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ORIGINAL RESEARCH

Biomass and Carbon Storage in an Age-Sequence of Korean Pine (*Pinus koraiensis*) Plantation Forests in Central Korea

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Abstract This study examined the biomass and carbon pools of the main ecosystem components in an age sequence of five Korean pine plantation forest stands in central Korea. The C contents in the tree and ground vegetation biomass, coarse woody debris, forest floor, and mineral soil were estimated by analyzing the C concentration of each component. The aboveground and total tree biomass increased with increasing stand age. The highest C concentration across this chronosequence was found in the tree branch while the lowest C concentration was found in the ground vegetation. The observed C contents for tree components, ground vegetation, and coarse woody debris were generally lower than the predicted C contents estimated from a biomass C factor of 0.5. Forest floor C content was age-independent. Total mineral soil C content appeared to decline initially after establishing Korean pine plantations and recover by the stand age of 35 years. Although aboveground tree biomass C content showed considerable accumulation with increasing age, the relative contribution of below ground C to total ecosystem C content varied substantially. These results suggest that successional development as temporal factor has a key role in estimating the C storage in Korean pine plantation forests.

Keywords Biomass · Carbon storage · Carbon concentration · Chronosequence · Korean pine plantation

Introduction

Biomass and carbon (C) storage in forest ecosystems plays an important role in global C cycle (e.g., Choi et al. 2002; Goodale et al. 2002; Houghton 2005). Because forests as a carbon reservoir store more carbon per unit area than any other terrestrial ecosystem (Houghton 2007), they may act as an effective measure to mitigate elevated atmospheric carbon dioxide (CO_2) concentrations by increasing forested land area (Peichl and Arain 2006; Taylor et al. 2007). The Republic of Korea (henceforth referred to as Korea) as a member is seeking to implement its commitments under the United Nations Framework Convention on Climate Change through nationwide amelioration of forest conditions to increase the level of C storage in its forest ecosystems. Although sporadic government efforts at reforestation had begun in the 1960s, the Korean government initiated three 10-year national reforestation programs in 1973 to recover its once-rich forests (Choi et al. 2002; Cho et al. 2007; Tak et al. 2007). After the three 10-year national reforestation, there is a need for accurate information concerning the C stocks in Korean forests.

Although there is no direct information regarding the forest area ratio and volume ratio of plantations to the baseline forests over time, recent studies have indicated that plantations made major contributions to C sequestration by

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Korean forests over the past three decades (Choi et al. 2002; Li et al. 2010). Especially, the total forest biomass C storage in pine plantations have increased significantly from 21.65 Tg C in 1975 to 82.63 Tg C in 2007, with a increase in biomass C accumulation rates from 1.23 to 2.25 Tg C/year (Li et al. 2010). The greatest potential for aboveground biomass and C storage in pine plantations is usually found within the tree biomass (Yi 1998; Son et al. 2001; Peichl and Arain 2006), but the biomass of shrubs and herbs, tree root biomass, forest floor, and mineral soil also provide large C pools (Lee and Park 1987; Johnson et al. 2003; Oliver et al. 2004; Taylor et al. 2007; Noh et al. 2010). Although biomass C content (Mg C ha^{-1}) in forest trees is normally estimated using the carbon concentration factor (0.5), which directly converts the carbon content from the tree biomass, recent analyses showed that the C concentration of tree components or tree species might be either above or below 50% (e.g., Laiho and Laine 1997; Lamlom and Savidge 2003; Bert and Danjon 2006; Zheng et al. 2008). The accuracy of the carbon content assessments has been improved by estimating the C concentration in each component. However, most studies have not been able to consider the potential variations within the tree components (Bert and Danjon 2006).

Korean pine (*Pinus koraiensis* Sieb. et Zucc.) is one of the major plantation tree species in Korea because of high-value wood products and nuts (Son et al. 2007), covering about 8.6% of the total forest area in Korea (Korea Forest Service 2008). Some studies on biomass and nutrients for this species in Korea have been reported (Lee and Park 1987; Lee and Kim 1997; Yi 1998; Son et al. 2001, 2007; Noh et al. 2005; Kwon and Lee 2006; Lee et al. 2009), including the nutrient distribution of Korean pine seedlings invading a mixed forest (Son et al. 2005), and a description of the aboveground biomass C dynamics following forest tending works (Hwang et al. 2008). However, there is still a lack of information on the biomass and C pools in planted Korean pine stands.

The objectives of this study were to (1) estimate the biomass and C storage of the main ecosystem components across an age-sequence of five Korean pine stands, and (2) determine the changes in the size and contribution of these C pools to total ecosystem C content with increasing stand age.

