carbon storage of organic layer and coarse woody debris in the nine *Quercus mongoilca* stands

Age-classes	Organic layer		Coarse woody debris			
	Dry weight (Mg ha^{-1})	Organic carbon (%)	Wood density (g cm^{-3})			Dry weight (Mg ha^{-1})
			Decay-I	Decay-II	Decay-III	
III	9.36a (±1.11)	46.46a (±0.64)	0.48Ba (±0.21)	0.30Aa (±0.08)	0.40ABb (±0.05)	0.68a (±0.14)
V	12.91b (±2.49)	44.03a (±0.47)	0.59Ba (±0.05)	0.41Aa (±0.16)	0.30Aab (±0.15)	1.66a (±1.32)
VII	11.60ab (±0.73)	44.10a (±0.39)	0.60Ba (±0.19)	0.37Aa (±0.14)	0.26Aa (±0.12)	1.90a (±0.43)

The numbers in parentheses of organic layer are standard errors(n=9), the numbers in parentheses of CWD are standard deviations(n=4). Different alphabet letters indicate statistically significant differences at $p = 0.05$ level according to the Duncan test for each subsection (upper-case alphabet letters indicate differences among decay class in the same age-classes, lower-case alphabet letters demonstrate differences among age-classes in the same subsection).

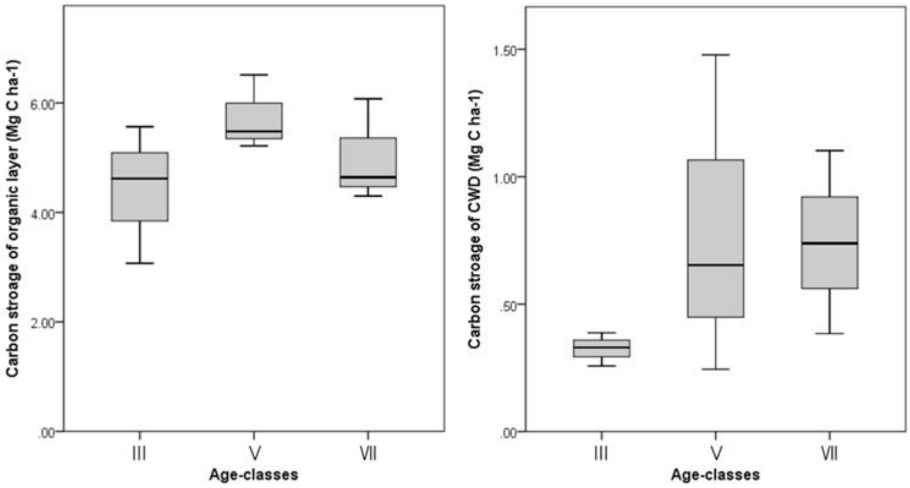

Fig. 1. Carbon storage of organic layer and coarse woody debris in the nine *Quercus mongoilca* stands. The vertical bars is the full range of variation (from min to max), the inside of the box is the first quartile to the third quartile.

Table 4. Coarse fraction, bulk density, and carbon concentration at different soil depths in nine *Quercus mongolica* stands

Soil depth	III			V			VII		
	Coarse fraction (%)	Bulk density (g cm^{-3})	Carbon concentration (%)	Coarse fraction (%)	Bulk density (g cm^{-3})	Carbon concentration (%)	Coarse fraction (%)	Bulk density (g cm^{-3})	Carbon concentration (%)
0-10 cm	33.96 (±0.03)	0.68 (±0.05)	6.46c (±1.58)	33.90 (±0.14)	0.83a (±0.17)	4.13b (±1.22)	23.47 (±0.05)	0.82a (±0.09)	5.14 (±1.24)
10-20 cm	42.04B (±0.10)	0.74 (±0.06)	3.87b (±1.12)	42.73AB (±0.07)	0.91a (±0.17)	2.18a (±0.69)	24.67A (±0.10)	0.95ab (±0.08)	3.92 (±1.88)
20-30 cm	55.13B (±0.20)	0.93 (±0.19)	2.08a (±1.00)	33.81AB (±0.13)	1.06a (±0.23)	1.19a (±0.60)	28.01A (±0.09)	1.04b (±0.14)	3.24 (±1.78)
30-50 cm	44.19 (±0.79)	0.79 (±0.09)	1.46a (±1.06)	38.22 (±0.15)	1.27b (±0.17)	0.63a (±0.27)	31.87 (±0.07)	1.14b (±0.11)	2.00 (±1.33)

