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Allometric equations, stem density and biomass expansion factors for *Cryptomeria japonica* in Mount Halla, Jeju Island, Korea

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Abstract

This study was conducted to develop allometric equations and to determine the stem density and biomass expansion factor (BEF) for the estimation of the aboveground and belowground biomass of *Cryptomeria japonica* in Jeju Island, Korea. A total of 18 trees were harvested from the 40-year-old *C. japonica* stands in Hannam experimental forest, Jeju Island. The mean biomass of the *C. japonica* was 50.4 Mg ha^{-1} in stem wood, 23.1 Mg ha^{-1} in root, 9.6 Mg ha^{-1} in branch, 4.6 Mg ha^{-1} in needle and 4.3 Mg ha^{-1} in stem bark. The diameter at breast height (DBH) was selected as independent variable for the development of allometric equations. To evaluate the performance of these equations, coefficient of determination (R^2) and root mean square error (*RMSE*) were used and results of the evaluation showed that R^2 ranged from 71% (root biomass equation) to 96% (aboveground biomass equation) and the *RMSE* ranged from 0.10 (aboveground biomass equation) to 0.33 (root biomass equation). The mean stem density of *C. japonica* was 0.37 g cm^{-3} and the mean aboveground BEF was 1.28 g g^{-1}. Furthermore, the ratio of the root biomass to aboveground biomass was 0.32.

Key words: allometric equation, biomass, biomass expansion factor, *Cryptomeria japonica*, Mount Halla, stem density

INTRODUCTION

Jeju Island is located in the southernmost part of Korea between 33°11′27″–33°33′50″ N and 126°08′43″–126°58′20″ E (Lee et al. 2009). The highest mountain in South Korea, Mount Halla, can be found in this island (highest peak: 1,950 m above sea level). This island has a total land area of 184,840 ha (1 ha = 10^4 m^2) and approximately 88,874 ha (48%) of this island has forest cover (Korea Forest Service 2012). A forest (approximately 1,203 ha) is located in the Hannam experimental forest, southeast of Mount Halla. This forest has diverse and essential roles because it is considered as timber production forest, recreational forest, water conservation forest, environmental conservation forest, and seed orchard (Korea Forest Service 2014). However, there is still insufficient study on the biomass of this forest, specifically for the *Cryptomeria japonica* that is considered as one of the most dominant tree species in the Hannam experimental forest.

Forest ecosystems are very important as they are considered as a major sink for carbon and have the potential to release this carbon in cases of deforestation and degradation (Lim et al. 2013). According to Dixon et al. (1994), approximately 80% of all aboveground carbon (C) and 40% of belowground C were stored in the forest biomass. Based on the United Nations Framework Convention on Climate Change (UNFCCC), different countries are mandated to accurately determine the biomass and carbon stocks available in their forests and regularly report their forest resources status (Levy et al. 2004, Basuki

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et al. 2009, Kim et al. 2011). Biomass estimations in forests have become a major research interest because of the significant role of forests in global climate change (Watson et al. 2000, Lehtonen et al. 2004, Tobin and Nieuwenhuis 2007, Bollandsas et al. 2009, Teobaldelli et al. 2009, Li et al. 2010). Therefore, accurately estimating the biomass of forests is a critical step in the estimation of carbon stored in the forest (Xiao and Ceulemans 2004, Fehrmann et al. 2008, Chung et al. 2009, Hosoda and Iehara 2010).

The 5th National Forest Inventory (NFI) in Korea was conducted from 2006 to 2010 by the Korea Forest Service to determine the state of the forests, but one of the disadvantages of the forest inventory data was the lack of direct biomass measurements (Lehtonen et al. 2004). Teobaldelli et al. (2009) suggested the allometric equations as one of the methods that can be applied to determine the biomass of the forests by using the data from the NFI. Various authors (Fang and Wang 2001, Tobin and Nieuwenhuis 2007, Lim et al. 2013) also suggested using stem densities and biomass expansion factors (BEF), which convert stem volume to total tree biomass including branches and leaves (Li et al. 2010). BEF can be applied in the NFI data to estimate the biomass in the forests. Such interpretations of forestry data and retrospective calculation of biomass are widely accepted as the Intergovernmental Panel on Climate Change (IPCC) guidelines (IPCC 2003) recommended stem density and BEF could be used to accurately estimate biomass and carbon stocks of a forest (Korea Forest Research Institute 2010). However, allometric equations for *C. japonica* in Jeju Island have not been developed before and information on the stem density and BEF for this species is still lacking. Thus, the objective of this study was to develop allometric equations for the biomass estimation and to measure the stem density and BEF of *C. japonica* in Jeju Island, Korea.