Materials and Methods

Site Description

The study was carried out at two areas in central Korea. One was located in a relatively pure Korean pine plantation forest at the Experimental Forest of Kangwon National University (37°46′–51′ N, 127°48′–52′ E). The Experimental Forest was established in 1953 and its total forest area was 3,146 ha in 2000, 522 ha of which was covered by Korean pine plantation forest. Sustainable forest management practices including building forest roads, forest tending works, and setting up study plots for research and training have been conducted in the Experimental Forest since 1974. Thinning treatments have been applied to the 35- and 51-year-old stands during the third (1985–1989) and fourth (1990–2000) management practices. The region has a temperate climate with a mean annual temperate of 9.2°C and a mean annual precipitation of 1,289 mm distributed mainly in summer. The average temperatures in January and July are −6.1 and 24.8°C, respectively. The soil texture is sandy clay loam. The other was also located in a relatively pure Korean pine plantation forest at the Yangpyeong area (37°30′ N, 127°42′ E), 40 km southwest of the Experimental Forest, where a 30-year-old stand was established. The area was previously vegetated with oaks-pine (*Pinus densiflora* Sieb.et Zucc.) mixed forests. Korean pine plantation forest was planted after the commercial harvest of oaks-pine mixed forests, and thinned heavily for seed production. The specific characteristics of the area were described in Son et al. (2001). Our study design consists of a Korean pine chronosequence that includes 8-, 19-, 30-, 35-, and 51-year-old stands. Four stands with different age (8-, 19-, 35-, and 51-year-old) were selected from the Experimental Forest.

Stand age was not replicated in our chronosequence because it is not possible to find replicate stands of same age with similar stand composition, soil type, and environmental conditions in the two regions. This study used the common software packages (SPSS v16) to analyze stand means and within-stand variations.

Destructive Tree Sampling

Destructive analysis of sample trees was similar to the work reported elsewhere (Yi 1998; Son et al. 2001). In early August 2008, five Korean pine trees representing the stand-specific diameter at breast height (DBH) range were selected and sampled destructively in each chronosequence stand (20×20 m; Table 1). The trees were cut at a height of 20 cm above the ground. Prior to branch removal, the diameter of each branch was measured, and five representative branches from the lowest to the highest throughout the crown were sampled. All branches were then clipped from the tree, and fresh weights were determined using balance. Those sampled branches were separated into foliage and branches, and subsamples of each component were oven-dried at 65°C to examine the moisture content. The stem of each tree was cut in 2 m sections and weighed on a balance. A disk (approximately 5 cm wide) was cut from the stump to the top of each stem section to determine moisture content in the laboratory. The dry weight of each

Table 1 Stand characteristics of the 8-, 19-, 30-, 35-, and 51-year-old Korean pine stands

Stand parameter	8-year-old	19-year-old	30-year-old	35-year-old	51-year-old
Altitude (m)	330	456	155	482	411
Slope (°)	42	24	25	18	28
Mean DBH (cm)	1.6	12.2	19.8	24.5	30.7
	(0.9–2.3)	(7.8–14.7)	(16.8–22.9)	(20.3–29.4)	(24.1–38.7)
Mean height (m)	1.8	6.9	13.1	15.0	19.3
	(1.4–2.2)	(5.3–8.1)	(11.8–14.4)	(13.3–16.5)	(17.8–22.2)
Stand density (stems/ha)	2,200	975	650	825	625
Management history			Thinning in 1995	Thinning in 2000	Thinning in 1989
Soil depth (cm)	45	50	35	50	50
Bulk density (g/cm^{-3})	0.96	1.32	1.09	1.16	1.19
Coarse rock fragment (%)	21.6	76.8	28.7	50.2	68.0

DBH diameter at breast height

Ranges are in parentheses

component (foliage, branches, and stem) was calculated for each sample tree. Radial growth along the longest, shortest, and intermediate radius on each section were determined to calculate the stem volume over the bark using the Smalian's formula (Avery and Burkhart 1983). The total volume of each stand was estimated by multiplying the mean volume of the sample trees by the stem density. For estimating the root biomass, two trees were harvested in each chronosequence stand based on stand-specific DBH range, and the entire root system was washed lightly to remove soil particles, oven-dried, and weighed. The total dry weight for each component (foliage, branches, stem, and root) was calculated, and the weights were related to the DBH in logarithmic regression equation (Son et al. 2001): $\mathrm{Log}_{10}\, Y = a + b\, \mathrm{Log}_{10}$ (DBH), where a and b are the equation parameters, Y is the biomass (g) of each tree component (Table 2). Correction factors were used in calculating the biomass of each tree component to eliminate any systematic bias in the log transformation (Sprugel 1983).

