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Carbon Storage of Pure and Mixed Pine-Deciduous Oak Forests in Gwangneung, Central Korea

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ABSTRACT: This study was conducted to determine the carbon (C) contents in different mixed stands of *P. densiflora* and deciduous oak species in Gwangneung, central Korea. Five mixed stands with different ratios of *P. densiflora* and deciduous oak species were chosen based on the basal area of all trees ≥ 5cm DBH: pure *P. densiflora* (P100D0), 70% *P. densiflora* + 30% deciduous oak species (P70D30), 44% *P. densiflora* + 56% deciduous oak species (P50D50), 37% *P. densiflora* + 63% deciduous oak species (P40D60), and 10% *P. densiflora* + 90% deciduous oak species (P10D90). Total C contents in the overstory (aboveground and belowground) vegetation were higher in the mixed stands (P70D30, P50D50, P40D60) than in the pure stands (P100D0, P10D90). Moreover, except for P40D60, C contents of forest floor (litter and coarse woody debris) were larger in the mixed stands (P70D30, P50D50) than in the pure stands. However, total soil C contents up to 30cm depth were highest in the pure deciduous oak stand than in the pure *P. densiflora* stand and mixed stands. Total ecosystem C contents (Mg/ha) were 163.3 for P100D0, 152.3 for P70D30, 188.8 for P50D50, 160.2 for P40D60, and 150.4 for P10D90, respectively. These differences in total ecosystem C contents among the different mixed stands for *P. densiflora* and deciduous oak species within the study stands were attributed by the differences in vegetation development and forest management practices. Among the five study stands, the total ecosystem C contents were maximized in the 1:1 mixed ratio of *P. densiflora* and deciduous oak species (P50D50).

Key words: biomass, carbon storage, coarse woody debris, litter, *Pinus densiflora*, *Quercus* species, soil, vegetation

INTRODUCTION

Forests comprise the major terrestrial carbon (C) pool and play an important role in temporary and permanent C storage (Gower 2003). Due to the effects of climate change resulting from increased CO_2 concentrations, researchers have studied the measurement of C sink and source and the estimation of C storage in specific ecosystem areas (McCarl and Schneider 2001). Generally, many of the forest areas are composed of mixed trees and the composition varied from pure to mixed species. This change might be associated with changes in C pool in total forest ecosystems (Welke and Hope 2005), which is highly affected by alterations of ecological properties (Prescott and Preston 1994, Thomas and Prescott 2000) and stand characteristics (Lee and Park 1986).

According to the Korea Forest Service (2008), there are two most dominant tree species in Korea: *Pinus densiflora* and *Quercus* species. *P. densiflora* occurs naturally and occupies approximately 55% of the total coniferous forests and 60% of the total wood stocking. *Quercus* species are the most dominant tree species in the natural deciduous and mixed forests. The proportion of mixed forests is approximately 29% of the total forest area (Korea Forest Service 2008) and most mixed forests in Korea are distributed with *P. densiflora* and *Quercus* species and their composition is showed that an intensive interspecific competition exists between older *P. densiflora* and *Quercus* species (Yun et al. 2001). Many studies have examined the C storage of pure stands in Korea (Son et al. 2004, Kim et al. 2009, Son 2009). However, little is known about the ecological characteristics in mixed forests of *P. densiflora* and *Quercus* species (Lee and Park 1986) and C sequestrations in mixed forests in the region (Park and Moon 1999). To understand C storage in mixed forests, the

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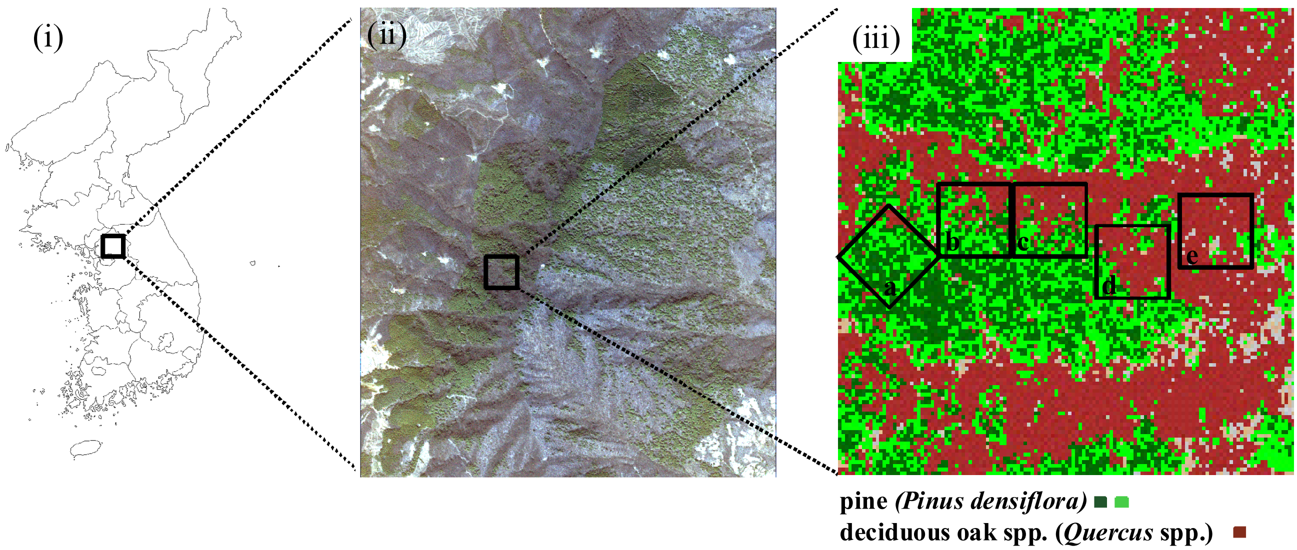

