Special Feature
J. Ecol. Field Biol. 34(1): 115-125, 2011

JEFB Journal of Ecology and Field Biology

Coarse woody debris mass dynamics in temperate natural forests of Mt. Jumbong, Korea

Tae Kyung Yoon[1], Haegeun Chung[1], Rae-Hyun Kim[2], Nam Jin Noh[1], Kyung Won Seo[2], Sue Kyoung Lee[1], Wooyong Jo[1], Yowhan Son[1,*]

[1] Division of Environmental Science and Ecological Engineering, Korea University, Seoul 136-713, Korea
[2] Korea Forest Research Institute, Seoul 130-712, Korea

Abstract

Coarse woody debris (CWD) mass dynamics in three temperate natural forests, dominated by *Quercus mongolica*, *Abies holophylla*, and *Pinus densiflora,* were studied for 5 to 8 years in a Korea National Long-Term Ecological Research (KNLTER) site located in Mt. Jumbong, Korea. CWD mass (Mg/ha), input rate of CWD mass (Mg ha^{-1} y^{-1}), and decay rate constant (1/y) were 20.6, 1.20, and 0.058 for *Q. mongolica* forest, 12.2, 0.44, 0.106 for *A. holophylla* forest, and 5.0, 0.00, and 0.086 for *P. densiflora* forest, respectively. CWD mass was classified into species, types (log, snag, and stump), and decay classes (I-V). The proportion of logs was higher than that of the other CWD types in *Q. mongolica* forest because of wind-related mortality, whereas the proportion of logs was similar to the proportion of snags in *A. holophylla* forest and *P. densiflora* forest. CWD mass, input rate, decay rate, and distribution reflected the status of forest regeneration and succession for three forests. Mass dynamics were affected interactively by a variety of factors including species, microclimate, and topography, but these effects were hardly distinguishable in this study because of the limited number of comparable sites and pieces of CWD. Thus, further studies will require data regarding long-term microclimate and CWD mass dynamics in a variety of forest types, which could represent diverse environmental factors.

Key words: coarse woody debris (CWD), decay rate constant, mass dynamics, temperate natural forest

INTRODUCTION

Coarse woody debris (CWD) is an important component of temperate forest ecosystems, and is relevant to biomass, habitats for plants, animals, and microorganisms, the nutrient cycle, and micro-geomorphology (Sollins 1982, Harmon et al. 1986). In particular, CWD performs an important function as a long-term carbon stock in the terrestrial carbon cycle because of its slow decomposition and long residence time (Harmon et al. 1986, Ganjegunte et al. 2004, Zhou et al. 2007, Garrett et al. 2008). Therefore, the National Greenhouse Gas Inventory Report for the Intergovernmental Panel on Climate Change (IPCC) requires a carbon stock of dead wood, which is one of the forest carbon stocks contained in forest ecosystems (Intergovernmental Panel on Climate Change 2006). Additionally, CWD dynamics reflect regeneration and succession processes in forests (Sturtevant et al. 1997, Motta et al. 2006).

CWD studies have generally focused on managed forests in which harvesting, clear cutting, or thinning have been practiced (Stone et al. 1998, Pedlar et al. 2002, Densmore et al. 2004, Janisch et al. 2005). However, only limited study has been conducted thus far into mass dynam-

Open Access DOI: 10.5141/JEFB.2011.014

 pISSN: 1975-020X eISSN: 2093-4521

Received 29 November 2010, **Accepted** 10 January 2011

***Corresponding Author**
E-mail: yson@korea.ac.kr
Tel: +82-2-3290-3015

ics in natural forests (Carmona et al. 2002, Wilcke et al. 2005, Sefidi and Marvie Mohadjer 2010). Additionally, little data is currently available on CWD in Korea, although some previous studies have been conducted on this subject (Jang and Youn 2003, Kim et al. 2006, Noh et al. 2010). Thus, the study of CWD mass and its dynamics on temperate natural forests in Korea is clearly important.

For the measurement of CWD dynamics, chronosequencing and long-term survey methods are generally used (Harmon and Sexton 1996, Tobin et al. 2007). The chronosequence method could be readily applied to trace the long-term CWD dynamics when the age of CWD and several sites of comparable conditions are available (Sturtevant et al. 1997, Idol et al. 2001, Carmona et al. 2002, Tobin et al. 2007, Sefidi and Marvie Mohadjer 2010). However, the chronosequence method is difficult to apply in natural forests because CWD in natural forests is not composed of homogenous age, history, and species. Moreover, the environmental conditions for each forest are hardly comparable. Thus, long-term surveys conducted in Long-Term Ecological Research (LTER) sites are clearly necessary for CWD mass dynamics studies in natural forests.

In this study, CWD mass dynamics in three temperate natural forests dominated by *Quercus mongolica*, *Abies holophylla*, and *Pinus densiflora* were studied at the Korea National Long-Term Ecological Research (KNLTER) site located in Mt. Jumbong, Korea. The primary objectives of this study were as follows: 1) to collect and provide data on long-term CWD mass dynamics, 2) to analyze the inventory of CWD mass with forest dynamics, and 3) to estimate the input rate of CWD mass and decay rate constants in temperate natural forests at Mt. Jumbong, Korea.

MATERIALS AND METHODS

Study site

This study was conducted on the KNLTER site of Mt. Jumbong (38°0'-38°5' E, 128°25'-128°30' N,) located in the Mt. Sorak Biosphere Reserve, designated by United Nations Educational, Scientific and Cultural Organization (UNESCO) in 1982 (http://www.unesco.org). At Mt. Jumbong, undisturbed and mature natural forests have developed well, allowing a variety of forest ecological studies including vegetation (Cho 1999, Lee and Cho 2000), regeneration (Kim and Kim 1995, Suh and Lee 1998), succession (Kim and Kim 1995, Lee et al. 2000, Jin and Kim 2005, 2006), and soil respiration (Kang et al. 2003) to be conducted. This site was included as one of the KNLTER sites since 2003 under the auspices of the KNLTER research project (http://www.knlter.net). The 30-year (1970-2000) mean temperature and annual precipitation of Inje, where the closest meteorological station from Mt. Jumbong is located, were 9.9°C (monthly mean temperature ranging from -5.2°C to 23.1°C) and 1,114 mm, respectively (http://www.kma.go.kr).

