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Estimation of Carbon Storage Using Mean Biomass Density in Korean Forests

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Abstract : This study examined the biomass data estimated from different allometric models and calculated the mean aboveground biomass, mean belowground biomass and root/shoot ratio values according to the forest types and age classes. These mean values and the forest inventories in 2009 were used to estimate the aboveground and total biomass carbon storage in different forest types (coniferous, deciduous and mixed forests). The aboveground and total biomass carbon storage for all forest types in Korea were 350.201 Tg C and 436.724 Tg C. Over the past 36 years, plantations by reforestation programs have accounted for more than 70% of the observed carbon storage. The carbon storage in Korean forest biomass was 436.724 Tg C, of which 175.154 Tg C for coniferous forests, 126.772 Tg C for deciduous forests and 134.518 Tg C for mixed forests, comprising approximately 1/20 of the total carbon storage of the East Asian countries. The total carbon storage for the whole forest sector in Korea was 1213.122 Tg C, of which 436.724 Tg C is stored in forest biomass if using the ratio of carbon storage in different pools examined from the United States. Such large carbon storage in Korean forests is due mainly to active plantations growth and management practices.

***Key words* :** *Korean forest biomass, carbon storage, carbon density, allometric model, plantation*

Introduction

Recent studies have shown that the mid- and high-latitude forests in the Northern Hemisphere are significant sinks for sequestrating atmospheric CO_2 (e.g. Choi *et al*., 2002; Janssens *et al*., 2003; Nabuurs *et al*., 2003; Fang *et al*., 2001, 2005). However, the regional magnitude, spatial pattern and causes of carbon sources and sinks remain uncertain (Goodale *et al*., 2002; Liski *et al*., 2003; Houghton 2005; Fang *et al*., 2006). With the increasing scientific and political interest in regional aspects of the global carbon cycle, there is a strong impetus to better understand carbon storage in Korean forests. This is not only because 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 (UNFCCC) through nationwide reforestation to increase the level of carbon storage in its forest ecosystems, but also because it has experienced intensive land change histories during the first half of last century.

Korea is comprised of 16 regions, 7 metropolitan cities (Soeul, Busan, Daegu, Incheon, Gwanju, Daejeon and Ulsan) and 9 provinces (Gyeonggi-do, Gangwon-do, Chungcheongbuk-do, Chungcheongnam-do, Jeollabuk-do, Jeollanam-do, Gyeongsangbuk-do, Gyeongsangnam-do and Jejudo), and has a unique climate that can allow more than three fifths of its land area to be covered with forest (Shin, 2002). Approximately 42% of forestland is coniferous forest, 26% is deciduous forest, 29.1% is mixed forest, and the remaining 2.9% are bamboo forest and non-wooded land (Statistical Yearbook of Forestry, 2009). Although sporadic government efforts at reforestation had begun in the 1960s, the Korean government initiated three ten-year national reforestation programs in 1973 to protect water, soil and biological resources and rehabilitate Korea's denuded landscape (Choi *et al*., 2002; Tak *et al*., 2007). In the meantime, forest ecologists developed series of allometric models to estimate the biomass and productivity in many forest types of Korea, with a large accumulation of field survey data. These field surveys and the latest forest inventories are complementary data sources for estimating the level of carbon storage in Korean forests.

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However, there are few reports of this type of study.

The aim of this study were to (1) estimate the biomass carbon storage in Korean forests using the mean aboveground biomass, mean belowground biomass and root/shoot ratio values based on field surveys and forest inventories, and (2) identify the regional carbon magnitude and distribution in forest biomass of each forest type.

Data and Methods

Two data sources were used in this study, namely forest inventory data and field survey data.

1. Forest inventory data

Forest is defined as land with 30% or more crown cover in government-, community- and privately-owned forests. The forest inventory data provides detailed information on the total area, age, site quality for each forest type (coniferous, deciduous and mixed forests) at a regional level (Statistical Yearbook of Forestry, 2009). Within each region, each forest type was stratified into three site classes (low, medium and high quality). Each site was subdivided into five age classes from II to VI (younger than 20 years old for II, 30 years old for III, 40 years old for IV, 50 years for V and over 50 years old for VI). The total area of each forest type was given by the age classes for each region.

2. Field survey data

This study examined the data from publications over the past 40 years on allometric models according to the tree species and also compiled data on biomass according to the forest type in Korea. Most studies focused on the major dominate species and developed allometric equations for the aboveground components such as stem, foliage and branches. Only few studies reported the belowground portion (root) (Table 1). The major dominate species for coniferous forests are *Pinus densiflora* (55%), *P. rigida* (15.2%), *P. koraiensis* (8.6%), and *Larix leptolepsis* (17.2%), whereas the major dominate species for deciduous forests are *Qercus* species, particularly *Q. Mongolica*, *Q. acutissima*, *Q. variabilis*, *Q. serrata*, and *Q. dentate* (Statistical Yearbook of Forestry, 2009). This study assumed that the major coniferous species represents all coniferous trees, *Quercus* species represents all deciduous trees, and that those coniferous species and *Quercus* species are representative of mixed forests because *Pinus* and *Quercus* species account for more than two-thirds of all coniferous and deciduous trees in Korea (Choi *et al*., 2002; Tak *et al*., 2007). It should be noted that not all original studies measured both the above- and below-ground biomass for the dominate tree species, and only few studies reported the forest floor mass, dead wood biomass and soil carbon content. The mean aboveground biomass, mean belowground biomass and root/shoot ratio values according to the forest types and age classes were then calculated (Table 2).