Fig. 1. Study site in Gwangneung, central Korea. The last figure showed the canopy species composition based on the supervised classification using ERDAS Imagine 9.0 and the five squares indicated the study stands; P100D0 (a), P70D30 (b), P50D50 (c), P40D60 (d), and P10D90 (e).

study stands must comprise mixed forests of *P. densiflora* and *Quercus* species.

The objectives of this study are (i) to examine the changes in biomass and C sequestration in vegetation (overstory and understory), forest floor (litter and coarse woody debris (CWD)) and soils with varying mixed ratios of *P. densiflora* and deciduous oak stands, and (ii) to investigate any relationship between biomass, C contents and stand characteristics (diameter at breast height (DBH), number of trees, basal area, etc.) in Gwangneung, central Korea.

MATERIALS AND METHODS

Study Site and Stand Description

The study site was located at Gwangneung Experimental Forest in central Korea (37° 33′ N, 128° 18′ E, elevation 337-348 m a.s.l.) (Fig. 1). The average annual temperature and precipitation over the 30-year period 1971-2000 were 10.8°C and 1300.7 mm, respectively. Moreover, 70% of the annual precipitation falls between June and August (http://www.kma.go.kr). The soils of Gwangneung Experimental Forest were classified as brown forest soils (mostly Inceptisols) developed from granitic parent material (Korea Forest Service 2004).

To examine the vegetation biomass and C contents in the total ecosystem, pure and mixed stands were selected. Satellite imagery (KOMSAT-2) taken in May 2005 was analyzed under the supervised classification (ERDAS Imagine 9.0) based on canopy area, and 15 candidate stands were selected. In late April 2008, a field survey was conducted with the satellite imagery data. Species and DBH for every tree with ≥ 5 cm DBH were recorded. Finally, five study stands (40 m × 40 m) were selected [pure *P. densiflora* (P100D0), 70% *P. densiflora* + 30% deciduous oak species (P70D30), 44% *P. densiflora* + 56% deciduous oak species (P50D50), 37% *P. densiflora* + 63% deciduous oak species (P40D60), and 10% *P. densiflora* + 90% deciduous oak species (P10D90)] based on basal area (m^2/ha) (Fig. 1).

The five study stands were dominated by *P. densiflora* and *Quercus* species. The pure *P. densiflora* stand was partially managed by irregular thinning practices for conserving and enhancing its growth. *Quercus* species (*Q. serrata*, *Q. variabilis*, and *Q. mongolica*) dominated in the deciduous mixed stands, while *Acer pseudo-sieboldianum*, *Styrax obassia*, *Carpinus laxiflora*, *Rhus javanica* var. *roxburghii*, *Kalopanax pictus* and *Prunus sargentii* occupied < 5% of the basal area. *Oplismenus undulatifolius* and *Disporum smilacinum* were the main understory vegetation species. The five study stands exhibited similar parent rocks, soil texture, slope and altitude. However, the pure *P. densiflora* stand was 70 m far from the other study stands (Table 1). Mean ages of *P. densiflora* and deciduous oak species were 50 to 60-year-old and 40 to 50-year-old, respectively. Mean DBH in the five study stands varied significantly from 27.5 to 40.6 cm and stand density (tree/ha) ranged from 238 to 488.

Table 1. Characteristics of study stands. Numbers in parentheses denote the standard error of mean. Significant differences between tree species in each study stand are printed in small letters at P = 0.05 level.

Stand type	Dominant species	Altitude (m)	Slope (°)	Aspect (°)	Mean age (year)	Mean DBH (cm)	Basal area (m^2/ha)	Density (tree/ha)
P100D0	*P. densiflora*	341	20	NE 40	50	40.56	46.0	344
	-				-	-	-	-
P70D30	*P. densiflora*	400	20	ES 150	52	39.26(2.34)[a]	18.5	138
	Q. mongolica *Q. variabilis*				42	26.11(1.42)[b]	7.8	138
P50D50	*P. densiflora*	348	23	ES 150	51	39.78(1.60)	16.8	138
	Q. mongolica *Q. serrata*				45	32.49(3.35)	13.2	131
P40D60	*P. densiflora*	412	22	ES 150	56	34.88(2.86)[a]	9.8	56
	Q. mogolica *Q. serrata* *Q. variabilis*				48	19.00(1.74)[b]	17.0	150
P10D90	*P. densiflora*	415	18	ES 150	60	27.02(2.27)	3.4	56
	Q. serrata				50	27.58(0.90)	23.3	364