To compare the differences in CWD dynamics among forests of Mt. Jumbong, three forests were selected (Table 1). The first was a naturally regenerated deciduous forest dominated by *Q. mongolica* with *Carpinus cordata*, *Tilia amurensis*, and *Acer pseudo-sieboldiana* located on a ridge at an altitude of 1,105 m a.s.l. The age of the *Q. mongolica* trees was 80 years for the smaller trees whose diameter at breath height (DBH) was smaller than 30 cm, and 240 years for trees with DBH in excess of 40 cm (Kim and Kim 1995, Cho 1999). This forest is made up of mature deciduous forest in mountainous regions (Lee and Cho 2000). The second was a mixed forest dominated by *A. holophylla* with *Q. mongolica* and *C. cordata* located in a valley at an altitude of 1,091 m a.s.l. The age of the *A. holophylla* was 80 years. The third forest evaluated was a coniferous forest dominated by 60-year-old *P. densiflora* with *Q. mongolica* and *C. condata* located at the bottom slope, at an altitude of 613 m a.s.l.

Field survey and CWD sampling

In each forest, plots of different number and size were designed based on the forest structure and CWD distribution. In the *Q. mongolica* forest, three 20 m × 20 m plots with areas of 0.12 ha were installed in November 2003.

Table 1. Characteristics of three forests at KNLTER site of Mt. Jumbong

Dominant species	Location	Altitude (m)	Slope (°)	Aspect	Topography
Quercus mongolica	38°02'44" N, 128°26'03" E	1,105	30	S	Ridge
Abies holophylla	38°02'00" N, 128°26'23" E	1,091	10	E	Valley
Pinus densiflora	38°02'24" N, 128°22'55" E	613	5	W	Bottom slope

KNLTER, Korea National Long-Term Ecological Research, S, south; E, east; W, west.

Two 20 m × 20 m plots and one 10 m × 10 m plot with an area of 0.09 ha for the *A. holophylla* forest and four 10 m × 10 m plots with an area of 0.04 ha for the *P. densiflora* forest were installed in May 2006. Within each plot, the CWD inventory was assessed via a fixed area plot sampling method (Harmon and Sexton 1996) twice per year in the early summer and early winter, except for the winter seasons of 2006 and 2009, due to heavy snowfall. Pieces of CWD with a base diameter greater than 5 cm were tagged and their species, types (log, snag, and stump), decay classes (I-V), diameters (base, middle, and top), and lengths were recorded in the field. Decay class was determined at five different levels according to a CWD decay classification system (Kim 2003, Kim et al. 2006), which was modified from the original criteria provided by Sollins (1982) and Sollins et al. (1987). For conversions of the CWD volume to CWD mass, cross-sections with a thickness of around 10 cm of all tagged pieces of CWD were sampled, wrapped in plastic bags, and stored at -15°C until their wood densities were analyzed.

Determination of initial CWD volume and mass

CWD mass was calculated from its initial volume and the wood density of cross-sections sampled every 6 months. The initial volume of logs and stumps was calculated via Newton's formula (Harmon and Sexton 1996) which requires length and diameter measurements at three positions (base, middle, and top):

$$V = L(A_b + 4A_m + A_t)/6$$

in which V is volume, L is length, and A_b, A_m and A_t are the areas of the base, middle, and top of the logs and stumps, respectively. The initial volume of snags was estimated using the formula developed by Whitmore (1984):

$$V = BA \times H \times 0.5$$

in which V is volume, BA is the basal area, and H is the height of snags.

The volume and dry weight of cross-sections were measured in order to calculate the wood densities. Diameters of each sample were measured at three points (base, middle, and top) with digital calipers and then their volumes were calculated. The samples were dried at 75°C to a constant mass and weighed. The wood density was calculated as the dry mass divided by the volume of each sample.

Analysis of CWD mass dynamics

The CWD mass obtained using the initial volume of CWD and wood density of each sample was classified into forest type, season, species, CWD type, and decay class. CWD mass input was calculated from the sum of newly tagged and recorded CWD mass at each survey. The mass loss rate of CWD was estimated from the difference in CWD mass between each survey interval. The decay rate constant was estimated based on a single exponential model:

$$k = -ln(X_t/X_0)/t$$

where k is the decay rate constant, X_t is the mass after t years, X_0 is the initial mass, and t is the time (y). In addition, the disappearance of CWD from the sampling of all parts of the sample due to repeated samplings could pose a problem; however, this was not considered a relevant issue because of the small size and proportion.

Statistical analysis

All descriptive statistics and natural logarithmic regression analysis to examine the relationship between decay class and wood density of CWD were conducted using SAS ver. 9.2 (SAS Institute Inc. 2009).

RESULTS

CWD mass dynamics

CWD mass (Mg/ha) ranged from 17.7 to 24.0 for the *Q. mongolica* forest in 2003-2010, from 12.6 to 15.1 for the *A. holophylla* forest in 2006-2010, and from 3.4 to 6.7 for *P. densiflora* forest in 2006-2010 (Fig. 1). The mean CWD mass (Mg/ha) of *Q. mongolica* forest, *A. holophylla* forest, and *P. densiflora* forest during these periods were 20.6, 12.2, and 5.0, respectively. The coefficients of variation (CV) were 43.9%, 80.1%, and 68.3% for the *Q. mongolica* forest, *A. holophylla* forest, and *P. densiflora* forest, respectively.