2. Estimation of forest biomass

The aboveground or total biomass (Y) for each forest type was calculated using Eq. (1):

$$Y = \sum_{e=1}^{16}\sum_{f=1}^{3}\sum_{g=1}^{5}(1+R)D_{efg}A_{efg} \qquad (1)$$

Where, D_{efg} and A_{efg} are the aboveground or total mean biomass density (Mg ha^{-1}) and total area for each age class ($g = 1, 2, 3, 4, 5$), site class ($f = 1, 2, 3$), and region ($e = 1, 2, 3, \ldots, 16$) (Statistical Yearbook of Forestry, 2009), and R is the ratio of root to shoot.

The biomass in bamboo forests was also analyzed, and the total biomass was estimated from the average values based on few case studies. The mean biomass density (including culms, branch, leave, rhizome and root) for the different bamboo species (*Phyllostachys pubescens*, *P. bambusoides*, *P. nigra var. henonis*) ranged from 36.8 to 103.6 Mg ha^{-1} (Park and Ryu, 1996; Hwang *et al*., 2005), with a mean biomass density of 79.4 Mg ha^{-1}. The biomass of bamboo forests in each region was calculated by multiplying the mean biomass density by total area in the region.

Results

Table 1 lists the allometric models for the major dominate species in Korean forests. The commonly used models for estimating the biomass of different trees are $W = a(\mathrm{DBH})^b$ or $\mathrm{Log}W = a+b\mathrm{Log(DBH)}$ and $W = a(\mathrm{DBH}^2\mathrm{H})^b$ or $\mathrm{Log}\ W = a+b\mathrm{Log}(\mathrm{DBH}^2\mathrm{H})$. Given that biomass growth is strongly related to the trunk diameter and height, the allometric model as a nondestructive method is useful for estimating the entire or partial weight of a tree from the measurable tree dimensions including diameter at breast height (DBH) or DBH and height together (Lee, 2004; Lee *et al*., 2004). However, this allometric relationship varies according to the specific site and species (Table 1).

The biomass data from publications was analyzed, and the mean aboveground biomass, mean belowground biomass and root/shoot ratio values were calculated for each age class (from II to VI) of different forest types (Table 2). In general, the mean aboveground biomass for all forest types increased significantly with age class, while the mean belowground biomass increased slightly with age class. The root/shoot ratio values fluctuated significantly between 0.180 and 0.344 for deciduous forests compared to that for coniferous and mixed forests, partly because of a small number of published data sources for age class II of deciduous forests.

Table 1. Allometric models for the major tree species of Korean forests based on DBH or DBH^{2}H (DBH: diameter at breast height. H: height. W_s: stem dry weight in kg. W_a: aboveground dry weight in kg. W_b: belowground dry weight in kg).