Sampling and Analysis

In late July and early August 2008, samples for overstory and understory vegetation, forest floor and soils were collected. Samples of foliage and branch for *P. densiflora*, *Quercus* species and other co-dominant overstory vegetation were collected from trees based on species and DBH distribution in each stand. Samples were collected from the same position of individual tree (mid-crown, southern aspect growing branches). Stemwood, stembark and roots were not sampled because destructive harvesting of trees had not been performed. Samples of understory vegetation were also collected from five 1 m × 1 m subplots within each stand. Those understory vegetation samples were separated into four categories: shrub, herb, aboveground and belowground components. However, samples were not classified into individual species because they were too small to measure of C concentration of each species. In addition, litter samples were collected from five 30 cm × 30 cm quadrats within each stand. Five soil samples were collected from each stand using a soil core (5.5 cm inner diameter, 50 cm length) to depths of 0-10 cm, 10-20 cm and 20-30 cm. All CWDs with diameter larger than 5cm and length longer than 1m were measured for weight, diameter (top, mid, and end) and length in each study stand (Korea Forest Research Institute 2007). CWDs were classified into the three decay classes derived from previous studies (Lee et al. 1997, Goodburn and Lorimer 1998, Pedlar et al. 2002).

All plant samples were oven-dried and grounded. Soil samples were air-dried and sieved with 2-mm sieves (US standard No. 10) to separate out the coarse fraction (larger than 2 mm). The remaining fine fraction of sample was grounded using a ball mill. C concentrations in vegetation, litter, CWD and soils were analyzed by a vario Macro Elemental Analyzer (Elementar Analysensysteme GmbH, Germany). C contents in vegetation, litter and CWD were calculated by multiplying the C concentration by dry weight. C contents in *P. densiflora* were calculated by multiplying the biomass by 0.51 for stemwood, 0.53 for stembark and 0.51 for roots (Korea Forest Research Institute, unpublished data). Meanwhile, C contents in deciduous oak species of stemwood, stembark and roots were calculated by multiplying the biomass by 0.5, which is a representative C concentration for all tree components suggested by IPCC (2001). Soil C contents were obtained by multiplying C concentration by bulk density and by volume of each soil depth.

Aboveground and belowground biomass of the overstory vegetation were estimated using allometric equation with one independent variable (DBH) (Table 2). The allometric equations of *P. densiflora* (Park and Lee 1990), *Q. variabilis* and *Q. mongolica* (Son et al. 2007) previously developed in the central part of Korea were used. The equation of *Q. serrata* (Park and Lee 2002) developed in northern part of Korea was also applied. The equations of other co-dominant species were based on mixed forest allometric equations (Kim and Kim 1986). As allometric equations do not generally

Table 2. Regressions of above- and below ground tree component biomass in four types of tree species.

Component	*Pinus densiflora* *				*Quercus serrata* **			
	a	b	r^2	*E*	a	b	r^2	*E*
Stem wood	2.062	2.157	0.998	1.065	2.123	2.169	0.980	0.105
Stem bark	1.437	1.945	0.977	1.239	1.919	1.760	0.960	0.141
Branch	1.200	2.392	0.967	1.231	0.725	2.934	0.930	0.309
Foliage	1.305	2.008	0.950	1.333	0.909	2.212	0.950	0.200
Aboveground total	2.269	2.152	0.996	1.099	-	-	-	-
Tree total	2.523	1.990	0.996	1.100	-	-	-	-
Component	*Quercus variabilis* ***				*Quercus mongolica* ***			
	a	b	r^2	*E*	a	b	r^2	*E*
Stem wood	2.148	2.455	0.973	1.140	2.389	2.110	0.966	1.211
Stem bark	1.864	2.115	0.889	1.273	2.122	1.718	0.940	1.234
Branch	-0.093	3.671	0.880	1.550	0.715	3.746	0.964	1.422
Foliage	-0.012	2.950	0.729	1.791	0.855	2.331	0.951	1.293
Aboveground total	2.234	2.518	0.988	1.095	2.340	2.390	0.995	1.082
Component	mixed forest (DBH 5-20 cm) ****				mixed forest (DBH >20 cm) ****			
	a	b	r^2	*E*	a	b	r^2	*E*
Stem wood	0.956	1.514	0.930	-	0.643	2.462	-	-
Branch	1.277	0.003	0.852	-	0.726	1.580	-	-
Foliage	0.857	0.469	0.490	-	0.691	0.119	-	-

Equations follow the form log Y = a + b$\log_{10}$ X, where Y is component dry mass (g); X is diameter at breast height (cm); a and b, regression coefficients; r^2, coefficient determination; E, estimate of relative error.
*: Park et al. 1989
**: Park and Lee 2002
***: Son et al. 2007
****: Kim and Kim 1986

contain information about the belowground biomass, the belowground biomass was estimated by multiplying the total aboveground biomass by 0.20 for *P. densiflora*, 0.18 for *Q. mongolica*, 0.25 for *Q. variabilis* and 0.12 for other deciduous species (Son et al. 2007, Korea Forest Research Institute, unpublished data).

Statistical analysis

The C concentrations in the overstory and understory vegetation, litter, CWD, and soils in each depth among the different mixed ratio stands were analyzed with a General Linear Model procedure. Duncan test ($P < 0.05$) was used to separate the means. The relationships between the stand characteristics (DBH and stand density) and biomass, C concentrations and contents of each stand were analyzed by Pearson's correlation analysis, while the correlation results were analyzed with regression analysis. All statistical analysis were conducted using SAS 9.1 software (SAS Institute Inc. USA).