The input rates of CWD mass (Mg ha^{-1} y^{-1}) for the *Q. mongolica* forest, *A. holophylla* forest, and *P. densiflora* forest were 1.20, 0.44, and 0.00, respectively. CWD mass input (Mg/ha) in each period ranged from 0.00 to 4.02 for the *Q. mongolica* forest, from 0.00 to 1.15 for *A. holophylla* forest, and from 0.00 to 0.02 for *P. densiflora* forest, respectively (Table 2). The mass loss rates of CWD (Mg ha^{-1}

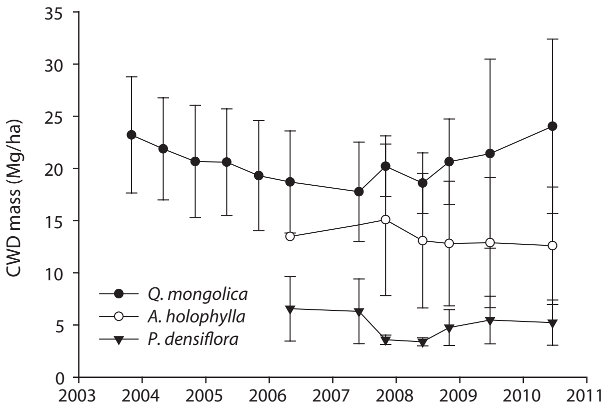

Fig. 1. Coarse woody debris (CWD) mass for three forests at Mt. Jumbong Korea National Long-Term Ecological Research (KNLTER) site from November 2003 to June 2010. CWD mass for *Abies holophylla* in June 2007 was excluded because of many missing values. Bars indicate one standard error. *Q. mongolica, Quercus mongolica*; *P. densiflora, Pinus densiflora.*

y^{-1}) were 1.07 for the *Q. mongolica* forest, 0.66 for the *A. holophylla* forest, and 0.33 for the *P. densiflora* forest. The decay rate constants (1/y) of the *Q. mongolica* forest, *A. holophylla* forest, and *P. densiflora* forest were estimated to be 0.058, 0.106, and 0.086, respectively.

CWD distribution

Table 3 describes the contribution of CWD by species for each forest. *Q. mongolica* comprised the largest proportion (84.5%) of the total CWD mass for *Q. mongolica* forest, followed by *C. cordata* (5.4%), *T. amurensis* (5.0%), *Acer* spp. (1.8%), other species (0.5%), and unidentified species (1.7%). *Acer* spp. contributed a relatively small proportion (1.8%) of the total CWD mass, considering that they occupied a large proportion (20.3%) of the total number of CWD pieces. In the case of the *A. holophylla* forest, mixed forest with *Q. mongolica* and *C. cordata*, a large proportion of the total CWD mass was contributed not only by *A. holophylla* (43.0%), but also by *Q. mongolica* (20.2%), other species (15.9%), and unidentified species (13.9%). A large number of CWD pieces was comprised by *Q. mongolica* (35.9%) and *Acer* spp. (33.5%) and *A. holophylla* contributed a small number of CWD pieces (11.0%) for the *A. holophylla* forest. *P. densiflora* contributed all CWD mass for the *P. densiflora* forest and no CWD was found for other species.

CWD mass by CWD type differed greatly among the three forests (Table 4). The proportion of CWD mass for logs was much higher than the other CWD types in the *Q. mongolica* forest (84.4% for logs), but was smaller than the proportion of snags in the *A. holophylla* forest (25.0% for logs and 50.0% for snags) or was similar to the proportion of snags in *P. densiflora* forest (41.6% for logs and 43.2% for snags). Although snags contributed a small number of CWD pieces in the *A. holophylla* forest (16.8%) and *P. densiflora* forest (15.0%), they comprised a large proportion of total CWD mass for both forests.

The distribution of CWD by decay classes for three forests in each period is shown in Table 5. In general, class II and class III comprised the majority of CWD mass in the *Q. mongolica* forest (29.5% and 51.6%, respectively) and in the *A. holophylla* forest (34.9% and 45.0%, respectively) while class III and class IV comprised the majority of CWD mass in the *P. densiflora* forest (58.6% and 34.7%, respectively). The proportion of CWD mass classified into class Ⅴ was nearly zero in all three of the forests.

Table 2. CWD mass input (Mg/ha) for each period and input rate of CWD mass (Mg ha^{-1} y^{-1}) in three forests at KNLTER site of Mt. Jumbong

	Quercus mongolica	*Abies holophylla*	*Pinus densiflora*
Nov 2003-May 2004	0.00 ± 0.00	-	-
May 2004-Nov 2004	1.44 ± 0.88	-	-
Nov 2004-May 2005	0.00 ± 0.00	-	-
May 2005-Nov 2005	0.32 ± 0.08	-	-
Nov 2005-May 2006	0.00 ± 0.00	-	-
May 2006-Jun 2007	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Jun 2007-Nov 2007	0.26 ± 0.11	1.15 ± 1.15	0.02 ± 0.02
Nov 2007-Jun 2008	0.07 ± 0.04	0.04 ± 0.04	0.00 ± 0.00
Jun 2008-Nov 2008	1.69 ± 1.33	0.49 ± 0.49	0.00 ± 0.00
Nov 2008-Jun 2009	4.02 ± 3.60	0.03 ± 0.03	0.00 ± 0.00
Jun 2009-Jun 2010	0.14 ± 0.14	0.09 ± 0.04	0.00 ± 0.00
Input rate	1.20	0.44	0.00

Values are means ± one standard error. Dash indicates not available.
CWD, coarse woody debris; KNLTER, Korea National Long-Term Ecological Research.

Table 3. CWD mass, number of CWD, and mean diameter of CWD pieces by species for three forests at KNLTER site of Mt. Jumbong

Forest	Species	Mass (Mg/ha)	No. of CWD (pieces)	Mean diameter (cm)
Quercus mongolica	*Q. mongolica*	18.40 ± 1.15	447 ± 31	17.4 ± 0.5
	Carpinus cordata	1.17 ± 0.25	77 ± 11	11.9 ± 0.6
	Tilia amurensis	1.10 ± 0.60	38 ± 8	13.6 ± 1.1
	Acer spp.	0.40 ± 0.03	169 ± 12	7.5 ± 0.1
	Betula spp.	0.22 ± 0.03	42 ± 10	8.0 ± 0.2
	Others*	0.12 ± 0.05	9 ± 3	7.2 ± 0.2
	Unclassified	0.37 ± 0.08	51 ± 7	12.0 ± 0.7
Abies holophylla	*A. holophylla*	6.89 ± 1.27	67 ± 14	19.5 ± 1.3
	Q. mongolica	3.23 ± 0.93	218 ± 37	9.5 ± 0.3
	Acer spp.	0.74 ± 0.12	204 ± 31	6.8 ± 0.1
	Betula spp.	0.37 ± 0.03	7 ± 3	5.8 ± 0.0
	Others†	2.54 ± 0.77	87 ± 24	13.7 ± 0.5
	Unclassified	2.23 ± 0.67	25 ± 5	41.9 ± 6.4
Pinus densiflora	*P. densiflora*	5.05 ± 0.75	739 ± 50	10.1 ± 0.2

Values are means ± one standard error.
CWD, coarse woody debris; KNLTER, Korea National Long-Term Ecological Research.
**Kalopanax pictus, Rhododendron schlippenbachii*.
†*Rhus javanica, Sorbus alnifolia, Alangium platanifolium*.