The numbers in parentheses are standard errors.
Different alphabet letters indicate statistically significant differences at $p=0.05$ level according to the Duncan test for each subsection (upper-case alphabet letters indicate differences among age-classes in the same soil depth, lower-case alphabet letters demonstrate differences among soil depth in the same subsection).

statistically nonsignificant ($p=0.183$), but age class V was found to have higher carbon storage than age class VII. These results were similar to the 5.6 Mg C ha^{-1} reported for the carbon storage of the natural deciduous forests of the Gwangneung arboretum, which are in the late stage of succession (Lim et al. 2003), but the results were less than the 9.9 Mg C ha^{-1} of pure oak stand in the Hoengseong (Lee et al. 2009). The reason for large differences between previous studies appears to be that carbon storage in the organic layer is strongly related to not only stand age but also tree species, temperature, precipitation, and moss (Schlesinger and Lichter, 2001; Smith and Heath, 2002).

As decomposition progressed, the wood density (g cm^{-3}) of CWD tended to be higher in decay stage 1 and lower in decay stage 3 ($p < 0.05$). Although carbon concentration of CWD was not directly analyzed in this study, the carbon concentration of 48% was applied according to results (47.2-48.1% of gymnosperms) by decay class of Harmon et al. (2013). The carbon storage of CWD was 0.32 Mg C ha^{-1} for age class III, 0.79 Mg C ha^{-1} for age class V, and 0.74 Mg C ha^{-1} for age class VII (Fig. 1). This was similar to the 0.65 Mg C ha^{-1} of 36-year-old pine stands in the

Muju region (Seo et al. 2016), but significantly less than the 1.31-2.80 Mg C ha^{-1} of age class VI pine stands in Gangneung region and the Gwangneung arboretum (Ko et al. 2014).

The fraction of coarse rock (more than 2 mm diameter) was higher in the subsoil than in the topsoil, but there was no significant difference by soil depth in all age classes (Table 4). The bulk density significantly increased with the soil depth and was similar to the average of Korea forest soil (A horizon 0.88 g cm^{-3}, B horizon 1.018 g cm^{-3}) (Jeong et al. 2002). In addition, Carbon concentrations were 1.46-6.46% for age class III, 0.63-4.13% for age class V, and 2.00-5.14% for age class VII. The carbon concentration of the topsoil was highest, significantly decreasing as the depth increased, depending on the accumulation and decomposition of organic matter (Armson 1977). Carbon concentration was in a similar range to 1.04-6.11% in Hoengseong area (Lee et al. 2009); 1.13-4.06% of *Pinus rigida* stands in the Muju area (Seo et al. 2016); and 4.35-6.99% of pine stands in the Gyeongnam region (Kim et al. 2009). Accordingly, carbon storage in soil was the highest for age class VII with 114.29 Mg C ha^{-1}, followed by age class III with 63.23 Mg C ha^{-1} and age class V with 47.75 Mg C ha^{-1} (Fig. 2). Carbon storage of soil, however, significantly varies depending on stand age, region, and tree species when compared to the findings of many previous researches. Therefore, it appears to yet be difficult to derive general trend of carbon storage of soil because of inconsistent research findings that soil carbon can increase, decrease, or stay depending on the stand age (Pérez et al., 2004; Rothstein et al., 2004; O'Neill et al., 2006).