Quercus mongolica

$\mathrm{Log}W_s = 5.600+1.002\mathrm{Log}(\mathrm{DBH}^2\mathrm{H})$ $r^2 = 0.990$, $n = 7$, Kwon and Lee (2006a)
$\mathrm{Log}W_s = 5.397+1.045\mathrm{Log}(\mathrm{DBH}^2\mathrm{H})$ $r^2 = 0.980$, $n = 6$, Kwon and Lee (2006a)
$\mathrm{Log}W_s = 5.691+0.974\ \mathrm{Log}(\mathrm{DBH}^2\mathrm{H})$ $r^2 = 0.990$, $n = 7$, Kwon and Lee (2006a)
$\mathrm{LogW}_s = 5.464+1.1.034\mathrm{Log}(\mathrm{DBH}^2\mathrm{H})$ $r^2 = 0.990$, $n = 6$, Kwon and Lee (2006a)
$\mathrm{Log}W_s = 5.765+0.949\mathrm{Log}(\mathrm{DBH}^2\mathrm{H})$ $r^2 = 0.990$, $n = 6$, Kwon and Lee (2006a)
$\mathrm{Log}W_a = 5.522+1.035\mathrm{Log}(\mathrm{DBH}^2\mathrm{H})$ $r^2 = 0.990$, $n = 5$, Kwon and Lee (2006a)
$\mathrm{Log}W_a = 2.076+2.579\mathrm{Log}(\mathrm{DBH})$ $r^2 = 0.955$ $n = 10$, Park et al. (2003)
$W_a = 1.909\mathrm{DBH}^{2.410}$ $r^2 = 0.980$, $n = 9$, Park (2003)
$W_a = 1.745\mathrm{DBH}^{2.587}$ $r^2 =0.990$, $n =9$, Park (2003)
$W_a = 1.865\mathrm{DBH}^{2.486}$ $r^2 = 0.980$, $n = 9$, Park (2003)
$W_a = 1.002\mathrm{DBH}^{3.866}\mathrm{H}^{-2.746}$ $r^2 = 0.98$, $n = 10$, Song and Lee (1996)
$\mathrm{Log}W_a = 1.982+2.546\mathrm{Log}(\mathrm{DBH})$ $r^2 = 0.97$, $n = 10$, Park and Moon (1994)
$\mathrm{Log}W_a = 2.144+2.366\mathrm{Log}(\mathrm{DBH})$ $r^2 = 0.994$, $n = 10$, Park et al. (1996)
$\mathrm{Log}W_s = 1.391+0.976\mathrm{Log}(\mathrm{DBH}^2\mathrm{H})$ $r^2 = 0.990$, $n = 7$, Kwon and Lee (2006b)
$\mathrm{Log}W_s = 1.197+1.028\mathrm{Log}(\mathrm{DBH}^2\mathrm{H})$ $r^2 = 0.990$, $n = 6$, Kwon and Lee (2006b)
$\mathrm{Log}W_s = 1.531+0.092\mathrm{Log}(\mathrm{DBH}^2\mathrm{H})$ $r^2 = 0.930$, $n = 10$, Lee and Kwon (2006)
$\mathrm{LogW}_a = 1.469+0.992\mathrm{Log}(\mathrm{DBH}^2\mathrm{H})$ $r^2 = 0.990$, $n = 18$, Kwon and Lee (2006b)
$\mathrm{Log}W_a = 0.823+1.134\mathrm{Log}(\mathrm{DBH}^2\mathrm{H})$ $r^2 = 0.990$, $n = 6$, Kwon and Lee (2006c)
$\mathrm{Log}W_a = 1.101+1.071\mathrm{Log}(\mathrm{DBH}^2\mathrm{H})$ $r^2 = 0.990$, $n = 9$, Kwon and Lee (2006c)
$\mathrm{Log}W_a = 0.923+1.117\mathrm{Log}(\mathrm{DBH}^2\mathrm{H})$ $r^2=0.990$, $n = 5$, Kwon and Lee (2006c)
$\mathrm{Log}W_a = 0.928+1.109\mathrm{Log}(\mathrm{DBH}^2\mathrm{H})$ $r^2 = 0.990$, $n = 5$, Kwon and Lee (2006c)
$\mathrm{Log}W_s = -1.2854+0.9013\mathrm{Log}(\mathrm{DBH})$ $r^2 = 0.978$, $n = 10$, Lee and Park (1987)
$\mathrm{Log}W_a = 2.102+2.360\mathrm{Log}(\mathrm{DBH})$ $r^2=0.979$, $n=10$, Park *et al.* (2005)
$\mathrm{Log}W_a = 2.234+2.518\mathrm{Log}(\mathrm{DBH})$ $r^2 = 0.988$, $n = 10$, Son *et al.* (2004)

Quercus variabilis

$\mathrm{Log}W_a = 1.702+2.678\mathrm{Log}(\mathrm{DBH})$ $r^2 = 0.990$, $n = 10$, Park *et al.* (2003)
$\mathrm{Log}W_a = 1.571+2.759\mathrm{Log}(\mathrm{DBH})$ $r^2 = 0.990$, $n = 10$, Park *et al.* (2003)
$\mathrm{Log}W_a = 1.702+2.678\mathrm{Log}(\mathrm{DBH})$ $r^2 = 0.980$, $n = 10$, Park and Lee (2001)
$\mathrm{Log}W_a = 1.329+2.823\mathrm{Log}(\mathrm{DBH})$ $r^2 = 0.973$, $n = 10$, Park *et al.* (2003)
$\mathrm{Log}W_s = 1.606+0.868\mathrm{Log}(\mathrm{DBH})$ $r^2 = 0.9518$, $n = 12$, Kim and Jeong (1985)
$\mathrm{Log}W_s = 1.000+1.124\mathrm{Log}(\mathrm{DBH})$ $r^2 = 0.9845$, $n = 12$, Kim and Jeong (1985)
$W_a = 1.000\mathrm{DBH}^{2.925}\mathrm{H}^{-1.638}$ $r^2 = 0.980$, $n = 10$, Song and Lee (1996)
$\mathrm{Log}W_a = 1.916+2.377\mathrm{Log}(\mathrm{DBH})$ $r^2 = 0.968$, $n = 10$, Choi and Park (1993)
$\mathrm{Log}W_a = 1.944+2.470\mathrm{Log}(\mathrm{DBH})$ $r^2 = 0.991$, $n = 10$, Park *et al.* (1996)
$\mathrm{Log}W_a = 2.063+2.445\mathrm{Log}(\mathrm{DBH})$ $r^2 = 0.990$, $n = 10$, Park and Moon (1994)
$\mathrm{Log}W_a = 1.905+2.545\mathrm{Log}(\mathrm{DBH})$ $r^2 = 0.962$, $n = 10$, Park *et al.* (2005)