Table 4. CWD mass and number by CWD types for three forests at KNLTER site of Mt. Jumbong

Forest	Type	Mass		No. of CWD	
		Mean (Mg/ha)	%	Mean (pieces)	%
Quercus mongolica	Log	17.86	84.4	660	79.2
	Snag	0.48	2.2	111	13.3
	Stump	2.84	13.4	63	7.5
Abies holophylla	Log	3.96	25.0	492	78.6
	Snag	7.95	50.0	105	16.8
	Stump	3.97	25.0	29	4.6
Pinus densiflora	Log	2.45	41.6	600	72.8
	Snag	2.54	43.2	124	15.0
	Stump	0.90	15.2	100	12.2

CWD, coarse woody debris; KNLTER, Korea National Long-Term Ecological Research.

Table 5. CWD mass (Mg/ha) by decay class for three forests at KNLTER site of Mt. Jumbong

	Quercus mongolica							*Abies holophylla*							*Pinus densiflora*						
	I	II	III	IV	V	UC	Total	I	II	III	IV	V	UC	Total	I	II	III	IV	V	UC	Total
Nov 2003	0.8	9.0	12.5	0.9	0.0	0.0	23.2	-	-	-	-	-	-	-	-	-	-	-	-	-	-
May 2004	0.9	8.6	11.6	0.8	0.0	0.0	21.9	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Nov 2004	1.2	7.5	8.2	3.8	0.0	0.0	20.7	-	-	-	-	-	-	-	-	-	-	-	-	-	-
May 2005	0.6	7.3	8.8	4.0	0.0	0.0	20.6	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Nov 2005	0.8	4.5	11.1	2.9	0.0	0.0	19.3	-	-	-	-	-	-	-	-	-	-	-	-	-	-
May 2006	0.7	4.8	9.6	3.5	0.0	0.1	18.7	6.0	2.2	0.9	4.4	0.0	0.8	14.3	0.0	0.0	5.0	1.5	0.0	0.0	6.6
Jun 2007	0.7	4.8	8.7	3.5	0.0	0.0	17.8	0.0	3.7	2.5	0.0	0.0	0.0	6.3	0.0	1.1	4.7	0.3	0.0	0.1	6.3
Nov 2007	0.0	2.6	11.3	6.3	0.0	0.0	20.2	0.0	3.6	10.0	1.5	0.0	0.1	15.1	0.0	0.0	1.2	2.4	0.0	0.0	3.6
Jun 2008	0.0	0.4	14.5	3.7	0.0	0.0	18.6	0.0	8.1	4.5	0.5	0.0	0.0	13.1	0.0	0.0	1.2	2.1	0.0	0.0	3.4
Nov 2008	1.7	4.4	13.1	1.0	0.0	0.4	20.6	0.2	3.0	8.0	1.5	0.0	0.0	12.8	0.0	0.1	1.1	3.5	0.1	0.0	4.8
Jun 2009	3.0	10.2	7.9	0.4	0.0	0.0	21.4	0.0	5.5	7.1	0.3	0.0	0.0	12.9	0.0	0.1	3.6	1.8	0.0	0.0	5.5
Jun 2010	2.6	9.0	10.2	2.3	0.0	0.0	24.0	0.1	4.3	6.2	1.7	0.0	0.4	12.8	0.1	0.7	3.9	0.5	0.0	0.0	5.2
Mean	1.1	6.1	10.6	2.8	0.0	0.0	20.6	0.9	4.4	5.6	1.4	0.0	0.2	12.5	0.0	0.3	3.0	1.8	0.0	0.0	5.1

Dash indicates not available.
CWD, coarse woody debris; KNLTER, Korea National Long-Term Ecological Research; UC, unclassified.

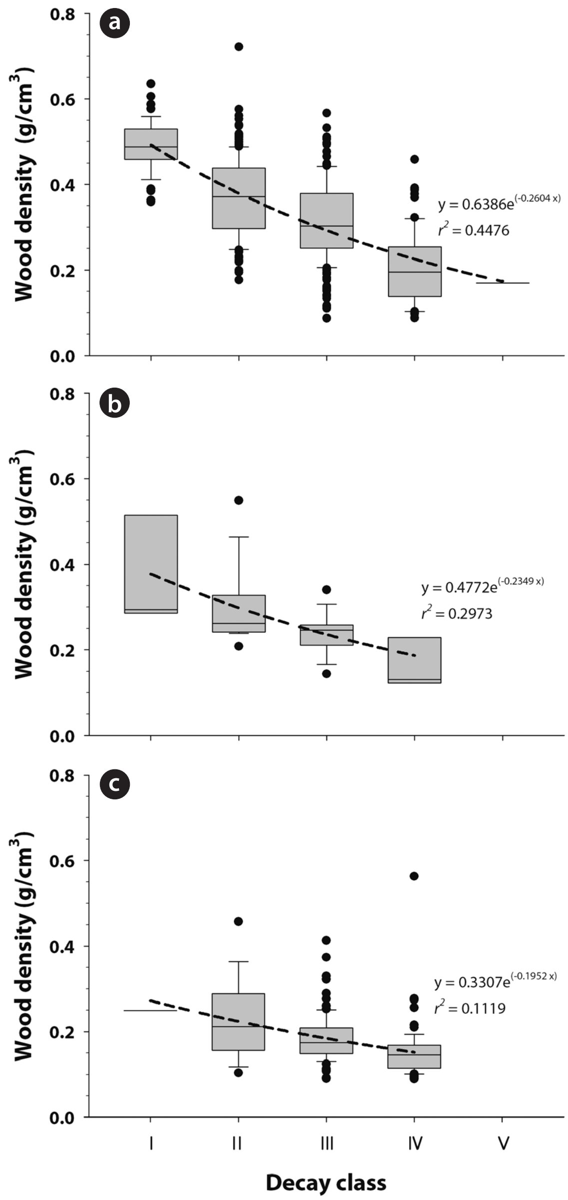

Fig. 2. Distribution of wood density by each decay class for *Quercus mongolica* (a), *Abies holophylla* (b) and *Pinus densiflora* (c). Box plots display median, 95% confidence interval, and minimum and maximum values and points outside the box plots represent outliers. Dashed curves represent a natural logarithmic regression between decay class and wood density of coarse woody debris ($P < 0.0001$).