RESULTS AND DISCUSSION

Biomass and Carbon Contents in Vegetation

Total overstory biomass (Mg/ha) was 225.9 for P100D0, 207.8 for P70D30, 274.4 for P50D50, 233.6 for P40D60 and 183.7 for P10D90 (Table 3). The overstory biomass of pure *P. densiflora* stand (P100D0) was lower than that of the 30 to 40-year-old pure *P. densiflora* stands which have similar DBH ranges in northern Korea (205.4 Mg/ha) (Park and Lee 1990). However, the current study value (225.9 Mg/ha) was higher than that of a 70 to 80-year-old pure *P. densiflora* stand (156.6 Mg/ha) in the same region (stand density: 375 tree/ha, mean DBH: 34.7 cm) (Son 2009). Total overstory biomass of deciduous oak stand (P10D90) was lower than that in another deciduous oak stands which were the 50-year-old *Q. mongolica* stand (438.0 Mg/ha), the 49-year-old *Q. variabilis* stand (279.9 Mg/ha) in Kangwon (Park et al. 2003), and the 45-year-old *Q. variabilis* stand (207.6 Mg/ha) in Kyungbuk (Park and Lee 2001). However, it was larger than the 54-year-old *Q. variabilis* stand (71.4 Mg/ha) in Kangwon and the 41-

Table 3. Biomass (Mg/ha) in vegetation (over- and understory) and forest floor (litter and CWD) in different mixed ratio stands.

Components		P100D0	P70D30	P50D50	P40D60	P10D90
Vegetation						
Overstory						
P. densiflora						
Stemwood		121.8	49.3	48.3	25.8	8.5
Stembark		13.0	5.2	5.1	2.8	1.0
Branch		40.5	16.6	16.2	8.5	2.6
Foliage		12.2	4.9	4.8	2.6	0.9
Root		38.5	15.6	14.9	7.9	2.6
Subtotal biomass		225.9	91.5	89.3	47.6	15.6
Deciduous oak species						
Stemwood		-	47.4	67.1	79.6	77.6
Stembark		-	7.4	9.0	14.0	12.1
Branch		-	40.8	72.7	55.2	46.0
Foliage		-	2.3	4.0	4.4	5.2
Root		-	18.9	32.3	32.8	27.2
Subtotal biomass		-	116.3	185.1	186.0	168.1
Understory						
Shrub	Aboveground	0.34	0.07	0.42	0.14	0.14
	Belowground	0.38	0.30	0.27	0.22	0.18
Herb	Aboveground	0.21	0.28	0.24	0.33	-
	Belowground	0.13	0.27	0.37	0.30	0.17
Understory total biomass		1.06	0.92	1.30	0.99	0.49
Vegetation total biomass		227.0	208.7	275.7	234.6	184.2
Forest floor						
Litter		14.2	16.8	14.7	14.0	17.4
CWD		6.4	7.5	8.1	3.7	2.6
Subtotal biomass		20.6	24.3	22.8	17.7	20.0
Ecosystem total biomass		247.6	233.0	298.5	252.3	204.2

year-old *Q. variabilis* stand (91.3 Mg/ha) in Chungchung (Park and Lee 2001). Total overstory biomass in the mixed stands (P70D30, P50D50 and P40D60) was higher than those in the pure *P. densiflora* and deciduous oak stands (P100D0 and P10D90). Similar results were also presented among various tree species in different climate zones. For example, in boreal forests, Betula species and *Picea abies* mixed forests exhibited higher overstory biomass than pure *Betula* species and *P. abies* stands (e.g., Bergqvist 1999, Fahlvik et al. 2005). Also in dry tropics, mixed plantation plots for 13 native plants had higher productivity than pure plantation plots (Piotto et al. 2004).

The total understory biomass (Mg/ha) was 1.06 for P100D0, 0.92 for P70D30, 1.30 for P50D50, 0.99 for P40D60, and 0.49 for P10D90 (Table 3). Understory vegetation occupied 0.3-0.6% of the overstory biomass, and the proportion was lower than that reported by Son et al. (2004) for the pure *Quercus* species stand.

Carbon concentrations of overstory vegetation in branch and foliage did not vary significantly among the study stands. However, it differed significantly between *P. densiflora* and deciduous oak species (51.3 and 51.8% for *P. densiflora* and 49.9 and 49.2% for deciduous species) due to the differences in the lignin contents of the two dominant species. According to Lamlom and Savidge (2003), C concentrations in conifers were higher than that in deciduous oak species and 19 coniferous species in Canada, because C in conifers had a higher lignin contents (ca 30%, versus ca 20% for deciduous species). C concentrations of understory vegetation differed significantly among the study stands and it differed significantly between the aboveground and belowground components among the five study stands (Table 4). Although the species composition of understory vegetation was similar, however, the dominant shrub species was different. Especially, the stands of P40D60 and P10D90 which exhibited significant difference in C concentrations of understory vegetation among the study stands were dominated by *Acer pseudo-sieboldianum* and *Q. mongolica*. C concentrations in the shrub components (aboveground and belowground components) were significantly higher than those in the herbs (44.4-50.0 for shrub vs. 38.1-45.3%

Table 4. C concentrations (%) of understory vegetation and litter in study stands. Numbers in parentheses denote the standard error of mean. The small letters indicate significant differences among the study stands at P = 0.05 level (n = 5).