Quercus dentata

$\mathrm{Log}W_a = 1.883+2.560\ \mathrm{Log}(\mathrm{DBH})$ $r^2 = 0.990$, $n = 10$, Park *et al.* (1996)

Quercus serrata

$W_a = 2.300\mathrm{DBH}^{2.257}$ $r^2 = 0.990$, $n = 9$, Park and Lee (2002)
$W_a = 1.904\mathrm{DBH}^{2.519}$ $r^2 = 0.990$, $n = 9$, Park and Lee (2002)
$W_a = 1.869\mathrm{DBH}^{2.602}$ $r^2 = 0.990$, $n = 9$, Park and Lee (2002)
$\mathrm{Log}W_a = 2.116+2.446\mathrm{Log}(\mathrm{DBH})$ $r^2 = 0.990$, $n = 10$, Park and Moon (1994)

Quercus acutissima

$\mathrm{Log}W_a = 2.094+2.417\mathrm{Log}(\mathrm{DBH})$ $r^2 = 0.990$, $n = 10$, Park and Moon (1994)
$\mathrm{Log}W_a = 1.799+2.693\mathrm{Log}(\mathrm{DBH})$ $r^2 = 0.994$, $n = 10$, Park *et al.* (1996)
$\mathrm{Log}W_a = -1.009+2.574\mathrm{Log}(\mathrm{DBH})$ $r^2= 0.978$, $n = 15$, Noh *et al.* (2007)
$\mathrm{Log}W_b = -0.634+1.772\mathrm{Log}(\mathrm{DBH})$ $r^2 = 0.962$, $n = 7$, Noh *et al.* (2007)

Pinus densiflora

$W_a = 0.0007\mathrm{DBH}^{1.951}\mathrm{H}^{2.142}$ $r^2 = 0.990$, $n = 10$, Lee (1985)
$\mathrm{Log}W_s = 1.684+0.828\mathrm{Log}(\mathrm{DBH}^2\mathrm{H})$ $r^2 = 0.990$, $n = 5$, Lee *et al.* (2006)
$\mathrm{Log}W_a = 2.582+1.592\mathrm{Log}(\mathrm{DBH})$ $r^2 = 0.959$, $n = 10$, Park and Kim (1989); Park and Lee (1990)
$\mathrm{Log}\ W_b = 1.787+1.730\mathrm{Log}(\mathrm{DBH})$ $r^2 = 0.969$, $n = 3$, Park and Kim (1989); Park and Lee (1990)
$\mathrm{Log}W_a = 2.272+2.149\mathrm{Log}(\mathrm{DBH})$ $r^2 = 0.999$, $n = 10$, Park and Kim (1989); Park and Lee (1990)
$\mathrm{Log}W_b = 1.717+1.972\mathrm{Log}(\mathrm{DBH})$ $r^2 = 0.971$, $n = 3$, Park and Kim (1989); Park and Lee (1990)
$\mathrm{Log}W_a = 2.269+2.152\mathrm{Log}(\mathrm{DBH})$ $r^2=0.996$, $n=10$, Park and Kim (1989); Park and Lee (1990)
$\mathrm{Log}W_b = 2.553+1.210\mathrm{Log}(\mathrm{DBH})$ $r^2 = 0.984$, $n = 3$, Park and Kim (1989); Park and Lee (1990)
$\mathrm{Log}W_a = 1.775+2.470\mathrm{Log}(\mathrm{DBH})$ $r^2 = 0.998$, $n = 10$, Park and Kim (1989); Park and Lee (1990)
$\mathrm{Log}W_b = 1.367+2.099\mathrm{Log}(\mathrm{DBH})$ $r^2 = 0.971$, $n = 3$, Park and Kim (1989); Park and Lee (1990)

Pinus rigida

$\mathrm{Log}\ W_s = 1.270+1.022\ \mathrm{Log}(\mathrm{DBH}^2\mathrm{H})$ $r^2 = 0.990$, $n = 5$, Kwon and Lee (2006d)
$\mathrm{Log}W_s = -1.642+0.977\mathrm{Log}(\mathrm{DBH}^2\mathrm{H})$ $r^2 = 0.962$, $n = 9$, Lee *et al.* (1985)
$\mathrm{Log}W_s = -1.504+0.928\mathrm{Log}(\mathrm{DBH}^2\mathrm{H})$ $r^2 = 0.954$, $n = 9$, Lee *et al.* (1985)