Three 1×1 m microplots were established within each chronosequence stand. In each microplot, whole ground vegetation (shrubs and herbs) including roots was harvested. Biomass of each ground vegetation component was air-dried and subsamples were oven-dried at 65°C to calculate dry biomass density (Mg ha^{-1}).

Tissue sample of each plant and ground vegetation was collected from each chronosequence stand. The tissue was dried, ground with a laboratory grinder, and then analyzed for the C concentration. The C content was obtained by multiplying each tissue C concentration by the total dry weight of each component.

Coarse Woody Debris, Forest Floor (LFH Layer), and Soil Sampling

Downed wood and standing dead trees longer than 1 m in length with a diameter ≥10 cm were considered coarse woody debris and coarse woody debris was classified into

Table 2 Regressions of dry weights (g) in different tree components on diameter at breast height (cm) for *Pinus koraiensis* in central Korea

Component	a	b	R^2	MSR	CF	Tree samples
Stem wood	2.113	2.084	0.981	0.063	1.014	25
Stem bark	1.742	1.667	0.970	0.066	1.014	25
Stem	2.267	2.006	0.980	0.063	1.013	25
Branch	2.182	1.716	0.960	0.093	1.020	25
Foliage	2.296	1.561	0.959	0.079	1.017	25
Total aboveground	2.725	1.831	0.982	0.046	1.010	25
Tree roots	1.891	2.019	0.978	0.069	1.015	10
Total tree	2.662	1.954	0.987	0.038	1.008	10

Equations follow the form $\mathrm{Log}_{10}\, Y = a + b\, \mathrm{Log}_{10}$ (DBH), where a and b are the equation parameters, Y is the dry weight of different components

MSR mean square residuals

CF correction factor (Sprugel 1983)

three decay classes (sound, intermediate, and rotten; Korea Forest Service 2007). The entire coarse woody debris within each chronosequence stand was collected and oven-dried at 65°C to calculate dry biomass density (Mg ha^{-1}). In order to obtain a mean value for coarse woody debris C concentration, samples were mixed across the three decay classes.

The forest floor was sampled by collecting the entire organic material within a 0.09 m^2 quadrat placed at the central point of each chronosequence stand, but also in two replicate quadrats situated within a radius of 5 m. The samples were oven dried separately at 65°C to constant weight. The three samples were mixed and ground to about 4 mm to reduce the size of large pieces. The roots were removed. Then subsamples were ground in a ring grinder to produce a fine powder with a particle size of about 1 µm. This powder was used for C concentration analysis.

Mineral soil samples were taken from a depth up to 50 cm with three replicates in each chronosequence stand. At each sampling point, soil samples were extracted from four depths (0–10, 10–20, 20–30, and 30–50 cm) using a soil corer. Bulk density for each soil depth was measured by weighing the whole sample and drying subsamples at 105°C. After measurement of bulk density samples were sieved with a 2-mm sieve, mixed and analyzed for total soil C concentration.

The C concentrations of all samples (tree and ground vegetation tissue, coarse woody debris, forest floor, and mineral soil) were analyzed by vario Macro Elemental Analyzer (Elementar Analysensysteme GmbH, Germany).

Results and Discussion

Allometric Equations, Biomass, and C Concentrations

The allometric equations that were developed explained more than 95% of the variability in all components of Korean pine (Table 2). The correlation was highest among the various tree components for the total aboveground and total tree biomass ($p<0.0001$). Previous studies also reported similar results and R^2 values over 95% calculated using the same equation for aboveground biomass of Korean pine plantations in central region of Korea (Son et al. 2001; Lee et al. 2009).

Using the logarithmic regression equations, the biomass of tree components was estimated in the five Korean pine stands (Table 3). Aboveground and total tree biomass increased from 1.26 to 1.54 Mg ha^{-1} in the 8-year-old stand to 198.40 and 250.39 54 Mg ha^{-1} in the 51-year-old stand, demonstrating a rapid increase from young age stand to old age stand. The biomass of each tree component increased steadily cross this chronosequence stands. Stem biomass represented 36%, 46%, 57%, 59%, and 74% of aboveground tree biomass in the 8-, 19-, 30-, 35-, and 51-year-old stands, respectively. Although our findings are lacking information from replicated chronosequence studies, results from previous reports showed that aboveground biomass in Korean pine plantation increased with plantation age (Yi 1998; Son et al. 2001; Noh et al. 2005). Yi (1998) sampled an age-sequence of Korean pine plantation forests