	P100D0	P70D30	P50D50	P40D60	P10D90
Understory					
Shrub					
Aboveground	45.6(0.32)[bc]	47.4(0.33)[ab]	49.0(0.88)[a]	44.8(0.51)[c]	44.4(0.13)[c]
Belowground	46.3(0.95)[b]	45.5(1.53)[b]	48.1(0.90)[ab]	50.0(0.49)[a]	47.6(0.82)[ab]
Herb					
Aboveground	43.8(0.39)[a]	41.2(0.89)[b]	44.3(0.36)[a]	42.3(0.75)[ab]	-
Belowground	45.3(0.62)[a]	38.1(3.68)[a]	43.7(0.26)[a]	43.8(0.71)[a]	45.1(0.73)[b]
Litter	46.6(0.32)[a]	45.2(0.31)[ab]	45.7(0.64)[ab]	44.1(0.64)[ab]	44.7(1.11)[b]

for herb).

Total C contents in the overstory and understory vegetation (Mg/ha) were 115.7 and 0.53 for P100D0, 105.3 and 0.11 for P70D30, 138.2 and 0.64 for P50D50, 117.4 and 0.36 for P40D60, and 91.7 and 0.26 for P10D90, respectively. Total C contents in the overstory vegetation were higher in the mixed stands than those in the pure stands. In Japan, stand biomass and annual stem-increment in *P. densiflora* and *Chamaecyparis obtusa* tended to be larger in mixed stands than in pure *C. obtusa* stands (Kawahara and Yamamoto 1982), because *C. obtusa* can survive at lower stratum where a substantial light is transmitted under the shade intolerant tree species such as *P. densiflora*. The same results were also observed in early studies involved plantations in the late 19th century in Germany and Switzerland (Assmann 1970). Two mixed forests of *Larix decidua* with *Fagus sylvatica* and of *Picea abies* with *Abies alba* formed stratified canopies, and produced greater stem biomass than either monoculture of those species. In the Czech Republic (Poleno 1981) and Perm region of Russia (Prokop'ev 1976), two plantation studies of *Pinus sylvestris* and *P. abies* produced stratified stands with the mixed forest having greater yields than the monoculture forest of those species.

Especially, total C contents in the overstory vegetation in P50D50 were the highest indicating that vegetation type of P50D50 might be highly unique for the aspects of C storage among pure and mixed forest stands. The proportion of tree species in mixed stands may effect on stand development (Kelty 2006), and the relationship between height growth and degree of shade tolerance plays an important role in mixed forests (Menalled et al. 1998). When two species are distributed with a 1:1 ratio, the upper canopy species may suppress the lower canopy species that have to grow more efficiently to make denser canopy layers (Paker and Schneider 1975). From Table 1, mean DBH differed significantly between the two species in the mixed stands, except for P50D50. The result indicated that a 1:1 mixed stand is a more efficient structure for radial growth among deciduous oak species. The same result was reported in Australia where 1:1 mixed stands of *Eucalyptus globules* and *Acacia mearnsii* showed larger overstory vegetation productivity than other mixed stands (100:0, 75:25, 25:75, and 0:100), because the stem volume and tree height were highest in this 1:1 mixture (Bauhus et al. 2000).

Carbon Contents in Litter, CWD and Soils

The litter mass (Mg/ha) was largest in P10D90: 14.2 for P100D0, 16.8 for P70D30, 14.7 for P50D50, 14.0 for P40D60, and 17.4 for P10D90 (Table 3). Comparing the pure *P. densiflora* (P100D0) and deciduous oak (P10D90) stand, the litter mass was higher in P10D90 than in P100D0. However, there was no relationship between litter mass and tree species composition or stand density of *P. densiflora* or deciduous oak species.

Coarse woody debris mass (Mg/ha) was largest in P50D50: 6.4 for P100D0, 7.5 for P70D30, 8.1 for P50D50, 3.7 for P40D60 and 2.6 for P10D90 (Table 3). From P100D0 to P50D0, CWD mass continuously increased with increasing proportion of deciduous oak species, however, from P50D50 to P10D90, CWD mass decreased. There was not observed statistical significant between CWD mass and the proportion of *P. densiflora* (P = 0.23) and deciduous oak species. (P = 0.23). However, several studies reported that the CWD mass in mature forests is proportional to the living tree biomass (Pedlar et al. 2002, Siitonen et al. 2000). According to Pedlar et al. (2002), in Canada, CWD mass was higher in mixed stands than in pure stands of three mature coniferous, mixed and deciduous forests. Instead of the significant relationship between CWD mass and mixed proportion in study stands, we found a positive correlation between CWD mass and mean DBH (cm) of *P. densiflora* (R = 0.91, P <