Carbon influx by litterfall

The carbon concentration of litterfall was not significantly different to stand age in all component ($p > 0.05$; Table 5). In addition, the carbon concentrations of the broad leaves litter in age classes III and V were 49.11% and 49.07%, respectively, which were significantly lower than the carbon concentrations of the needle litter (50.54-51.51%) or branches (50.27%-53.23%) ($p < 0.01$). Meanwhile, annual carbon influx by total litterfall was the highest for age class V with 3.93 Mg C ha^{-1} yr^{-1}, followed by age class VII with 3.15 Mg ha^{-1} yr^{-1} and age class III with 2.48 Mg ha^{-1} yr^{-1}. This was similar to the litterfall production of oak stands in Korea, which was 1.24-4.38 Mg C ha^{-1} yr^{-1} (Son et al. 2004), and the litterfall production of temperate deciduous hardwood stands, which was 1.20-3.55 Mg C ha^{-1} yr^{-1} (Raich and Nadelhoffer, 1989). Since carbon influx by litterfall is positively correlated with the accumulation of biomass according to the increase of succession stage of stands (Zhou et al. 2007), the litterfall production of age class V, which has a larger basal area and biomass, was the largest compared to age class VII (Kwon et al. 2016). The production of broad leaf litter was the highest ratio in all age classes, and was 62.1% in age class III, which had the lowest annual litterfall production, while that of age classes VII and V were 50.8% and 48.1%, respectively. As larger the biomass, the higher the influx rate of the xylem, such as branches and bark (Kwon et al. 2016). In this study, the ratio of branches and bark of age class III was 22.2%, which was higher than the 18.4% of age class VII.

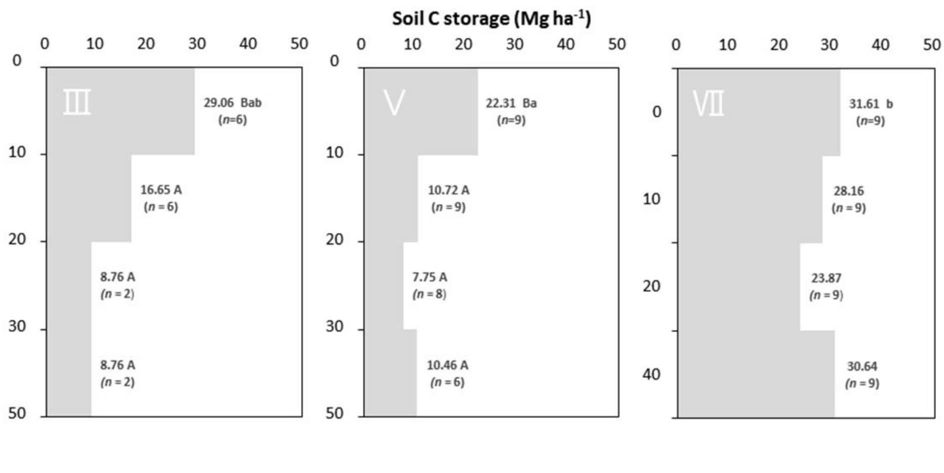

Fig. 2. Carbon storage by soil depth in each age class of the *Quercus mongolica* stands.

Table 5. Carbon concentration (%) and organic carbon inputs (Mg C ha^{-1} yr^{-1}) of the litter component in nine *Quercus mongolica* stands