CWD wood density

CWD wood density by decay class was calculated for each species. CWD wood density (g/cm^3) was 0.49 ± 0.01, 0.37 ± 0.01, 0.31 ± 0.01, 0.20 ± 0.01, and 0.17 ± 0.00 for class Ⅰ, Ⅱ, Ⅲ, Ⅳ, and Ⅴ of *Q. mongolica*, 0.38 ± 0.05, 0.40 ± 0.02, 0.23 ± 0.01, and 0.16 ± 0.03 for class Ⅰ, Ⅱ, Ⅲ, and Ⅳ of *A. holophylla*, and 0.25 ± 0.00, 0.23 ± 0.02, 0.18 ± 0.01, and 0.15 ± 0.01 for class Ⅰ, Ⅱ, Ⅲ, and Ⅳ of *P. densiflora*, respectively. Natural logarithmic regression between decay class and wood density was established for three species ($P < 0.0001$) and the r-square of each regression was 0.45, 0.30, and 0.11 for *Q. mongolica*, *A. holophylla*, and *P. densiflora*, respectively (Fig. 2).

DISCUSSION

CWD mass and distribution

The CWD mass for *Q. mongolica* forest in Mt. Jumbong ranges within that for mature temperate oak forests. This is similar to the range of CWD mass in temperate oak forests (9-24 Mg/ha) as reviewed by Harmon et al. (1986) and a mature *Quercus* spp. forest (15.9-20.1 Mg/ha) in the Gwangneung Experimental Forest (Kim et al. 2004); however, it was higher than in younger forests such as the 30-year-old *Quercus serrata* stand (1.5-1.9 Mg/ha) and 40-year-old *Quercus variabilis* stand (7.0-7.5 Mg/ha) in Yangpyeong as previously reported by Kim et al. (2004).

Distribution of CWD number and mass by species would be similar to the distribution of living tree number and basal area in *Q. mongolica* forest. CWD distribution is reflective of living tree structure (Harmon et al. 1986). Kim and Kim (1995) reported that *Q. mongolica* and *A. pseudosieboldianum* represented approximately 75% of the total basal area and 33% of the total density in this forest. This could explain the large proportion of CWD mass by *Q. mongolica* and of the CWD number by *Acer* spp. in the *Q. mongolica* forest (Table 3). However, the large contribution of CWD input by *Q. mongolica* with *A. pseudosieboldianum* and *T. amurensis* in this research differs from that demonstrated in a mortality report conducted in this forest by Cho (1999), who asserted that small trees of *A. pseudosieboldianum* and *T. amurensis* contributed most to the mortality of trees in the *Q. mongolica* forest from 1995 to 1999. These differences may be attributable to the differences in the study periods of the two studies (from 2003 to 2010 in this study).

The majority of the CWD in *Q. mongolica* forest was classified into log. This is similar to a previous study conducted by Kim and Kim (1995) in which it was reported that a large proportion of the canopy gap in *Q. mongolica* forest was contributed by stem breakage (40%) and branch snap-off (32%), generating logs. Additionally, the *Q. mongolica* forest is located on a ridge where strong winds are frequent throughout the year (Lee and Cho 2000), and this may be one reason why the proportion of logs in *Q. mongolica* forest is larger than that in the *A. holophylla* forest located in the valley and the *P. densiflora* forest located on the bottom slope. Generally, wind-related mortality, which promotes input of logs from fallen stems and broken branches, is probably a salient issue in mature forests (Harmon et al. 1986). Previous studies have reported that *Q. mongolica* is one of the major climax species for cool temperate forests in Korea (Song and Jang 1997, Byun et al. 1998) and Mt. Jumbong (Lee et al. 2000, Jin and Kim 2005). Thus, the large amount of logs observed in the *Q. mongolica* forest might be attributable to specific climate events such as rainfall and windstorms on ridge topography, rather than competition among other species.

The proportion of CWD for *A. holophylla* (43.0%) in the *A. holophylla* forest at Mt. Jumbong is similar to that observed on Mt. Sorak (Jang and Youn 2003) which is close to Mt. Jumbong. However, CWD mass for the *A. holophylla* forest (12.2 Mg/ha) was lower than that for *A. holophylla* forest (17.3 Mg/ha) on Mt. Sorak which is converted from the CWD volume measured by Jang and Youn (2003) using the mean CWD wood density (0.29 g/cm^3) obtained from this study. The proportion of snags and stumps for the *A. holophylla* forest was higher than that measured in the *Q. mongolica* forest. This may be attributable to the competition among species or individual trees (Harmon et al. 1986, Sturtevant et al. 1997). A large number of CWD was determined into *Q. mongolica*, which is expected to decrease in future (Lee et al. 2000) and *Acer* spp., which are major understory species suppressed by overstory trees.

CWD mass for the *P. densiflora* forest (5.0 Mg/ha) is similar to that for 50-year-old *P. densiflora* stand (6.4 Mg/ha) in Gwangneung, Korea (Lee et al. 2009), but lower than that for other forests in Mt. Jumbong (20.6 Mg/ha for *Q. mongolica* forest and 12.2 Mg/ha for *A. holophylla* forest in the present study) or *Pinus contorta* forests (29-121 Mg/ha) in Wyoming, USA (Tinker and Knight 2000). This may represent the middle stage of the succession sequence of *P. densiflora* forest as the lowest position in the general "U-shaped" temporal pattern of CWD mass. The "U-shaped" pattern explains the decline in the initially high CWD level after disturbance and higher inputs as the mature stand senescence through time sequence (Sturtevant et al. 1997, Tarasov and Birdsey 2001, Carmona et al. 2002). Moreover, the homogenous CWD composition by *P. densiflora* and the absence of CWD by other species may correspond to the succession studies in this region (Song and Jang 1997, Lee et al. 2000), which concluded that *P. densiflora* forest is generally altered to *Q. mongolica* or *Q. variabilis* forest. Thus, we anticipate that *P. densiflora* would tend to decline with the increasing presence of CWD; additionally, other understory trees such as *Q. mongolica* and *C. condata*, which are shade-tolerant (Cho 1999), may potentially be dominant without mortality in this forest for the foreseeable future.