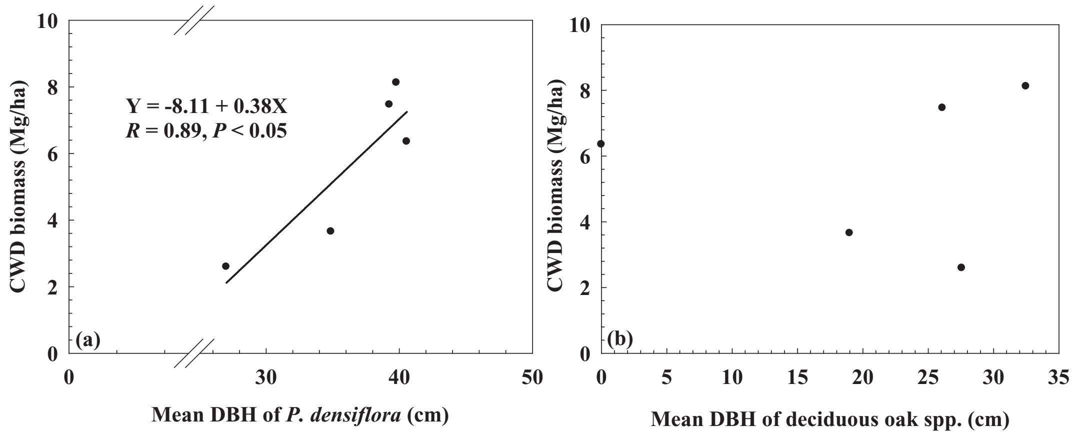

Fig. 2. Relationships between CWD mass (Mg/ha) and mean DBH (cm) of *P. densiflora* (a) and deciduous oak species (b) in the study stands.

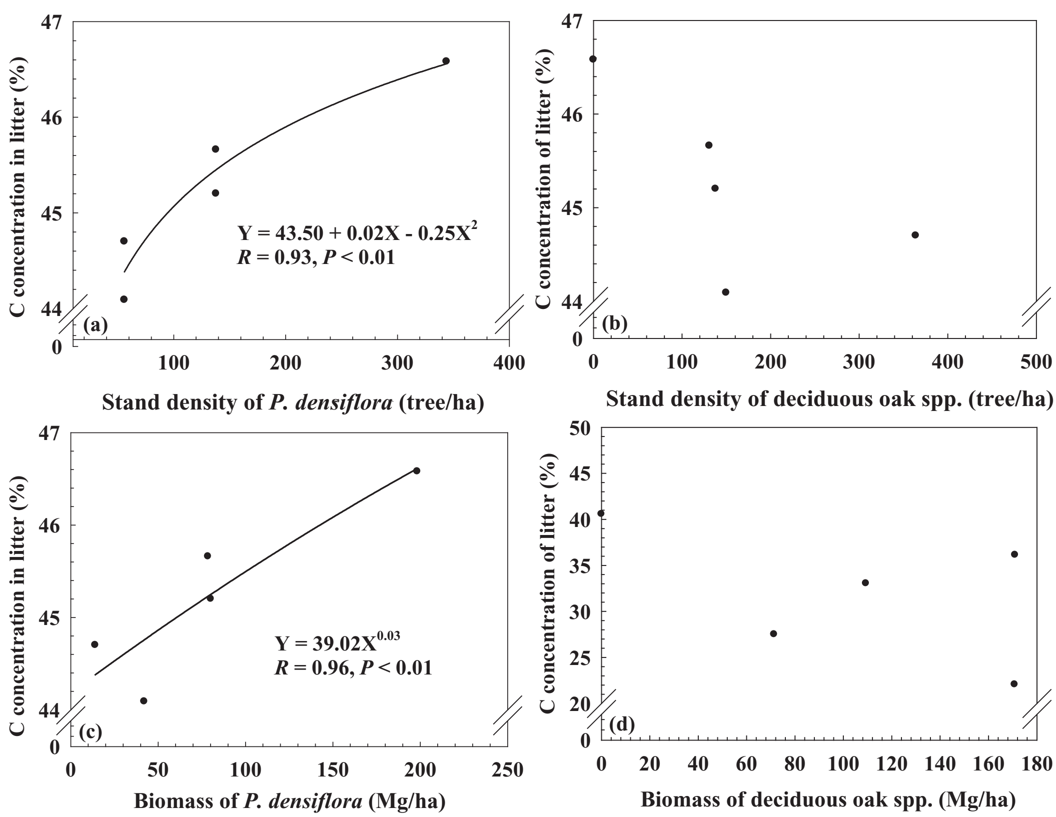

Fig. 3. Relationships between C concentration in litter (%) and stand density (tree/ha) of *P. densiflora* (a), deciduous oak species (b), biomass of *P. densiflora* (Mg/ha) (c), and deciduous oak species (d) in the study stands.

0.05) (Fig. 2), but no significant correlation between CWD mass and overstory vegetation biomass ($P = 0.25$). Our result suggested that CWD mass was highly affected by the tree size of *P. densiflora*.

Mean litter C concentrations differed significantly among the stands, varying from 44.09 to 46.58% (Table 4). We found a significant positive correlation between C concentration in the litter and stand density of *P. densiflora* ($R = 0.93$, $P < 0.01$) (Fig. 3a) and biomass of *P. densiflora* ($R = 0.96$, $P < 0.01$) (Fig. 3c). However, there was no significant correlation between C concentration and stand density of deciduous oak species. ($P = 0.23$) (Fig. 3b) and biomass of deciduous oak species ($P = 0.12$) (Fig. 3d). These results suggested that litter C concentrations might

Table 5. Soil C concentration (%) and content (Mg/ha) in different mixed ratio stands. Numbers in parentheses denote the standard error of mean. The first letters indicate differences between study stands within the same soil depth, and the second letters indicate differences among soil depths within a study stand.