Table 3 Biomass (Mg ha^{-2}) in tree, forest ground vegetation and detritus in the 8-, 19-, 30-, 35-, and 51-year-old Korean pine stands

Component	8-year-old	19-year-old	30-year-old	35-year-old	51-year-old
Tree					
Stem wood	0.32	13.25	43.75	83.54	133.16
Stem bark	0.14	2.59	5.67	9.29	12.86
Stem	0.46	15.84	49.41	92.83	146.02
Branch	0.32	11.29	23.01	30.45	24.37
Foliage	0.48	7.15	13.81	34.50	28.01
Aboveground tree	1.26	34.28	86.23	157.78	198.40
Roots	0.28	7.59	17.27	57.35	51.99
Total tree	1.54	41.87	103.50	215.14	250.39
Ground vegetation					
Shrub	0	2.31	2.76	3.44	2.32
Herb	1.61	0.03	0.07	0.32	0.19
Total vegetation	1.61	2.34	2.83	3.76	2.51
Detritus					
Coarse woody debris	0	0	2.95	9.14	0.50
Forest floor	6.83	10.33	15.22	16.68	13.38
Total detritus	6.83	10.33	18.16	25.82	13.88
Total	9.99	54.54	124.49	244.71	266.78

in the Experimental Forest of Kangwon National University, and the aboveground biomass increased from 20.56 Mg ha^{-1} in 9-year-old stand to 130.77 Mg ha^{-1} in 66-year-old stand. Son et al. (2001) reported that aboveground biomass in seven age class stands of Korean pine plantation located in Yangpyeong area increased from 53.6 Mg ha^{-1} in 17-year-old stand to 339.9 Mg ha^{-1} in 74-year-old stand. Biomass distribution pattern among aboveground tree components for Korean pine species was distributed as stem>branch>foliage in general (Lee and Park 1987; Son et al. 2007), however, this study found that foliage biomass was higher than branch biomass in the 8-year-old stand but lower than branch biomass in the 35- and 51-year-old stands, which is mainly due to the large within-stand variability. Aboveground biomass seemed different between stands with the similar ages. For example, Son et al. (2001) reported that aboveground biomass in the 46-year-old stand was 279.7 Mg ha^{-1} while the result was 127.8 Mg ha^{-1} in the same age stand reported by Yi (1998).

The proportion of stem to aboveground tree biomass varied significantly in this chronosequence study. Hence, aboveground tree biomass (especially in young stands) may be considerably underestimated by forest inventories that are normally limited to stem biomass. Moreover, the significant change in the contribution of stem biomass to aboveground and total tree biomass in this Korean pine age-sequence suggests that it is imperative to use age-related biomass expansion factors which are used for estimating tree biomass from stem volume (Noh et al. 2005; Peichl and Arain 2007). Tree root biomass increased steadily over time (Table 3). Tree root to aboveground tree biomass ratio ranged from 0.20 for the 30-year-old stand to 0.36 for the 35-year-old stand, resulting in a mean ratio of 0.26 across the entire age sequence. On average, tree root biomass accounted for more than one quarter of the total tree biomass in this chronosequence study, which highlights the importance of roots in a biomass estimation of the Korean pine stands (Lee et al. 2009; Noh et al. 2005).

Few studies measured ground vegetation (shrub and herb) and coarse woody debris biomass for Korean pine species in Korea (Lee and Park 1987; Yi 1998). Ground vegetation biomass ranged from 1.61 Mg ha^{-1} in the 8-year-old stand to 3.76 Mg ha^{-1} in the 35-year-old stand (Table 3). Coarse woody debris was only found in the 30-, 35-, and 51-year-old stands ranging from 0.50 to 9.14 Mg ha^{-1} in this study. Such a large variation was mainly due to heavy thinning work at the age of 20–30 years for seed production in Korean pine plantations.

Table 4 lists the C concentrations of tree components, ground vegetation, and coarse woody debris in the five Korean pine stands. The C concentration of each ecosystem component was significantly different ($p<0.05$). On average, the highest C concentration was showed in the tree while the lowest in the ground vegetation. Within tree components, higher C concentration was found in the branch than that in the other components, with a mean value of 51.40% across this chronosequence. The C concentrations in the tree roots had the lowest values compared to the other components. The C concentrations of the tree components from the same species may be affected by the analysis means, stand age, pedoclimatic conditions, and origin (Bert and Danjon 2006). For example, Janssens et al. (1999) determined the C concentrations of the branch, stem, and needles of Scots pine in Belgium as 51.6%, 48.9%, and 48.2%, respectively. However, Laiho and Laine (1997) found that the highest C concentration was in the needles (53.8%) of the same species, whereas the lowest was found in the stems (51.8%).