Decay rate

We collected 20 decay rate constants for coniferous forests from 6 countries and 7 decay rate constants for deciduous forests from temperate ecosystems in 4 countries. Annual precipitation and mean temperature ranged from 660 mm to 2,500 mm and from 3.9°C to 14.8°C, respectively (Table 6). Overall, the decay rate constants (1/y) ranged from 0.015 to 0.157 for coniferous forests and from 0.018 to 0.109 for deciduous forests in temperate ecosystems, regardless of CWD type. We noted no significant differences in decay rate constants between coniferous forests and deciduous forests ($P = 0.45$). The value for *A. holophylla* forest (0.106) and *P. densiflora* forest (0.086) from this study was higher than the mean value of coniferous forests (0.068). On the other hand, the value for *Q. mongolica* (0.058) reported herein is similar to the mean value of deciduous forests (0.055) and the value for *Quercus* spp. (0.069) from the USA (Schowalter et al. 1998), where the climate conditions are similar to those on Mt. Jumbong.

In this study, the decay rate for the *Q. mongolica* forest was lower than that for the *A. holophylla* and *P. densiflora* forests; one possible explanation for this may involve the differences in initial wood density (g/cm^3), which were 0.44 and 0.78 for *P. densiflora* and *Q. mongolica*, respectively (Korea Forest Research Institute 2007). Generally speaking, the decomposition process is affected by microclimate and woody substrate quality (Harmon et al. 1986, Ganjegunte et al. 2004, Zhou et al. 2007). Wood density, one indicator of substrate quality, is correlated negatively with humidity, because lower void volumes in wood with high wood density inhibit the infiltration of moisture into wood structures, and attenuate decomposition processes (Harmon et al. 1986, Yin 1999, Zhou et al. 2007). Thus, deciduous species tend to evidence lower decay rates than coniferous species because of the hardness and wood density of deciduous species.

Decay class classification

Decay classification systems are representative of mean wood density for each class with external charac-

Table 6. Decay rate constants estimated for temperate forest ecosystems

Location	Species	Annual precipitation (mm), temperature (°C)	CWD type	Decay rate (1/y)	References
Coniferous forest					
New Zealand	*Pinus radiate*	1,820, 14.8	Stem	0.137	Garrett et al. 2008
			Stump	0.157	
			Root	0.110	
New Zealand	*P. radiate*	787, 4.6-16.2	Log wood	0.074	Ganjegunte et al. 2004
			Log bark	0.056	
			Side branches	0.015	
			All average	0.052	
Australia	*P. radiate*	791, 7.3-19.5	Log	0.127	Mackensen and Bauhus 2003
Mt. Rocky, USA	*Pinus cortorta*	660, -10-14	Log	0.072	Herrmann and Prescott 2008
			Log	0.088	Laiho and Prescott 1999
Mt. Changbai, China	*Pinus koraiensis*	782, 3.9	Log	0.016	Chen 1989
British Colombia, Canada	*Pseudotsuga menziesii*	2,123, 10.0	-	0.022	Stone et al. 1998
Washington, USA	*P. menziesii*	2,500, 8.7	Log	0.015	Janisch et al. 2005
Mt. Rocky, USA	*Abies lasiocarpa*	660, -10-14	Log	0.052	Herrmann and Prescott 2008
			Log	0.036	Laiho and Prescott 1999
Washington, USA	*Tsuga heterophylla*	2,500, 8.7	Log	0.036	Janisch et al. 2005
Ireland	*Picea sitchensis* (Bong.) Carr.	850, 9.3	Log	0.046	Tobin et al. 2007
			Stump	0.059	
Mt. Jumbong, Korea	*Abies holophylla*	1,114, 9.9	All CWD	0.106	This study
	Pinus densiflora		All CWD	0.086	This study
Deciduous forest					
Indiana, USA	*Quercus* spp.	-	-	0.018	MacMillan 1988
Oregon, Minnesota, Kansas and North Carolina, USA	*Quercus* spp.	660-1,800, 6-13*	Log	0.069	Schowalter et al. 1998
Germany	*Fagus sylvatica* L.	1,032, 7.0	Wood	0.089	Muller-Using and Bartsch 2009
			Bark	0.109	
Indiana, USA	*Fagus grandifolia*	-	-	0.019	MacMillan 1988
New Zealand	*Nothofagus* spp.	1,700, 9.5	Log	0.024	Beets et al. 2008
Mt. Jumbong, Korea	*Quercus mongolica*	1,114, 9.9	All CWD	0.058	This study

Dash indicates not available.
CWD, coarse woody debris.
*Range of mean annual temperature among four sites.

teristics of CWD such as bark cover, fungal cover, or color (Harmon et al. 1986). In this study, 45%, 30%, and 11% of the variation in CWD wood density was explained by decay classes in the *Q. mongolica*, *A. holophylla*, and *P. densiflora* forests, respectively (Fig. 2). The limited representativeness of the decay class to wood density in coniferous forests is attributable to the lack of a CWD decay classification system for coniferous species. The CWD decay classification system (Kim 2003, Kim et al. 2006) applied in this research was developed originally for *Quercus* spp. forest and may not be suitable for coniferous forests because CWD from each forest could have different external characteristics due to species, microclimate, and biota on CWD. The decay classification system could be regarded as specific to a site (Harmon and Sexton 1996). Thus, improvement and validation are necessary for reliable decay classifications for coniferous forests. For example, Naesset (1999) developed three classification systems for *Picea abies* CWD and evaluated the relationship between these classification system and relative wood density.

Limitation

CV for *A. holophylla* forest and *P. densiflora* forest was larger than that for *Q. mongolica* forest. This may be due to plot size, which is a crucial consideration for CWD inventory (Harmon and Sexton 1996). Harmon and Sexton (1996) recommended that the cumulative areas of plots should be at least 0.1 ha to represent a normally stocked stand in CWD research. The cumulative area of plots for *A. holophylla* forest (0.09 ha) and *P. densiflora* forest (0.04 ha) were lower than the value of their recommendation. Although the plot size was determined with consideration of forest structures and CWD distribution in this study, further studies will be required, involving the installation of plots with cumulative areas greater than 0.1 ha to achieve better representativeness.