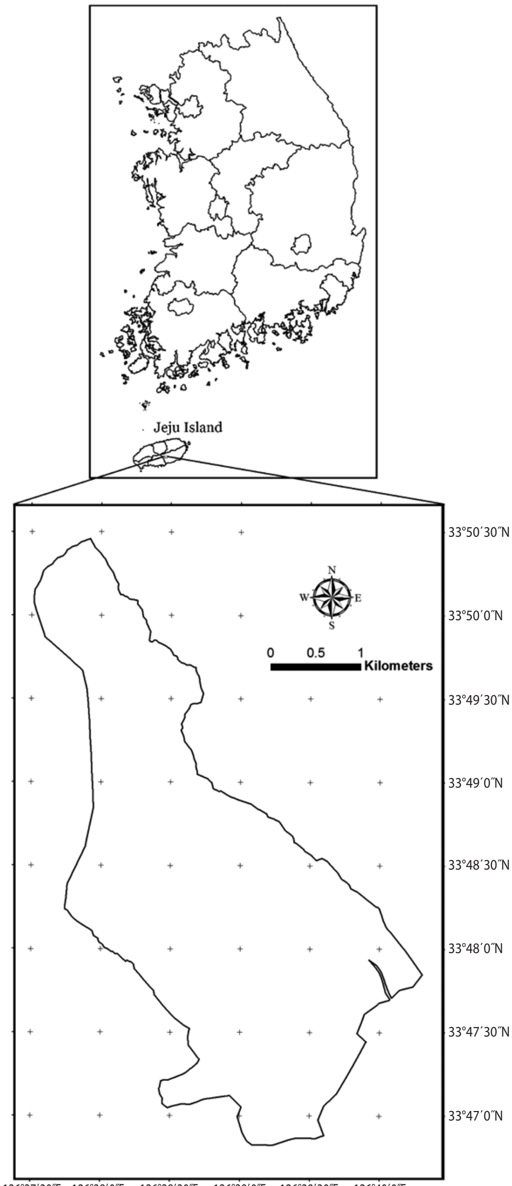

Fig. 1. Geographic location of the Hannam Experimental Forest in Jeju Island, South Korea.

MATERIALS AND METHODS

Study site

In 1920, the *C. japonica* was one of the species used for the afforestation in Korea; it was also planted in Jeju Island during the 1970's afforestation. Approximately, 40,000 ha in Jeju Island were planted with *C. japonica* (Korea Forest Research Institute 2006a). The study site was located in the Hannam experimental forests in Jeju Island with a coordinates of 33°21′ N and 126°39′ E (Fig. 1). Specifically, this study was conducted in the even-aged (40-year-old) *C. japonica* forest stands. The lower vegetation in this area is comprised of *Neolitsea aciculata, Ardisia japonica,* and *Osmunda japonica*. The elevation of this experimental forest ranged from 400 m to 800 m above sea level (Korea Forest Service 2014). Based on the three decades (1981-2010) climate records, the mean annual precipitation was 1,887 mm and mean annual temperature was 16.40°C, with a minimum mean annual temperature of 13.30°C and mean maximum annual temperature of 20.00ºC (Korea Meteorological Administration 2013). The soil type in the *C. japonica* stands was silt loam with a soil acidity of 5.4 (Korea Forest Research Institute 2005).

Data collection

Plots with a size of 30 m by 30 m were established in the *C. japonica* stands. A total of 18 representative sample trees were selected based on their DBH class. Suppressed trees, wolf-trees, and damaged parts of trees were not measured or included in the estimations. These sample trees were harvested at 0.2 m from the ground, and their stem discs were collected in every 2 m log section starting from 0.2 m from the ground (e.g., 0.2 m, 1.2 m, 3.2 m, 5.2 m, etc.) as suggested by Korea Forest Research Institute (2010). The fresh weights of the stem discs were then measured, and they were dried after at 85°C until constant weights were observed. After collecting the stem discs, the remaining trunks were weighed to get the fresh weight by using a weighing scale. The stem wood volume was calculated using Smalian's formula, and the tip volume was calculated using the conical formula (Avery and Burkhart 2002). This calculation of volume is a common practice in Korea and is recommended by the Korea Forest Research Institute (2010). The calculated volumes by these formulas were added together to determine the total volume of each *C. japonica* tree. Other biomass components of the trees, such as needles and branches, were partitioned, and the total fresh weights were determined. A 350 g sample of each biomass component was collected and was also dried at 85°C of constant temperature until constant weight was reached (taking about 10-14 days). The roots of the harvested trees were excavated by using a fork crane, and the total fresh weight of the belowground biomass was determined on site after soils from the roots were removed. A 350 g root biomass samples were also collected and were dried at 85ºC until a constant weight was obtained.