Biomass C

Table 5 provides observed C contents (OC, Mg C ha^{-1}) for tree components, which were determined from the biomass

Table 4 Carbon concentration (%) by ecosystem component for the 8-, 19-, 30-, 35-, and 51-year-old Korean pine stands (stand mean ± within-stand SD)

Component	8-year-old	19-year-old	30-year-old	35-year-old	51-year-old
Stem wood	48.15 ± 0.49^{de}	48.30 ± 0.31^{d}	47.93 ± 0.38^{cd}	49.00 ± 1.91^{cde}	48.17 ± 0.43^{bc}
Stem bark	48.91 ± 0.84^{ce}	49.20 ± 1.13^{d}	49.24 ± 0.78^{de}	49.46 ± 2.45^{cde}	48.88 ± 0.43^{d}
Branch	50.34 ± 0.98^{c}	50.28 ± 0.83^{c}	50.17 ± 0.90^{e}	50.35 ± 1.17^{e}	50.79 ± 2.73^{d}
Foliage	49.66 ± 0.17^{ce}	49.45 ± 0.45^{cd}	50.66 ± 0.96^{de}	49.51 ± 0.65^{cde}	49.62 ± 0.49^{d}
Tree roots	46.20 ± 4.28^{bd}	48.82 ± 0.07^{cd}	50.04 ± 0.41^{de}	48.83 ± 0.24^{cde}	49.26 ± 1.43^{bcd}
Shrub	0	45.94 ± 1.01^{b}	46.31 ± 0.56^{b}	46.45 ± 1.62^{b}	45.55 ± 1.03^{ab}
Herb	39.93 ± 1.65^{a}	41.57 ± 1.40^{a}	41.09 ± 0.05^{a}	42.44 ± 1.42^{a}	43.04 ± 1.37^{a}
Coarse woody debris	0	0	47.93 ± 0.10^{cd}	47.93 ± 0.17^{bcd}	49.03 ± 0.59^{bcd}
Forest floor	45.94 ± 1.10^{b}	45.62 ± 1.35^{b}	46.61 ± 0.99^{bc}	48.05 ± 0.48^{bc}	45.71 ± 2.37^{abc}

Means with different letters within columns are statistically different at $p<0.05$

Table 5 Observed C content (Mg C ha^{-1}) of tree components in the 8-, 19-, 30-, 35-, and 51-year-old Korean pine stands

Tree component	8-year-old		19-year-old		30-year-old		35-year-old		51-year-old	
	OC	ERD[a]	OC	ERD	OC	ERD	OC	ERD	OC	ERD
Stem wood	0.15	−0.04	6.40	−0.04	20.97	−0.04	40.94	−0.02	64.14	−0.04
Stem bark	0.07	−0.02	1.28	−0.02	2.79	−0.02	4.59	−0.01	6.29	−0.02
Stem	0.22	−0.03	7.67	−0.03	23.76	−0.04	45.53	−0.02	70.43	−0.04
Branch	0.16	0.01	5.68	0.01	11.54	0.003	15.33	0.01	12.38	0.02
Foliage	0.24	−0.01	3.54	−0.01	7.00	0.01	17.08	−0.01	13.90	−0.01
Aboveground tree	0.62	−0.01	16.89	−0.02	42.30	−0.02	77.94	−0.01	96.71	−0.03
Tree roots	0.13	−0.08	3.70	−0.02	8.64	0.001	28.01	−0.02	25.61	−0.02
Total tree	0.75	−0.03	20.59	−0.02	50.94	−0.02	105.95	−0.02	122.31	−0.02

[a] ERD (estimation of relative difference)=(observed C amount−predicted C amount)/observed C amount×100. Predicted C content converted from biomass using a factor of 0.5

and mean C concentrations in Tables 3 and 4. The aboveground and total tree biomass C content increased significantly from 0.62 to 0.75 Mg C ha^{-1} in the 8-year-old stand to 96.71 and 122.31 Mg C ha^{-1} in the 51-year-old stand. The observed C content in each tree component increased steadily with stand age. The contribution from stem biomass C to total tree biomass C increased with stand age from 29% for the 8-year-old stand to 58% for the 51-year-old stand. If a factor of 0.5 is used to estimate the predicted C content (PC, Mg C ha^{-1}) from the biomass in this chronosequence study, the relative difference (ERD,%) to compare the uncertainties between the C contents could be estimated simply by the following formula: ERD=(OC−PC)/OC×100. As shown in Table 5, the ERD varied from one tree component to another, depending on the stand age and the section of the tree. Overall, these results clearly show that the predicted C content for the tree components were generally higher than the observed C content, whereas the C content may be underestimated in the branch across this chronosequence if using a C content factor of 0.5. Therefore, the 50% value is an oversimplification when dealing with the C content in forests, even though other values have also been reported (Lamlom and Savidge 2003). For example, Zheng et al. (2008) estimated a mean C concentration of 55.66% for slash pine, 47.94% for Chinese fir, 50.34% for tea oil camellia, 57.72% for masson pine, and 48.02% for blue Japanese oak trees. Lamlom and Savidge (2003) reassessed the C content of North American trees, and reported that the C content of wood in mature stems of hardwood and softwood species ranged from 46.27% to 49.97% and from 47.21% to 55.20%, mainly due to the higher lignin content in conifers.