Components		Broad leaf	Needle leaf	Branch (<5mm)	Branch (>5mm)	Bark	Others	Total
Carbon concentration (%)	III	49.11Aa (±0.38) (n=44)	53.23Ba (±1.36) (n=6)	50.54ABa (±0.49) (n=35)	50.74ABab (±0.33) (n=1)	51.13AB (±1.93) (n=2)	48.63Aa (±0.93) (n=17)	-
	V	49.07Aa (±0.40) (n=45)	50.27ABa (±0.64) (n=6)	50.87ABa (±0.31) (n=38)	51.51Bb (±0.55) (n=7)	-	49.78ABa (±0.29) (n=17)	-
	VII	48.84Aa (±0.77) (n=39)	51.91Aa (±1.77) (n=2)	50.13Aa (±0.30) (n=33)	49.42Aa (±0.75) (n=4)	48.73A (±2.49) (n=3)	48.85Aa (±0.33) (n=18)	-
Organic carbon inputs (Mg C ha^{-1} yr^{-1})	III	1.54Ba (±0.14)	0.13Aa (±0.07)	0.28Aa (±0.08)	0.24Aa (±0.14)	0.03A (±0.02)	0.25Aa (±0.05)	2.48Ca (±0.39)
	V	1.89Bb (±0.08)	0.06Aa (±0.03)	0.39Aa (±0.08)	0.81Aa (±0.52)	-	0.78Ab (±0.11)	3.93Ca (±0.62)
	VII	1.60Dab (±0.02)	0.02Aa (±0.02)	0.26Ba (±0.05)	0.14ABa (±0.07)	0.18AB (±0.11)	0.95Cb (±0.11)	3.15Ea (±0.01)

The numbers in parentheses are standard errors.
Different alphabet letters indicate statistically significant differences at $p=0.05$ level according to the Duncan test for each subsection (upper-case alphabet letters indicate differences among components in the same age-class, lower-case alphabet letters demonstrate differences among age-classes in the same subsection).

Conclusion

This study estimated the total carbon storage in an age-sequence of *Quercus mongolica* stands, resulting 132.2 Mg C ha^{-1} for age class III, 241.1 Mg C ha^{-1} for age class V, and 374.4 Mg C ha^{-1} for age class VII ($p<0.05$). The proportions of vegetation to total carbon storage were similar age classes V and VII with 77.5% and 67.9%, respectively, but that of age class III was low with 43.9%. Therefore, soil was the largest carbon pool in the age class III, and the second carbon pool in the others. Organic layers and CWD were in the ranges of 1.34-3.34% and 0.20-0.33% to total carbon storage, respectively. In addition, 1.2%-4.3% of the above-tree carbon storage was put into the soil as litterfall. These results will help to simulate whether carbon storage will increase, maintain or decrease by the ecological succession of forest and to develop appropriate forest management techniques in natural broad-leaved forests of Korea.

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References

Armson K. 1977. Forest Soils: Properties and processes. University of Toronto press, Toronto.

Bellamy PH, Loveland PJ, Bradley RI, Lark RM, Kirk GJ. 2005. Carbon losses from all soils across England and Wales 1978-2003. Nature 437: 245-248.

Davidson EA, Janssens IA. 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 440: 165-173.

Davis MR, Allen RB, Clinton PW. 2003. Carbon storage along a stand development sequence in a New Zealand Nothofagus forest. For Ecol Manag 177: 313-321.

Dixon RK, Solomon AM, Brown S, Houghton RA, Trexier MC, Wisniewski J. 1994. Carbon pools and flux of global forest ecosystems. Science 263: 185-190.

Gower ST. 2003. Patterns and mechanisms of the forest carbon cycle. Annu Rev Environ Resour 28: 169-204.

Harmon ME, Fasth B, Woodall CW, Sexton J. 2013. Carbon concentration of standing and downed woody detritus: Effects of tree taxa, decay class, position, and tissue type. For Ecol Manag 291, 259-267.

Harmon ME, Ferrell WK, Franklin JF. 1990. Effects on carbon storage of conversion of old-growth forests to young forests. Science 247: 699-702.

Houghton JT; IPCC. 2001. Climate change 2001: The scientific basis. Cambridge University Press, Cambridge, pp 188.

Houghton RA, Hall F, Goetz SJ. 2009. Importance of biomass in the global carbon cycle. J Geophys Res Biogeosciences 114: G00E03.