Depth	P100D0		P70D30		P50D50		P40D60		P10D90	
	Conc. (%)	Cont. (Mg/ha)	Conc. (%)	Cont. (Mg/ha)	Conc. (%)	Cont. (Mg/ha)	Conc. (%)	Cont. (Mg/ha)	Conc. (%)	Cont. (Mg/ha)
0-10 cm	6.23^{aA} (5.05)	13.0 ^{aA} (3.65)	3.10^{aA} (2.65)	13.9^{aA} (3.75)	4.81^{aA} (5.27)	18.0^{aA} (2.50)	3.30^{aA} (0.85)	14.9^{aA} (2.43)	4.07^{aA} (1.07)	18.9^{aA} (5.19)
10-20 cm	1.59^{aB} (1.32)	18.6^{aA} (5.13)	1.43^{aAB} (0.79)	11.7^{aA} (0.86)	2.14^{aA} (2.54)	14.7^{aA} (2.52)	1.47^{aB} (0.48)	15.6^{aA} (1.99)	1.58^{aB} (0.58)	21.0^{aA} (2.79)
20-30 cm	0.57^{aB} (0.30)	5.7^{aA} (2.27)	0.82^{aB} (0.45)	10.0^{aA} (2.88)	2.11^{aA} (3.01)	6.4^{aB} (2.29)	0.82^{aB} (0.74)	7.1^{aA} (4.13)	1.18^{aB} (0.61)	9.3^{aA} (2.88)
Total C content		37.3^{a} (5.03)		35.6^{a} (5.52)		39.1^{a} (2.76)		37.6^{a} (2.48)		49.2^{b} (9.47)

be influenced by *P. densiflora* tree composition among the study stands. Berg and McClaughetry (2008) also reported that plant species affected the chemical composition of the litter and that this represents a major factor affecting litter formation. Thus, we assumed that litter C concentrations were influenced by the tree species in the stands. Based on their assessment of 41 North American species, Lamlom and Savidge (2003) claimed that C concentrations in coniferous species were higher than those in deciduous oak species. Our results presented a similar pattern in which the litter C concentrations decreased with decreasing portion of *P. densiflora* among the stands.

CWD C concentrations significantly decreased with decay class for *P. densiflora* (55.36% for class I, 53.01% for class II, and 51.53% for class III). However, there was no significant trend for deciduous oak species (50.44% for class II and 49.95% for class III). In general, the CWD C concentrations for *P. densiflora* and deciduous oak species were slightly higher than the widely recognized value of 50% by IPCC (2001). Soil C concentrations varied from 3.10 to 6.23% at 0-10 cm, 1.43 to 2.14% at 10-20 cm, and 0.57 to 2.11% at 20-30 cm (Table 5). Except for P50D50, the soil C concentrations in the other stands decreased significantly with increasing soil depths. Comparing two different pure study stands (P100D0, P10D90), soil C concentrations in the pure *P. densiflora* stand, except for the depth of 20-30 cm, were higher than in the pure deciduous oak stand. This has been observed in the previous studies of *P. densiflora* and *Q. variabilis* stands (Choi et al. 2006, Jeon et al. 2007). The differences of soil C concentration among those different stands might be influenced by the differences of litter qualities and tree composition (Choi et al. 2006, Shin et al. 2006). However, our results showed no significant difference in variations among the stands at the same soil depth (Table 5).

C contents (Mg/ha) of forest floor (litter and CWD) were largest in P70D30: 9.8 for P100D0, 11.3 for P70D30, 10.9 for P50D50, 4.8 for P40D60, and 9.2 for P10D90. C contents of forest floor in the pure *P. densiflora* (P100D0) was higher than the other previous studies on Mt. Worak (4.3 Mg/ha) (Jeon et al. 2007), Mt. Jiri (7.62 Mg/ha) and Mt. Hanla (7.88 Mg/ha) (Park and Lee 1981). Mean soil C contents (Mg/ha) were 16.7 at 0-10 cm, 15.8 at 10-20 cm and 6.4 at 20-30 cm. Total soil C contents down to 30 cm depth (Mg/ha) were 37.3 for P100D0, 35.6 for P70D30, 39.1 for P50D50, 37.6 for P40D60, and 49.2 for P10D90 (Table 5). Soil C contents in the pure deciduous oak stand (P10D90) were significantly greater than in the other stands. The same results were observed in previous studies among *P. densiflora* stand and *Quercus* species stands (Choi et al. 2006). We speculated that soil C contents might be influenced by two factors: tree species composition and thinning practice for conserving *P. densiflora*. Many studies have observed differences in soil nutrient cycling between broadleaves and conifers stands (Prescott and Preston 1994, Thomas and Prescott 2000), as well as the effects of mixed species on forest floor processes and soil nutrient cycling (Peterson et al. 1997, Rothe and Binkley 2001). According to de Vries et al. (2003), the forest management practice of thinning was intended to increase the radial growth and enhance the crown projection area of residual trees, especially oak trees rather than pine trees (Juodvalkis et al. 2005), which is highly effective in conserving the C storage in soils (Shan et al. 2001). Our data also supported the same effect: the basal area (m^2/ha) dramatically increased with increasing proportion of deciduous oak trees among the study stands, and soil C contents were significantly higher in the pure