Table 6 lists a summary of observed C contents stored in the ground vegetation and coarse woody debris biomass. The predicted C content stored in ground vegetation biomass was generally higher than the observed C content if using the C content factor (0.5). The observed C content in the 8-, 19-, 30-, 35-, and 51-year-old stands was 0.64, 1.07, 1.31, 1.73, 1.14 Mg C ha^{-1}, respectively, indicating the significance of ground vegetation as an additional C pool in this pine chronosequence. Ground vegetation biomass C content was generally highly variable compared to other studies in Korea. For example, Yi (1998) estimated ground vegetation biomass C content of 1.38 and 1.67 Mg

Table 6 Observed C content (Mg C ha^{-1}) in forest ground vegetation and coarse woody debris in the 8-, 19-, 30-, 35-, and 51-year-old Korean pine stands

Component	8-year-old		19-year-old		30-year-old		35-year-old		51-year-old	
	OC	ERD[a]	OC	ERD	OC	ERD	OC	ERD	OC	ERD
Shrub	0	0	1.06	−0.09	1.28	−0.08	1.60	−0.08	1.06	−0.10
Herb	0.64	−0.25	0.01	−0.20	0.03	−0.22	0.14	−0.18	0.08	−0.16
Ground vegetation	0.64	−0.25	1.07	−0.09	1.31	−0.08	1.73	−0.08	1.14	−0.10
Coarse woody debris	0	0	0	0	1.41	−0.04	4.34	−0.05	0.24	−0.02
Total	0.64	−0.25	1.07	−0.09	2.72	−0.06	6.08	−0.06	1.38	−0.09

[a] ERD (estimation of relative difference)=(observed C amount−predicted C amount)/observed C amount×100. Predicted C content converted from biomass using a factor of 0.5

Table 7 Above- and belowground ecosystem C pools (Mg C ha^{-1}) in the 8-, 19-, 30-, 35-, and 51-year-old Korean pine stands

Ecosystem component	8-year-old	19-year-old	30-year-old	35-year-old	51-year-old
Aboveground tree	0.62	16.89	42.30	77.94	96.71
Ground vegetation	0.64	1.07	1.31	1.73	1.14
Coarse woody debris	0	0	1.41	4.34	0.24
Forest floor	3.14	4.71	7.09	8.01	6.12
Aboveground ecosystem	4.40	22.67	52.11	92.03	104.20
Tree roots	0.13	3.70	8.64	28.01	25.61
Mineral soil	37.62	13.98	19.21	37.58	32.91
Belowground ecosystem	37.75	17.68	27.85	65.59	58.52
Total ecosystem	42.16	40.36	79.96	157.62	162.72

C ha^{-1} in the 9- and 22-year-old Korean pine plantations while Lee and Park (1987) reported that of 1.03 Mg C ha^{-1} in a 22-year-old stand of this pine plantation. Such high variation may depend on forest management, stand-specific canopy, and soil conditions, which affect light, water, and nutrient availability for the development of ground vegetation (Peichl and Arain 2006).

Biomass C content stored in the coarse woody debris was 1.41, 4.34, and 0.24 Mg C ha^{-1} in the 30-, 35-, and 51-year-old stands (Table 6). Large input following thinning work for seed production might increase coarse woody debris C mass in the two younger stands. However, the pattern of coarse woody debris during stand development was not similar to the U-shaped pattern (Martin et al. 2005; Taylor et al. 2007).