Jeong JH, Koo KS, Lee CH, Kim CS. 2002. Physico-chemical properties of Korean forest soils by regions. Korean For Soc 91: 694-700. (in Korean with English abstract)

Ju NG, Seo KS, Son Y, Kim RH, Son YM, Kim C. 2015. Belowground carbon storage by stand age classes and regions of red pine (*Pinus densiflora*) and cork oak (*Quercus variabilis*) stands in Western Gyeongnam province. J Agric Life Sci 49: 29-39. (in Korean with English abstract)

Kim C, Son Y, Lee WK, Jeong J, Noh NJ. 2009. Influences of forest tending works on carbon distribution and cycling in a *Pinus densiflora* S. et Z. stand in Korea. For Ecol Manag 257: 1420-1426. (in Korean with English abstract)

Kim J, Gil B. 2000. The mongolian oak forest in Korea. Wonkwang University Press, Iksan, pp 511. (in Korean with English abstract)

KNU. 2018. http://expfor.kangwon.ac.kr/. Accessed Nov 2018.

Ko SI, Yoon TK, Kim SJ, Kim CS, Lee ST, Seo KW, Son YW. 2014. Thinning intensity effects on carbon storage of soil, forest floor and coarse woody debris in *Pinus densiflora* stands. Korean Soc For Sci 103: 30-36. (in Korean with English abstract)

Korea Forestry Promotion Institute. 2018. https://www.kofpi.or.kr/. Accessed Nov 2018.

Korea Meteorological Administration. 2018. http://www.weather.go.kr/. Accessed Nov 2018.

Kueh RJH, Majid NM, Ahmed OH, Gandaseca S. 2016. Assessment of carbon stock in chronosequence rehabilitated tropical forest stands in Malaysia. J For Environ Sci 32: 302-310.

Kwon B, Jeon J, Kim HS, Yi MJ. 2016. Estimation of specific leaf area index using direct method by leaf litter in Gwangneung, Mt. Taewha and Mt. Gariwang. Korean J Agric For Meteorol 18: 1-15. (in Korean with English abstract)

Kwon KC, Lee DK. 2006. Biomass and annual net production of *Quercus mongolica* stands in Mt. Joongwang with respect to altitude and aspect. Korean For Soc 95: 398-404. (in Korean with English abstract)

Lee J, Han SH, Kim S, Chang H, Yi MJ, Park GS, Kim C, Son YM, Kim R, Son Y. 2015. Estimating the changes in forest carbon dynamics of *Pinus densiflora* and *Quercus variabilis* forests in South Korea under the RCP 8.5 climate change scenario. Korean J Agric For Meteorol 17: 35-44. (in Korean with English abstract)

Lee JY, Han SH, Kim SJ, Lee SH, Son YM, Son YW. 2015. A meta-analysis on the effect of forest thinning on diameter growth and carbon stocks in Korea. Korean Soc For Sci 104: 527-535. (in Korean with English abstract)

Lee NY, Na KT, Noh JM, Shim S. 2015. Estimation of carbon storage in a forest ecosystem at Mudeungsan Mt. National Park, Korea. J Nat Park Res 6: 1-6. (in Korean with English abstract)

Lee SK, Son YH, Noh NJ, Heo SJ, Yoon TK, Lee AR, Razak SA, Lee WK. 2009. Carbon storage of natural pine and oak pure and mixed forests in Hoengseong, Kangwon. Korean For Soc 98: 772-779. (in Korean with English abstract)

Lim JH, Shin JH, Jin GZ, Chun JH, Oh JS. 2003. Forest stand structure, site characteristics and carbon budget of the Kwangneung natural forest in Korea. Korean J Agric For Meteorol 5: 101-109. (in Korean with English abstract)

Luyssaert S, Schulze ED, Börner A, Knohl A, Hessenmöller D, Law BE, Ciais P, Grace J. 2008. Old-growth forests as global carbon sinks. Nature 455: 213-215.