Data analysis

The relationship of DBH to the different biomass components such as stem, stem wood, stem bark, needles, branches, and root and to the total biomass was analyzed. The model form used to develop the biomass equations was presented below:

$$Y = \exp\,[a + b^{*}\ln(\mathrm{X})],$$

where *Y* represents biomass (kg), *X* is DBH (cm), exp is the base of natural logarithm, and *a* and *b* are estimated parameters.

This model form was used in this study as it was recommended by the Korea Forest Research Institute (2006b) for Korean tree species and was previously used to develop biomass equations for the different Korean tree species (Park and Moon 1994, Kim et al. 1995, Son and Kim 1998, Son et al. 2001, Seo et al. 2013). To correct the bias in log-transformed allometric equations, Sprugel correction factors (Sprugel 1983) were used (Son and Kim 1998, Son et al. 2001, Annighofer et al. 2012) and was calculated as:

$$CF = \exp\,(\mathrm{SEE}^2/2),$$

where CF represents correction factor and SEE is standard error of estimate.

The collected data were statistically analyzed by using SAS 9.1 (SAS Institute Inc. 2004). The coefficient of determination (R^2) and root mean square error (*RMSE*) were determined for the performance evaluation of the developed allometric equations. These were calculated as:

$$R^2 = 1 - \left[\frac{\sum_{i=1}^{n} (Y_i - \hat{Y}_i)^2}{\sum_{i=1}^{n} (Y_i - \bar{Y})^2} \right]$$

$$RMSE = \sqrt{\sum_{i=1}^{n} (Y_i - \hat{Y}_i)^2 / n},$$

where Y_i = observed biomass for the *i*th tree, $\hat{Y}_i$ = predicted biomass for the *i*th tree, $\bar{Y}$ = observed mean biomass, and *n* = number of observations.

Stem density was calculated by dividing the dry weight of the stem (biomass) by its total volume (g cm^{-3}) (IPCC 2006). BEF was determined by dividing the biomass of the upper part of a tree (such as branches and foliage) by the stem biomass (stem wood and bark) (Hosoda and Iehara 2010, Korea Forest Research Institute 2010).

RESULTS AND DISCUSSION

Biomass estimation and allometric equation

Results of the data collection showed that the mean DBH was 20 cm ranging from 13 to 28 cm. For the total height, the mean was 12 m ranging from 9 to 14 m and the mean age was 40 years ranging from 35 to 43 years (Table 1). Results also showed that the mean total biomass was

Table 1. Summary of the observed statistics of the harvested *Cryptomeria japonica* trees in Hannam experimental forest, Jeju Island, Korea

Variables	Mean (Range)	SD
Age (years)	40 (35-43)	2.00
DBH (cm)	20 (13-28)	4.60
Total height (m)	12 (9-14)	1.60

DBH, diameter at breast height; SD, standard deviation.