Pinus koraiensis

$\mathrm{Log}W_a = 1.388+0.954\ \mathrm{Log}(\mathrm{DBH}^2\mathrm{H})$ $r^2 = 0.990$, $n = 9$, Kwon and Lee (2006e)
$\mathrm{Log}W_a = -2.679+2.486\mathrm{Log}(\mathrm{DBH})$ $r^2 = 0.978$, $n = 5$, Lee *et al.* (2009)
$\mathrm{Log}W_b = -1.268+1.638\mathrm{Log}(\mathrm{DBH})$ $r^2 = 0.955$, $n = 5$, Lee *et al.* (2009)
$\mathrm{Log}W_s = -1.1579+0.9297\mathrm{Log}(\mathrm{DBH})$ $r^2 = 0.984$, $n = 10$, Lee and Park (1987)
$\mathrm{Log}\ W_a = -0.856+2.386\ \mathrm{Log}(\mathrm{DBH})$ $r^2 = 0.974$, $n = 20$, Son *et al.* (2001)
$\mathrm{Log}\ W_s = -1.2889+1.2152\mathrm{Log}(\mathrm{DBH})$ $r^2 = 0.960$, $n = 21$, Yi (1998)

Larix leptolepis

$\mathrm{Log}W_a = -1.175+2.580\mathrm{Log}(\mathrm{DBH})$ $r^2 = 0.991$, $n = 15$, Noh *et al.* (2006)
$\mathrm{Log}W_b = -1.648+2.566\mathrm{Log}(\mathrm{DBH})$ $r^2 = 0.955$, $n = 5$, Noh *et al.* (2006)
$\mathrm{Log}\ W_a = -0.726+2.234\mathrm{Log}(\mathrm{DBH})$ $r^2 = 0.903$, $n = 10$, Kim *et al.* (1996)
$\mathrm{Log}W_a = -1.071+2.459\mathrm{Log}(\mathrm{DBH})$ $r^2 = 0.975$, $n = 25$, Kim (2008)
$\mathrm{Log}W_b = -2.097+2.792\mathrm{Log}(\mathrm{DBH})$ $r^2 = 0.920$, $n = 10$, Kim (2008)

Table 2. Mean aboveground biomass densities (Mg ha^{-1}), mean belowground biomass densities and root/shoot ratio values for the different forest types in the different age classes based on the publications in Korea (n: data numbers, SD: standard deviation).

Age class[a]	Coniferous forests			Deciduous forests			Mixed forests		
	Above-ground	Below-ground	R	Above-ground	Below-ground	R	Above-ground	Below-ground	R
II	46.221 (n = 11, SD = 19.583)	12.484 (n = 9, SD = 6.418)	0.264 (n = 9, SD = 0.078)	52.500 (n = 2, SD = 19.091)	22.700 (n = 1)	0.344 (n = 1)	47.187 (n = 13, SD = 18.855)	13.506 (n = 10, SD = 6.859)	0.272 (n = 10, SD = 0.077)
III	116.340 (n = 11, SD = 48.444)	40.206 (n = 5, SD = 21.911)	0.279 (n = 5, SD = 0.063)	113.880 (n = 9, SD = 65.836)	29.408 (n = 6, SD = 8.498)	0.202 (n = 6, SD = 0.055)	115.230 (n = 20, SD = 55.333)	34.316 (n = 11, SD = 16.121)	0.229 (n = 11, SD = 0.067)
IV	145.620 (n = 16, SD = 64.549)	33.303 (n = 10, SD = 20.715)	0.246 (n = 10, SD = 0.084)	136.49 (n = 23, SD = 84.580)	36.999 (n = 15, SD = 13.840)	0.253 (n = 15, SD = 0.073)	136.120 (n = 41, SD = 76.515)	34.901 (n = 27, SD = 16.119)	0.267 (n = 27, SD = 0.096)
V	137.310 (n = 8, SD = 62.386)	37.784 (n = 7, SD = 20.732)	0.265 (n = 7, SD = 0.069)	178.270 (n = 8, SD = 70.474)	36.449 (n = 5, SD = 4.154)	0.175 (n = 5, SD = 0.029)	157.790 (n = 16, SD = 67.686)	37.228 (n = 12, SD = 15.531)	0.227 (n = 12, SD = 0.071)
VI	185.710 (n = 4, SD = 97.873)	42.693 (n = 2, SD = 12.959)	0.306 (n = 2, SD = 0.063)	204.750 (n = 14, SD = 88.019)	41.291 (n = 10, SD = 8.551)	0.180 (n = 10, SD = 0.024)	193.610 (n = 17, SD = 85.145)	41.525 (n = 12, SD = 8.683)	0.201 (n = 12, SD = 0.057)

[a] Age class means that the forest ages are younger than 20 years old for class II, 30 years old for class III, 40 years old for class IV, 50 years for class V and over 50 years old for class VI.