The chief objective of this study was to build an inventory of CWD mass and analyze its long-term dynamics in cool-temperate forests located at the Mt. Jumbong site in Korea. CWD mass and its dynamics are affected by microclimate factors including temperature, humidity, O_2 and CO_2 concentrations inside of CWD, and woody substrate quality including diameter, components, species, and organisms (Harmon et al. 1986, Ganjegunte et al. 2004, Zhou et al. 2007). Topography also affects the distribution of CWD loads across the landscape (Rubino and McCarthy 2003). However, it was difficult to analyze the effects of microclimate or topography in this study, because microclimate and topography data were insufficient and distinguishing the effects of dominant species, topography, and microclimate is difficult in natural forests where these factors are generally related and interact with one another. Thus, further studies will require data of long-term microclimate and CWD mass dynamics in a variety of forest types that can represent a variety of environmental factors.

We developed decay rate constants for each forest regardless of CWD type, decay class, and species in this study. However, decay rate constants could be developed with regard to other factors such as CWD size (Tarasov and Birdsey 2001, Beets et al. 2008), decay class (Tobin et al. 2007) and CWD type (Ganjegunte et al. 2004, Garrett et al. 2008). This study did not install enough CWD replicates to reflect all these factors, principally because it was tightly focused on CWD mass dynamics in natural forests, not developing heterogenous CWD decay rate constants. However, further research into the development of CWD decay rate constants should take into consideration these factors, which affect CWD decomposition. In particular, the development of CWD decay rate constants by decay class may prove essential, as further research into CWD mass inventory and its dynamics is necessary for the development of a CWD mass dynamics model in forests with continuous long-term monitoring. Stage-based CWD decomposition models according to decay classes by different transition rates (Kruys et al. 2002, Ranius et al. 2003, Montes and Canellas 2006) could be applied in the construction of CWD mass dynamics models in the future using the CWD inventory compiled in this study.

ACKNOWLEDGMENTS

This work was supported by research grants from the National Institution of Environmental Research as a component of the "National Long-Term Ecological Research Project." We would like to extend special thanks to Chul Han Kim and his Sulpibat Jisune lodge, which provided a warm and cozy rest during our field work. We also would like to give thanks to Ah Reum Lee, Koong Yi and A-Ram Yang for their assistance in both the laboratory and the field.

LITERATURE CITED

Beets PN, Hood IA, Kimberley MO, Oliver GR, Pearce SH, Gardner JF. 2008. Coarse woody debris decay rates for seven indigenous tree species in the central North Island of New Zealand. For Ecol Manag 256: 548-557.

Byun DW, Lee HJ, Kim CH. 1998. Vegetation pattern and successional sere in the forest of Mt. Odae. Korean J Ecol 21: 283-290.

Carmona MR, Armesto JJ, Aravena JC, Perez CA. 2002. Coarse woody debris biomass in successional and primary temperate forests in Chiloe Island, Chile. For Ecol Manag 164: 265-275.

Chen H. 1989. Studies on tree mortality and log decomposition of main species in Korean pine deciduous mixed forest. MS Thesis. Academia Sinica, Shengyang, China.

Cho DS. 1999. Population dynamics of *Quercus mongolica* in

Mt. Jumbong. Korean J Ecol 22: 355-361.
Densmore N, Parminter J, Stevens V. 2004. Coarse woody debris: inventory, decay modelling, and management implications in three biogeoclimatic zones. BC J Ecosyst Manag 5: 14-29.
Ganjegunte GK, Condron LM, Clinton PW, Davis MR, Mahieu N. 2004. Decomposition and nutrient release from radiata pine (*Pinus radiata*) coarse woody debris. For Ecol Manag 187: 197-211.
Garrett LG, Oliver GR, Pearce SH, Davis MR. 2008. Decomposition of *Pinus radiata* coarse woody debris in New Zealand. For Ecol Manag 255: 3839-3845.
Harmon ME, Franklin JF, Swanson FJ, Sollins P, Gregory SV, Lattin JD, Anderson NH, Cline SP, Aumen NG, Sedell JR, Lienkaemper GW, Cromack K Jr, Cummins KW. 1986. Ecology of coarse woody debris in temperate ecosystems. Adv Ecol Res 15: 133-302.
Harmon ME, Sexton J. 1996. Guidelines for Measurements of Woody Detritus in Forest Ecosystems. US Long-Term Ecological Research Network Office, University of Washington, Seattle, WA.
Herrmann S, Prescott CE. 2008. Mass loss and nutrient dynamics of coarse woody debris in three Rocky Mountain coniferous forests: 21 year results. Can J For Res 38: 125-132.
Idol TW, Figler RA, Pope PE, Ponder F. 2001. Characterization of coarse woody debris across a 100 year chronosequence of upland oak-hickory forests. For Ecol Manag 149: 153-161.
Intergovernmental Panel on Climate Change. 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Institute for Global Environmental Strategies, Kanagawa.
Jang DW, Youn YI. 2003. A basic survey about dead tree of old Korean fir stands in Mt. Sorak. Korean J Environ Biol 21: 251-256.
Janisch JE, Harmon ME, Chen H, Fasth B, Sexton J. 2005. Decomposition of coarse woody debris originating by clearcutting of an old-growth conifer forest. Ecoscience 12: 151-160.
Jin GZ, Kim JH. 2005. The analysis of successional trends by community types in the natural deciduous forest of Mt. Jumbong. J Korean For Soc 94: 387-396.
Jin GZ, Kim JH 2006. The estimation of succession index by community types in the natural deciduous forest at Mt. Jumbong. J Korean For Soc 95: 723-728.
Kang S, Doh S, Lee D, Jin VL, Kimball JS. 2003. Topographic and climatic controls on soil respiration in six temperate mixed-hardwood forest slopes, Korea. Global Change Biol 9: 1427-1437.
Korea Forest Research Institute. 2007. Forest Biomass Assessment in Korea. Korea Forest Research Institute, Seoul.
Kim R, Son Y, Hwang J. 2004. Comparison of mass and nutrient dynamics of coarse woody debris between *Quercus serrata* and *Q. variabilis* stands in Yangpyeong. Korean J Ecol 27: 115-120.
Kim RH. 2003. Mass and nutrient dynamics of coarse woody debris in a natural deciduous forest of Kwangneung. MS Thesis. Korea University, Seoul, Korea.
Kim RH, Son Y, Lim JH, Lee IK, Seo KW, Koo JW, Noh NJ, Ryu SR, Hong SK, Ihm BS. 2006. Coarse woody debris mass and nutrients in forest ecosystems of Korea. Ecol Res 21: 819-827.
Kim SD, Kim YD. 1995. Studies on the regeneration process of a *Quercus mongolica* forest in Mt. Jumbong. J Korean For Soc 84: 447-455.
Kruys N, Jonsson BG, Stahl G. 2002. A stage-based matrix model for decay-class dynamics of woody debris. Ecol Appl 12: 773-781.
Laiho R, Prescott CE. 1999. The contribution of coarse woody debris to carbon, nitrogen, and phosphorus cycles in three Rocky Mountain coniferous forests. Can J For Res 29: 1592-1603.
Lee KS, Cho DS. 2000. Relationships between the spatial distribution of vegetation and microenvironment in a temperate hardwood forest in Mt. Jumbong Biosphere Reserve Area, Korea. Korean J Ecol 23: 241-253.
Lee SK, Son Y, Noh NJ, Yoon TK, Lee AR, Seo KW, Hwang J, Bae SW. 2009. Carbon storage of pure and mixed pine-deciduous oak forests in Gwangneung, central Korea. J Ecol Field Biol 32: 237-247.
Lee WS, Kim JH, Jin GZ. 2000. The analyasis of succesional trends by topographic positions in the natural deciduous forest of Mt. Chumbong. J Korean For Soc 89: 655-665.
Mackensen J, Bauhus J. 2003. Density loss and respiration rates in coarse woody debris of *Pinus radiata*, *Eucalyptus regnans* and *Eucalyptus maculata*. Soil Biol Biochem 35: 177-186.
MacMillan PC. 1988. Decomposition of coarse woody debris in an old-growth Indiana forest. Can J For Res 18: 1353-1362.
Montes F, Canellas I. 2006. Modelling coarse woody debris dynamics in even-aged Scots pine forests. For Ecol Manag 221: 220-232.
Motta R, Berretti R, Lingua E, Piussi P. 2006. Coarse woody debris, forest structure and regeneration in the Valbona Forest Reserve, Paneveggio, Italian Alps. For Ecol Manag 235: 155-163.
Muller-Using S, Bartsch N. 2009. Decay dynamic of coarse