McCarl BA, Schneider UA. Schneider. 2001. Climate change. Greenhouse gas mitigation in U.S. agriculture and forestry. Science 294: 2481-2482.

O'Neill KP, Richter DD, Kasischke ES. 2006. Succession-driven changes in soil respiration following fire in black spruce stands of interior Alaska. Biogeochemistry 80: 1-20.

Odum EP. 1966. The strategy of ecosystem development. Science 164: 262-270.

Oren R, Ellsworth DS, Johnsen KH, Phillips N, Ewers BE, Maier C, Schäfer KV, McCarthy H, Hendrey G, McNulty SG, Katul GG. 2001. Soil fertility limits carbon sequestration by forest ecosystems in a CO2-enriched atmosphere. Nature 411: 469-472.

Peichl M, Arain MA. 2006. Above- and belowground ecosystem biomass and carbon pools in an age-sequence of temperate pine plantation forests. Agric For Meteorol 140: 51-63.

Pérez CA, Carmona MR, Aravena JC, Armesto JJ. 2004. Successional changes in soil nitrogen availability, non-symbiotic nitrogen fixation and carbon/nitrogen ratios in southern Chilean forest ecosystems. Oecologia 140: 617-625.

Pregitzer KS, Euskirchen ES. 2004. Carbon cycling and storage in world forests: Biome patterns related to forest age. Glob Change Biol 10: 2052-2077.

Raich JW, Nadelhoffer KJ. 1989. Belowground carbon allocation in forest ecosystems: Global trends. Ecology 70: 1346-1354.

Rothstein DE, Yermakov Z, Buell AL. 2004. Loss and recovery of ecosystem carbon pools following stand-replacing wildfire in Michigan jack pine forests. Can J For Res 34: 1908-1918.

Schlesinger WH, Lichter J. 2001. Limited carbon storage in soil and litter of experimental forest plots under increased atmospheric CO_2. Nature 411: 466-469.

Seo YO, Jung SC, Lee YJ. 2016. Estimation of carbon storage for

Pinus rigida stands in Muju. Korean J Enviro Ecol 30: 399-405. (in Korean with English abstract)

Shukla G, Chakravarty S. 2018. Biomass, primary nutrient and carbon stock in a sub-Himalayan forest of West Bengal, India. J For Environ Sci 34: 12-23.

Smith JE, Heath LS. 2002. A model of forest floor carbon mass for United States forest types. US Department of Agriculture, Forest Service, Northeastern Research Station, Newtown Square, PA, pp 722.

Son SY, Kwon KC, Jeong TS. 2002. Productive structure and net production of *Quercus mongolica* forest in Mt. Taehwa (Kwangju, Kyonggi-do). J Korea For Energy 21: 76-82. (in Korean with English abstract)

Son Y, Kim D, Park I, Yi M, Jin H. 2007. Production and nutrient cycling of oak forests in Korea: A case study of *Quercus mongolica* and *Q. variabilis* stands. Kangwon National University, Chuncheon. (in Korean with English abstract)

Son Y, Park IH, Jin HO, Yi MJ, Kim DY, Kim RH, Hwang JO. 2004. Biomass and nutrient cycling of natural oak forests in Korea. Springer, Dordrecht, pp 217-232.

Zhou G, Guan L, Wei X, Zhang D, Zhang Q, Yan J, Wen D, Liu J, Liu S, Huang Z, Kong G, Mo J, Yu Q. 2007. Litterfall production along successional and altitudinal gradients of subtropical monsoon evergreen broadleaved forests in Guangdong, China. Plant Ecol 188: 77-89.

Zhou G, Liu S, Li Z, Zhang D, Tang X, Zhou C, Yan J, Mo J. 2006. Old-growth forests can accumulate carbon in soils. Science 314: 1417.