Because the forest inventories recorded detailed information on the total area and age class for each forest type according to the region, the regional aboveground and total biomass carbon storage were estimated for each age class of different forest types using equation (1) and the mean values in Table 2. Tables 3 and 4 summarize the regional aboveground and total biomass carbon stocks. The distributions of the aboveground and total biomass carbon storage for all forest types showed regional differences. Gangwon-do and Gyeongsangbuk-do provinces markedly occupied greater aboveground (77.211 Tg C and 70.367 Tg C) and total biomass carbon storage (95.721 Tg C and 87.856 Tg C) for all forest types than the other regions, whereas Seoul city possessed the smallest aboveground and total biomass carbon storage (0.914 Tg C and 1.134 Tg C) of all forest types of all regions, mainly because Seoul city is primarily an industrial and urban hub holding the highest population density in Korea (Tak *et al.*, 2007). The aboveground and total biomass carbon storage of age classes III and IV for each region had higher values than those of the other age classes and also varied within each region. Summing the aboveground and total biomass carbon storage of age classes III and IV for all regions, the ratios of the aboveground and total biomass carbon storage to the corresponding national biomass carbon storage were 74.4% and 74.9%. In other words, age classes III and IV made major contributions to carbon sequestration by Korean forests, which is also in accordance with the statistical documents. Statistical Yearbook of Forestry (2009) demonstrated that the ratios of the total area and total stem volume of age classes III and IV to that of all age classes were 67.2% and 71.4%.

Discussion

The aboveground and total biomass carbon storage for all forest types of Korea were 350.201 Tg C and 436.724 Tg C in 2009 (Table 5). Such large carbon storage in Korean forests is due mainly to the contribution of active plantation growth and management practices. Over the past four decades, plantations by nationwide reforestation have accounted for more than 70% of the observed carbon storage (261.698 Tg C for the aboveground biomass and 327.085 Tg C for the total biomass of age classes III and IV). Choi *et al.* (2002) estimated a carbon content of 200 Tg C in the total Korean forest biomass during the period 1973-2000 and reported an annual uptake rate of 12 Tg C yr^{-1} in the late 1990s after the 30-year forest restoration programs. If this annual uptake rate is used to estimate the carbon changes in Korean forests since 2000 while the forest growth rates vary within different periods, the estimated value of 320 Tg C in 2009 was still lower than the present result (436.724 Tg C). The discrepancy between values might result from the different methods used. For example, Choi *et al.* (2002) used the biomass expansion factor method to estimate the carbon content in the total Korean forest biomass based on the stem volume data.

The land-based Global Forest Resources Assessment 2005 (FRA2005), released by the UN Food and Agriculture Organization (FAO 2006) who has been coordinating global forest resources assessments every five to ten years since 1946, provides available information on the forest biomass carbon storage of Democratic Peo-

Table 3. Regional distribution of aboveground biomass carbon storage (Tg C) for the different forest types in the different age classes in Korea.

Region	Forest type	Age class[a]					
		All	II	III	IV	V	VI
Seoul	Coniferous	0.086	0.002	0.060	0.015	0.007	0.001
	Deciduous	0.524	0.001	0.082	0.368	0.055	0.018
	Mixed	0.304	0.002	0.084	0.165	0.036	0.017
Busan	Coniferous	0.953	0.031	0.234	0.671	0.015	0.002
	Deciduous	0.450	0.008	0.068	0.340	0.029	0.005
	Mixed	0.847	0.009	0.172	0.642	0.023	0.001
Daegu	Coniferous	0.859	0.251	0.478	0.108	0.023	0.000
	Deciduous	0.320	0.042	0.123	0.119	0.027	0.009
	Mixed	1.251	0.086	0.559	0.549	0.037	0.021
Incheon	Coniferous	0.459	0.023	0.266	0.151	0.018	0.001
	Deciduous	0.915	0.027	0.544	0.312	0.030	0.002
	Mixed	0.878	0.022	0.391	0.442	0.023	0.000
Gwangju	Coniferous	0.802	0.036	0.231	0.525	0.010	0.000
	Deciduous	0.193	0.008	0.018	0.125	0.039	0.003
	Mixed	0.231	0.003	0.039	0.167	0.016	0.005
Daejeon	Coniferous	0.824	0.070	0.534	0.217	0.004	0.000
	Deciduous	0.497	0.025	0.305	0.153	0.011	0.002
	Mixed	0.321	0.022	0.204	0.095	0.000	0.000
Ulsan	Coniferous	1.367	0.107	0.791	0.449	0.012	0.009
	Deciduous	1.282	0.020	0.515	0.673	0.027	0.047
	Mixed	1.276	0.016	0.904	0.345	0.007	0.005
Gyeonggi-do	Coniferous	10.516	1.098	4.487	3.727	0.897	0.307
	Deciduous	11.961	0.445	2.997	6.002	2.082	0.434
	Mixed	7.911	0.241	3.898	3.361	0.370	0.041
Gangwon-do	Coniferous	22.597	4.661	7.502	6.652	2.937	0.846
	Deciduous	29.626	2.781	6.589	7.857	8.482	3.918
	Mixed	24.988	1.341	6.753	8.827	6.110	1.957
Chungcheong buk-do	Coniferous	12.016	1.644	5.287	4.181	0.700	0.205
	Deciduous	8.079	0.343	2.330	3.272	1.883	0.251
	Mixed	7.203	0.342	3.128	2.770	0.833	0.130
Chungcheong nam-do	Coniferous	11.024	0.966	5.336	4.396	0.276	0.049
	Deciduous	6.754	0.653	2.386	2.295	1.345	0.075
	Mixed	6.297	0.361	2.740	2.552	0.626	0.018
Jeollabuk-do	Coniferous	11.025	0.973	4.190	5.447	0.340	0.075
	Deciduous	9.553	0.600	2.549	3.764	1.514	1.126
	Mixed	5.240	0.277	2.447	2.225	0.167	0.124
Jeollanam-do	Coniferous	19.875	3.047	8.419	7.826	0.510	0.073
	Deciduous	7.171	0.910	2.240	2.574	0.607	0.839
	Mixed	8.280	0.531	4.110	3.429	0.167	0.043
Gyeongsang buk-do	Coniferous	27.059	4.985	12.422	7.009	2.154	0.490
	Deciduous	14.875	0.920	4.750	5.832	3.024	0.349
	Mixed	28.433	2.283	16.357	8.287	1.437	0.068
Gyeongsang nam-do	Coniferous	17.430	1.359	9.580	5.921	0.390	0.180
	Deciduous	9.096	0.711	2.191	3.382	1.978	0.834
	Mixed	13.998	0.513	7.111	5.182	0.650	0.542
Jejudo	Coniferous	1.554	0.065	0.421	0.558	0.219	0.291
	Deciduous	2.342	0.078	0.265	0.339	0.719	0.941
	Mixed	0.659	0.070	0.126	0.186	0.117	0.160
Total		350.201	33.007	137.214	124.484	40.981	14.514