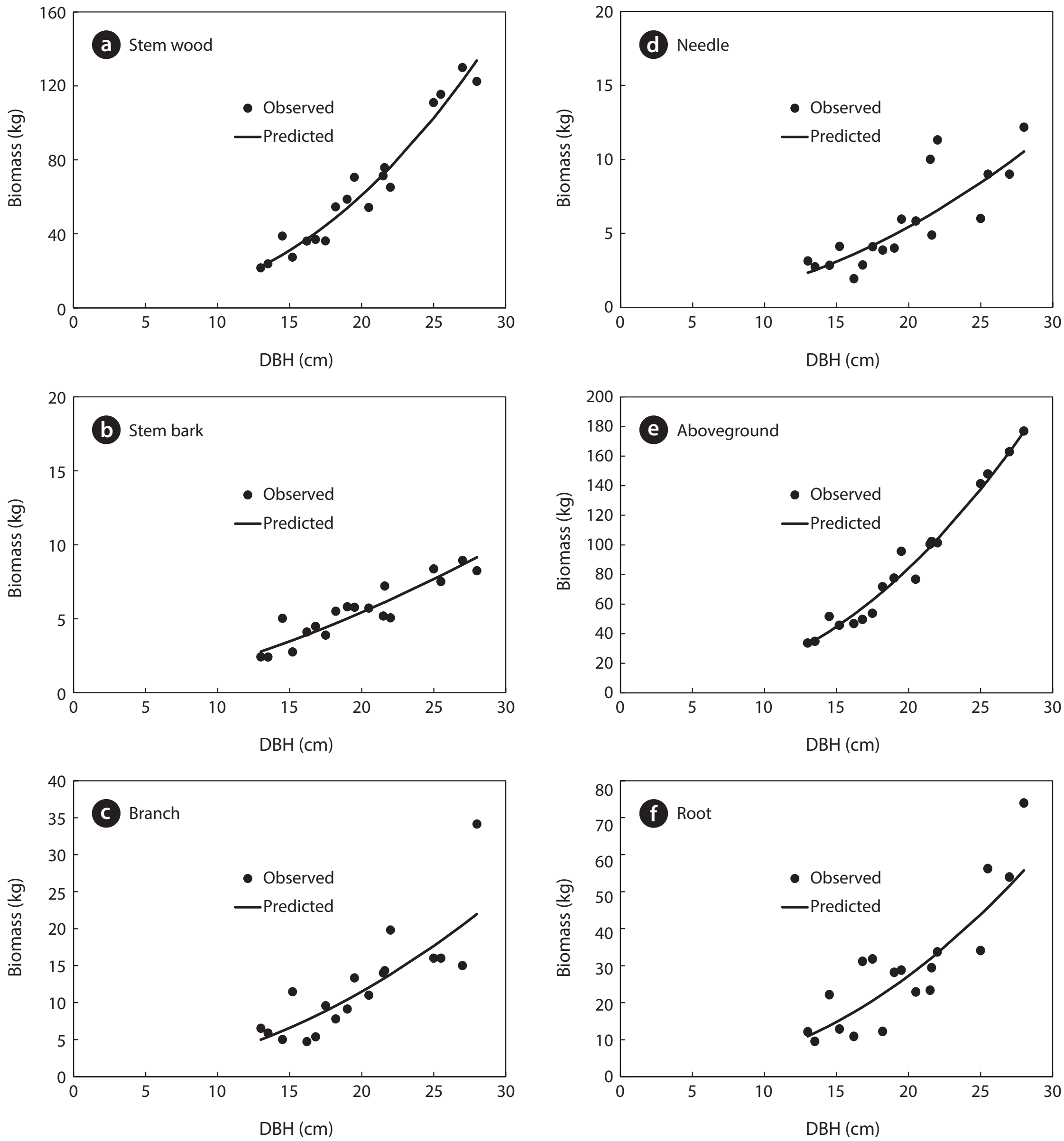

Fig. 2. Comparison between observed and predicted tree component biomass (kg) for *Cryptomeria japonica* in Hannam experimental forest, Jeju Island, Korea.

Table 2. Tree component biomass and the biomass distribution ratio of *Cryptomeria japonica* in Hannam experimental forest, Jeju Island, Korea

Tree component	Biomass (kg)	Biomass (Mg ha^{-1})	Biomass percentage (%)
Stem wood	63.90 (8.2)	50.40 (6.5)	55
Stem bark	5.40 (0.5)	4.30 (0.4)	5
Branch	12.20 (1.7)	9.60 (1.3)	10
Needle	5.80 (0.7)	4.60 (0.6)	5
Root	29.30 (4.1)	23.10 (3.2)	25
Total	116.60 (14.3)	92.00 (11.3)	100.0

Note: values are mean with standard error in parenthesis.

116.60 kg, with the stem wood having the highest mean biomass with 63.90 kg followed by root (29.30 kg), branch (12.30 kg), needle (5.80 kg), and stem bark (5.40 kg), respectively (Table 2). On the stand level, the biomass density of the *C. japonica* stand was 92 Mg ha^{-1}. In the study of Seo and Lee (2013), the estimated biomass of the *C. japonica* stands (21-40 year old) in Jangseong county in Korea was 227.77 Mg ha^{-1}. Kim et al. (1987) reported that the biomass density of the 20 year old *C. japonica* stand was 108.75 Mg ha^{-1}. The biomass densities of the previous studies were higher than those in the present study. This could be attributed to the stand density. The mean stand density of the present study was 789 trees ha^{-1} while the mean stand density in the study of Seo and Lee (2013) was 1,350 trees ha^{-1} and the mean stand density in the study of Kim et al. (1987) was 2,075 trees ha^{-1}. The stand density in the *C. japonica* stands in Hannam experimental forests was much lower due to the thinning activities conducted in this forest.