Forest Floor

Using the biomass and mean C concentration of forest floor in Tables 2 and 3, mean C content within forest floor in the five Korean pine stands was 3.14, 4.71, 7.09, 8.01, and 6.12 Mg C ha^{-1}, respectively (Table 7). Forest floor C content in our 8-year-old stand was close to 3.0 Mg C ha^{-1} (using 0.5 to convert biomass C) stored within the forest floor of a 9-year-old Korean pine plantation in the same region, as reported by Yi (1998). Meanwhile, forest floor C content in our 30-year-old stand was slightly greater than 5.4 Mg C ha^{-1} stored in the forest floor of a same age *Pinus strobus* plantation (Peichl and Arain 2006). Although forest floor C content increased between the 8- and 35-year-old stand, our results suggests that there was no further age-related increase beyond the stand age of 35 years. Our results were not in accordance with the results from Pregitzer and Euskirchen (2004), who reported that the forest floor C content in temperate forests increases with stand age. High spatial variation that exists in forest floor organic matter may help to understand why no age-related trend in this chronosequence. Forest floor organic matter has been reported to be highly susceptible to disturbances and variations in stand treatment, litter input, and decomposition rate (Yanai et al. 2000; Johnson et al. 2003; Pregitzer and Euskirchen 2004; Peichl and Arain 2006; Taylor et al. 2007). Our findings suggest that forest floor C content is an important variable in the aboveground C budget due to its size and variability.

Mineral Soil C

C concentrations stored in the mineral soil for each stand decreased with increasing soil depth classes from approximately 1.95% at 0–10 cm depth to 0.42% at 30–50 cm depth (data not shown). Mean total C content of mineral soil from 0 cm to 50 cm depth in the 8-, 19-, 30-, 35-, and 51-year-old stands was 37.62, 13.98, 19.21, 37.58, and 32.91 Mg C ha^{-1}, respectively. The mineral soil C content within 0–10 cm was much greater when compared to the C content in other soil depths. More than 50% of mineral soil C was sequestrated within the upper 20 cm of each stand (Fig. 1). The mean total C content of mineral soil across this pine chronosequence was much lower when compared to 82.3 Mg C ha^{-1} stored in the overall soil of temperate forests across all age classes described by Pregitzer and Euskirchen (2004).

Recent studies examined the change in soil C content following forest establishment from abandoned or former agricultural lands. Although some studies reported no significant increase in mineral soil C content with stand age (e.g., Paul et al. 2002; Farley et al. 2004; Peltoniemi et al. 2004; Peichl and Arain 2006), other studies indicate an increasing soil C content in the early decades after afforestation (e.g., Hooker and Compton 2003; Pregitzer and Euskirchen 2004; Lemma et al. 2006; Grünzweig et al. 2007). In this Korean pine chronosequence study, the observed soil C content appeared to decline initially after establishing Korean pine plantations and recover by the stand age of 35 years. Our data trend was very close to the

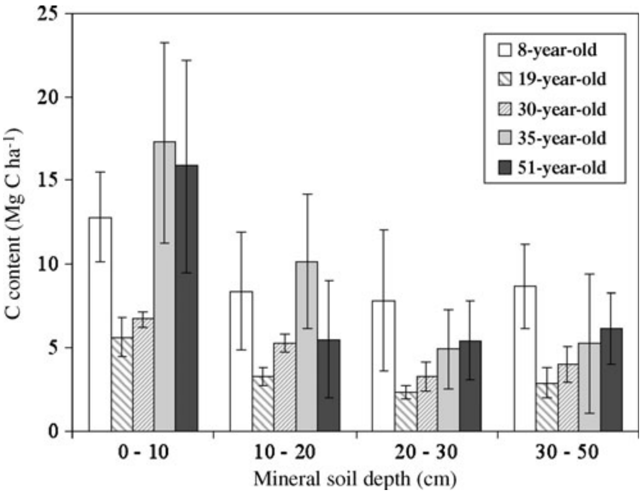

Fig. 1 C content of the different mineral soil depth in the five Korean pine stands (*error bars* within-stand SD)

results described by Paul et al. (2002), who reported that the mineral soil C content decreases initially after establishing plantations on arable lands and recovers by the age of 30. In contrast, Tang et al. (2009) reported a continuous increase in total soil C content over 10-year-old aspen stands. These contradictory reports may result from a range of factors that are responsible for restoring the soil organic C stocks after afforestation, such as previous land use, forest type, tree species planted, soil properties, pre-planting disturbance, and climate, all of which may overshadow the effect of the stand age on the soil C content (Paul et al. 2002; Pregitzer and Euskirchen 2004; Sun et al. 2004; Peichl and Arain 2006; Laganiere et al. 2010). However, our results suggest that mineral soil as a large C pool is an important component of the forest ecosystem C budget.