[a] Age class means that the forest ages are younger than 20 years old for class II, 30 years old for class III, 40 years old for class IV, 50 years for class V and over 50 years old for class VI. A factor of 0.5 was used to convert carbon content from biomass.

Table 4. Regional distribution of total biomass carbon storage (Tg C) for the different forest types in the different age classes in Korea.

Region	Forest type	Age class[a]				
		All	II	III	IV	V	VI
Seoul	Coniferous	0.109	0.003	0.076	0.018	0.009	0.002
	Deciduous	0.646	0.001	0.099	0.461	0.064	0.021
	Mixed	0.379	0.002	0.103	0.209	0.044	0.020
Busan	Coniferous	1.196	0.039	0.299	0.836	0.019	0.003
	Deciduous	0.559	0.011	0.082	0.426	0.034	0.006
	Mixed	1.066	0.011	0.212	0.813	0.028	0.002
Daegu	Coniferous	1.091	0.317	0.611	0.134	0.029	0.000
	Deciduous	0.396	0.056	0.148	0.149	0.032	0.011
	Mixed	1.561	0.109	0.687	0.695	0.045	0.025
Incheon	Coniferous	0.582	0.029	0.341	0.189	0.022	0.001
	Deciduous	1.119	0.036	0.654	0.391	0.036	0.002
	Mixed	1.097	0.028	0.481	0.560	0.028	0.000
Gwangju	Coniferous	1.008	0.045	0.296	0.654	0.013	0.000
	Deciduous	0.239	0.011	0.021	0.157	0.046	0.004
	Mixed	0.290	0.004	0.048	0.211	0.020	0.007
Daejeon	Coniferous	1.046	0.088	0.683	0.270	0.004	0.000
	Deciduous	0.608	0.034	0.367	0.192	0.013	0.002
	Mixed	0.398	0.028	0.250	0.120	0.000	0.000
Ulsan	Coniferous	1.733	0.135	1.012	0.559	0.015	0.011
	Deciduous	1.577	0.027	0.619	0.844	0.032	0.055
	Mixed	1.582	0.020	1.111	0.438	0.008	0.006
Gyeonggi-do	Coniferous	13.306	1.388	5.739	4.643	1.135	0.402
	Deciduous	14.680	0.599	3.603	7.521	2.447	0.512
	Mixed	9.859	0.307	4.791	4.258	0.454	0.049
Gangwon-do	Coniferous	28.594	5.891	9.595	8.289	3.715	1.105
	Deciduous	36.091	3.738	7.919	9.844	9.966	4.623
	Mixed	31.036	1.706	8.299	11.184	7.497	2.351
Chungcheong buk-do	Coniferous	15.202	2.078	6.762	5.210	0.885	0.268
	Deciduous	9.871	0.461	2.801	4.100	2.212	0.296
	Mixed	8.967	0.435	3.845	3.509	1.022	0.156
Chungcheong nam-do	Coniferous	13.938	1.221	6.825	5.477	0.349	0.064
	Deciduous	8.290	0.877	2.868	2.876	1.581	0.088
	Mixed	7.849	0.459	3.367	3.233	0.769	0.022
Jeollabuk-do	Coniferous	13.904	1.229	5.359	6.787	0.430	0.099
	Deciduous	11.694	0.806	3.064	4.716	1.779	1.328
	Mixed	6.532	0.352	3.007	2.819	0.205	0.150
Jeollanam-do	Coniferous	25.111	3.852	10.768	9.751	0.645	0.096
	Deciduous	8.846	1.223	2.693	3.226	0.714	0.990
	Mixed	10.328	0.675	5.052	4.344	0.205	0.052
Gyeongsang buk-do	Coniferous	34.285	6.300	15.887	8.733	2.725	0.640
	Deciduous	18.218	1.236	5.710	7.308	3.553	0.412
	Mixed	35.353	2.904	20.103	10.500	1.763	0.082
Gyeongsang nam-do	Coniferous	22.076	1.717	12.253	7.378	0.494	0.235
	Deciduous	11.135	0.956	2.634	4.238	2.324	0.984
	Mixed	17.406	0.652	8.740	6.566	0.798	0.650
Jejudo	Coniferous	1.973	0.082	0.539	0.696	0.277	0.379
	Deciduous	2.804	0.105	0.318	0.425	0.845	1.110
	Mixed	0.815	0.089	0.154	0.236	0.143	0.193
Total		436.444	42.376	170.893	156.192	49.471	17.512