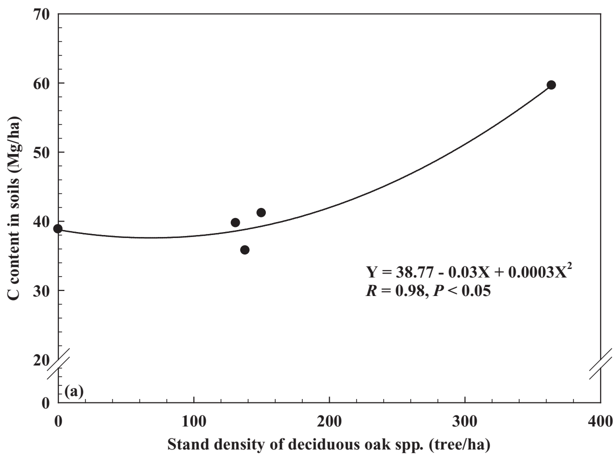

Fig. 4. Relationships between soil C content (Mg/ha) and stand density of deciduous oak species (tree/ha) in the study stands.

deciduous oak stand. In addition, we found a significantly positive correlation between soil C contents and stand density of deciduous oak species (R = 0.98, P < 0.05) (Fig. 4).

Carbon contents in Total Ecosystem

Total ecosystem C contents (Mg/ha) were 163.3 for P100D0, 152.3 for P70D30, 188.8 for P50D50, 160.2 for P40D60, and 150.4 for P10D90, respectively. Total ecosystem C content in the pure *P. densiflora* stand (163.3 Mg/ha) of the current study was higher than those in the 70 to 80-year-old *P. densiflora* stand near the study stand (140.2 Mg/ha) (Son 2009), however, our value was much lower than those in a 40 to 50-year-old, periodically thinned, *P. densiflora* forest (277.6 Mg/ha) in southern Korea (stand density: 350 tree/ha, mean DBH: 25.7cm) (Son 2009). Comparing the two different pure stands (100D0 and P10D90), the former had higher C contents (163.3 Mg/ha) than the latter (150.4 Mg/ha). The proportion of overstory vegetation to total ecosystem C contents was 70.8% for P100D0, 69.1% for P70D30, 73.2% for P50D50, 73.3% for P40D60, and 61.0% for P10D90 (Fig. 5). This result may have been influenced by the radial increment of individual trees between the two species. The overstory vegetation C content was related to DBH (cm) because of the application of DBH-dependent allometric equations for calculating the biomass. Mean DBH (cm) of individual trees in P100D0 was almost twice (40.6 cm) as larger as that in P10D90 (27.0 cm). The proportion of understory vegetation ecosystem to total C contents ranged from 0.1 to 0.3%. These values were smaller than those in pure natural *Quercus* species forests (0.9 to 4.2%) (Son et al. 2004). The proportion of forest floor (litter plus

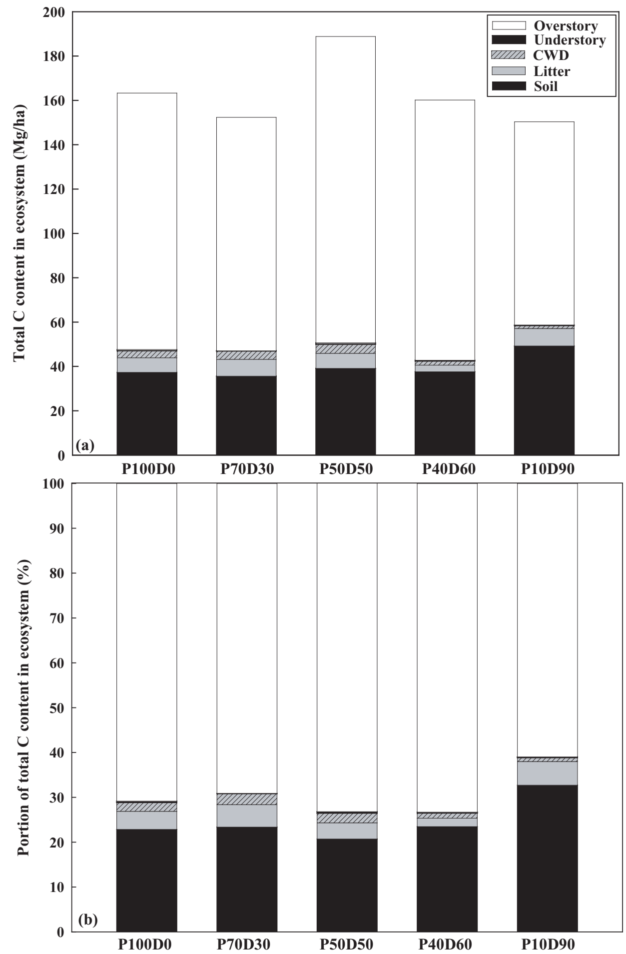

Fig. 5. Total ecosystem C contents (Mg/ha) (a) and proportions of ecosystem components to total ecosystem C contents (b) in the study stands.

CWD) to total ecosystem C contents ranged from 3.0 to 7.4% while that of soil was 22.8% for P100D0, 23.4% for P70D30, 20.7% for P50D50, 23.5% for P40D60 and 32.7% for P10D90.

The differences in total ecosystem C contents among the pure and mixed stands of *P. densiflora* and deciduous oak species seemed to result from the differences in vegetation development and forest management practices. Mixed stands exhibited greater total ecosystem C conservation than the pure stands did; the total ecosystem C contents were maximized in the 1:1 mixed ratio of *P. densiflora* and *Quercus* species. Also we postulated that the total ecosystem C storage could be increased by forest management practices such as changing species composition.

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