Ecosystem C Pools

Table 7 summarizes the C pools of the main ecosystem components in the five Korean pine stands. The aboveground and total ecosystem C pools increased with stand age. Due to the limited information on replicating age-sequence study, our results do not represent the growth patterns of a fixed stand over time. The ratio of belowground to aboveground ecosystem C was 8.57, 0.78, 0.53, 0.71, and 0.56 for the 8-, 19-, 30-, 35-, and 51-year-old stands, respectively, showing a rapid decline from the 8- to the 19-year-old stand. This rapid decline might result from the fast C accumulation in aboveground tree biomass combined with relatively mineral soil C decrease in the 19-year-old stand. With gradual recovery of soil C from 19- to 35-year-old stand, the ratio of belowground to aboveground ecosystem C in the19-year-old stand was very close to 0.71 in the 35-year-old stand, which suggests that C accumulation rate between aboveground and belowground ecosystem C is similar during this soil C recovery phase of stand development.

Figure 2 shows the relative contribution of each individual C pool to the total ecosystem C content in this chronosequence study. Aboveground tree and mineral soil were two dominant C pools in our age sequence stands. Aboveground tree biomass became the major C pool in the four older stands, increasing from 42% in the 19-year-old stand to 59% in the 51-year-old stand, whereas mineral soil was the dominant C pool in the youngest stand (89% in the 8-year-old stand). The contribution of ground vegetation plus forest floor C pools ranged from 4% in the 51-year-old stand to 14% in the 19-year-old stand, with a mean contribution of 9% across the entire chronosequence study. The contribution of C content in tree root biomass to total ecosystem C ranged from 0.3% in the 8-year-old stand to 16% in the 51-year-old stand. If the C accumulation trends in tree root biomass observed in our chronosequence study continue, the contribution of tree root C may further increase with stand age.

Although the C content in aboveground tree biomass increased with stand age, the contribution of belowground C (tree roots plus mineral soil) to total ecosystem C content was relatively unstable. For example, the contribution of belowground C in our chronosequence seemed to appear fairly variable with a range of 35–90% while the results observed in an age sequence of white pine plantation showed that the contribution of belowground C decreased with increasing stand age, as reported by Peichl and Arain (2006). Martin et al. (2005) also reported slight variation (45–50%) in the contribution from belowground C content stored in the four different-aged boreal mixedwood stands.

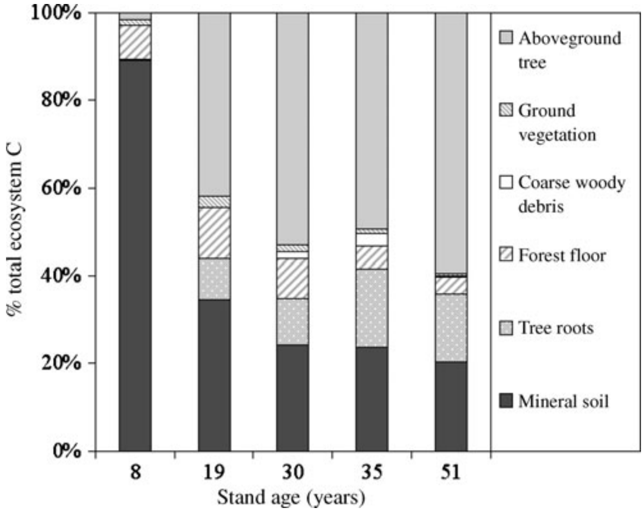

Fig. 2 C content of total aboveground tree biomass, forest floor, tree roots, and mineral soil in the five Korean pine stands expressed as a percent

Different comparisons suggest that total ecosystem C content may be dependent on the belowground C pool due to the instability, whereas aboveground tree biomass may make major contribution to total ecosystem C development over time. Therefore, further chronosequence studies will be needed to confirm the effect of the stand age on the development of the ecosystem C pool.

Conclusions

The aboveground and total tree biomass increased with stand age, particularly the biomass within tree stem which comprised the main proportion of the aboveground and total tree biomass with increasing stand age. The highest C concentration was found in tree branch while the lowest C concentration was observed in the ground vegetation. The observed C contents for tree components, ground vegetation, and coarse woody debris in this chronosequence study were generally lower than the predicted C contents estimated from a biomass C factor of 0.5. Hence, care should be taken when using a 50% value to estimate the C content from biomass in forests. Forest floor C content increased considerably between the 8- and 35-year-old stand. However, no further age-related increase observed in the 51-year-old stand, indicating no clear age-effect on the forest floor C content. The total mineral soil C content appeared to decline initially after establishing Korean pine plantations and recover by the stand age of 35 years, and approximately 50% of total mineral soil C content was sequestrated within the upper 20 cm of each stand. Although the aboveground tree biomass C showed considerable accumulation with age, the contribution of belowground C to the total ecosystem C content showed substantial variations. Further evidence of the effect of stand age on ecosystem C pool development will be needed from replicated chronosequence studies.

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