[a] Age class means that the forest ages are younger than 20 years old for class II, 30 years old for class III, 40 years old for class IV, 50 years for class V and over 50 years old for class VI. A factor of 0.5 was used to convert carbon content from biomass.

Table 5. Forest area, aboveground and total biomass carbon storage (Tg C) of the different forest types in Korea.

Forest type	Forest area[a] (M ha)	Aboveground C	Total C
Coniferous	2.680	138.447	175.154
Deciduous	1.659	103.638	126.772
Mixed	1.853	108.115	134.518
Bamboo	0.007	…	0.280
Total	6.199	350.201	436.724

[a]Excluding non-wooded land (Statistical Yearbook of Forestry 2009). A factor of 0.5 was used to convert carbon content from biomass.

Table 6. Estimation of forest biomass carbon storage of East Asian countries.

Country	Forest area (M ha)	Ratio (%) of forest area to land area	Total carbon in forest biomass (Tg C)	Mean biomass carbon density (Mg ha^{-1})	Reference
China	197.290	21.2	6096	30.899	FAO (2006)
Democratic People's Republic of Korea	6.187	51.4	232	37.498	FAO (2006)
Japan	24.868	68.2	1892	76.082	FAO (2006)
Mongolia	10.252	6.5	574	55.989	FAO (2006)
Republic of Korea	6.199	62.096	436.724	70.451	This study
Total	244.796		9230.724		
Mean		41.879		54.184	

ple's Republic of Korea and Mongolia. This study used the data set from the FRA2005 and summarized the national total biomass carbon storage of East Asian countries to compare the size of carbon storage with Korea (Table 6). With a total forest area of 244.796 M ha for these countries, the total carbon storage was 9230.724 Tg C, and the mean carbon density was 54.193 Mg C ha^{-1}. With a relatively small forest area, the carbon storage in Korean forest biomass was 436.724 Tg C, comprising approximately 1/20 of the total carbon storage of East Asian countries. Although the mean carbon density of Korea did not surpass Japan, Korea had the largest carbon sequestration rate of 1.5 Mg C ha^{-1} yr^{-1} in the late 1990s due to its reforestation and forest management practices (Choi *et al.*, 2002). The largest carbon storage in Chinese forest biomass was also due to extensive reforestation efforts (Fang *et al.*, 2001). Followed by China, the large carbon storage in Japan was a result of plantation regrowth, which accounted for approximately 80% of the observed carbon sinks by forest with a typical oceanic climate for plant growth (Fang *et al.*, 2005). Although Mongolia has slightly greater forest biomass carbon storage than Korea, almost half of its land comprises the Gobi desert, which has lesser < 10% forest cover. The Democratic People's Republic of Korea has higher forest cover than China and Mongolia but the lowest forest biomass C storage.

To estimate the forest sector carbon budget, the following four carbon pools are necessary: (1) down dead wood, (2) forest floor, (3) soil organic C, and (4) forest products (Woodbury *et al.*, 2007). With the exception of forest products, there is no information on the other three carbon pools at the national level in Korea. However, the ratios of carbon pools examined in the United States could be used to approximate the carbon budget in the Korean forest sector due to the similar climatic conditions compared to the eastern United States. The ratios of carbon storage in the United States for living vegetation (trees and understory), down dead wood, forest floor, soil organic carbon and forest products (wood products and landfilled wood) were 0.36, 0.03, 0.08, 0.48 and 0.05, respectively (Woodbury *et al.*, 2007). If this ratio is used to estimate the carbon storage in different pools, then the nonliving carbon storage may be 776.398 Tg C, and the total carbon storage for the whole forest sector in Korea could be 1213.122 Tg C, of which 436.724 Tg C is stored in forest biomass. This is substantial carbon storage considering the land area of Korea.

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