and fine woody debris of a beech (*Fagus sylvatica* L.) forest in Central Germany. Eur J Forest Res 128: 287-296.

Naesset E. 1999. Relationship between relative wood density of *Picea abies* logs and simple classification systems of decayed coarse woody debris. Scand J For Res 14: 454-461.

Noh NJ, Son Y, Lee SK, Seo KW, Heo SJ, Yi MJ, Park PS, Kim RH, Son YM, Lee KH. 2010. Carbon and nitrogen storage in an age-sequence of *Pinus densiflora* stands in Korea. Sci China Life Sci 53: 822-830.

Pedlar JH, Pearce JL, Venier LA, McKenney DW. 2002. Coarse woody debris in relation to disturbance and forest type in boreal Canada. For Ecol Manag 158: 189-194.

Ranius T, Kindvall O, Kruys N, Jonsson BG. 2003. Modelling dead wood in Norway spruce stands subject to different management regimes. For Ecol Manag 182: 13-29.

Rubino DL, McCarthy BC. 2003. Evaluation of coarse woody debris and forest vegetation across topographic gradients in a southern Ohio forest. For Ecol Manag 183: 221-238.

SAS Institute Inc. 2009. SAS/STAT® 9.2 User's Guide. 2nd ed. SAS Institute Inc., Cary, NC.

Schowalter TD, Zhang YL, Sabin TE. 1998. Decomposition and nutrient dynamics of oak *Quercus* spp. logs after five years of decomposition. Ecography 21: 3-10.

Sefidi K, Marvie Mohadjer MR. 2010. Characteristics of coarse woody debris in successional stages of natural beech (*Fagus orientalis*) forests of Northern Iran. J For Sci 56: 7-17.

Sollins P. 1982. Input and decay of coarse woody debris in coniferous stands in western Oregon and Washington. Can J For Res 12: 18-28.

Sollins P, Cline SP, Verhoeven T, Sachs D, Spycher G. 1987. Patterns of log decay in old-growth Douglas-fir forests. Can J For Res 17: 1585-1595.

Song HK, Jang KK. 1997. Study on the DBH analysis and forest succession of *Pinus densiflora* and *Quercus mongolica* forests. J Korean For Soc 86: 223-232.

Stone JN, MacKinnon A, Parminter JV, Lertzman KP. 1998. Coarse woody debris decomposition documented over 65 years on southern Vancouver Island. Can J For Res 28: 788-793.

Sturtevant BR, Bissonette JA, Long JN, Roberts DW. 1997. Coarse woody debris as a function of age, stand structure, and disturbance in boreal Newfoundland. Ecol Appl 7: 702-712.

Suh MH, Lee DK. 1998. Stand structure and regeneration of *Quercus mongolica* forests in Korea. For Ecol Manag 106: 27-34.

Tarasov ME, Birdsey RA. 2001. Decay rate and potential storage of coarse woody debris in the Leningrad region. Ecol Bull 49: 137-147.

Tinker DB, Knight DH. 2000. Coarse woody debris following fire and logging in Wyoming lodgepole pine forests. Ecosystems 3: 472-483.

Tobin B, Black K, McGurdy L, Nieuwenhuis M. 2007. Estimates of decay rates of components of coarse woody debris in thinned Sitka spruce forests. Forestry 80: 455-469.

Whitmore TC. 1984. Tropical Rain Forests of the Far East. Oxford University Press, Oxford.

Wilcke W, Hess T, Bengel C, Homeier J, Valarezo C, Zech W. 2005. Coarse woody debris in a montane forest in Ecuador: mass, C and nutrient stock, and turnover. For Ecol Manag 205: 139-147.

Yin XW. 1999. The decay of forest woody debris: numerical modeling and implications based on some 300 data cases from North America. Oecologia 121: 81-98.

Zhou L, Dai L, Gu H, Zhong L. 2007. Review on the decomposition and influence factors of coarse woody debris in forest ecosystem. J For Res 18: 48-54.