For the biomass distribution, the stem wood accounted for the highest biomass percentage of 55%; followed by the root, 25%; branch, 10%; needle, 5%; and stem bark, 5% (Table 2). This result showed that excluding secondary tree biomass components like needles, branches, and roots was not recommended as it would significantly underestimate the total biomass and carbon storage potential of a forest (Peichl and Arain 2007, Seo et al. 2013). In comparison to the study of Seo and Lee (2013), the biomass distribution of the younger *C. japonica* stands (mean age of 11 years) was 45.50% in needle, 19.70% in stem wood, 16.70% in root, 14.80% in branch, and 3.20% in stem bark. This comparison showed that the biomass distribution percentage of the needle and branch biomass decreased while the stem wood biomass significantly increased as the age increased which was consistent with the study of Lim et al. (2013). Seo et al. (2013) also reported that biomass percentage of the needle and branch of *Pinus rigida* in Korea also decreased as the age increased. Furthermore, Peichl and Arain (2007) reported that age was a significant factor that affected the biomass partitioning or distribution.

Table 3. Allometric equations for the different tree biomass component of *Cryptomeria japonica* in Hannam experimental forest, Jeju Island, Korea

Tree component	*a*	*b*	*RMSE*	R^2	CF
Stem	-2.629	2.278	0.139	0.939	1.001
Stem wood	-2.911	2.343	0.139	0.943	1.001
Stem bark	-2.968	1.555	0.178	0.816	1.001
Branch	-3.340	1.930	0.294	0.714	1.003
Needle	-4.195	1.965	0.301	0.711	1.003
Aboveground	-2.155	2.199	0.103	0.963	1.000
Root	-3.059	2.124	0.327	0.709	1.003
Total	-1.777	2.169	0.116	0.953	1.000

a and *b*, estimated parameters; *RMSE*, root mean square error; R^2, coefficient of determination; *CF*, correction factor.

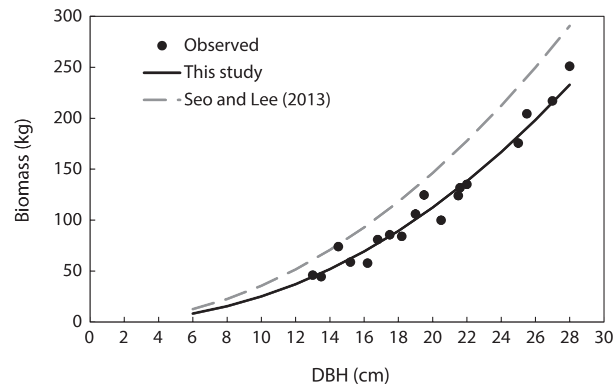

Fig. 3. Comparison between the biomass allometric equation developed in the previous study (Seo and Lee 2013) and that developed in this study for *Cryptomeria japonica* in Korea.

Allometric equations that estimated the different biomass components and total biomass of *C. japonica* in Jeju Island, utilizing DBH as predictor variable, were developed and compared to the observed biomass as shown in Fig. 2. Results of the evaluations showed that the R^2 ranged from 71% to 96% with the root biomass equation having the lowest R^2 while the aboveground biomass equation had the highest R^2 (Table 3). For the *RMSE*, it ranged from 0.10 to 0.33 with the aboveground biomass equation also having the best *RMSE* and the root biomass equation having the highest *RMSE*. The correction factor ranged from 1.001-1.003. The previously developed allometric equation for the biomass estimation of *C. japonica* in the Jangseong County (Seo and Lee 2013) was compared to the allometric equation developed in this study (Fig. 3). It showed that the equation of Seo and Lee (2013) had higher biomass prediction compared to the allometric equation of this study. Moreover, the predicted biomass of the developed allometric equation of this study was closer to the observed biomass than to the predicted biomass of the previously developed allometric equation. This could be attributed to the different site-specific factors, which according to other studies affect the allometric equations (Wang et al. 2000, Litton et al. 2003, Lehtonen et al. 2004). Lim et al. (2013) recommended that allometric equation must be site-specific to accurately assess the biomass and carbon stocks of the forests.

Total height was not used as a predictor variable in this

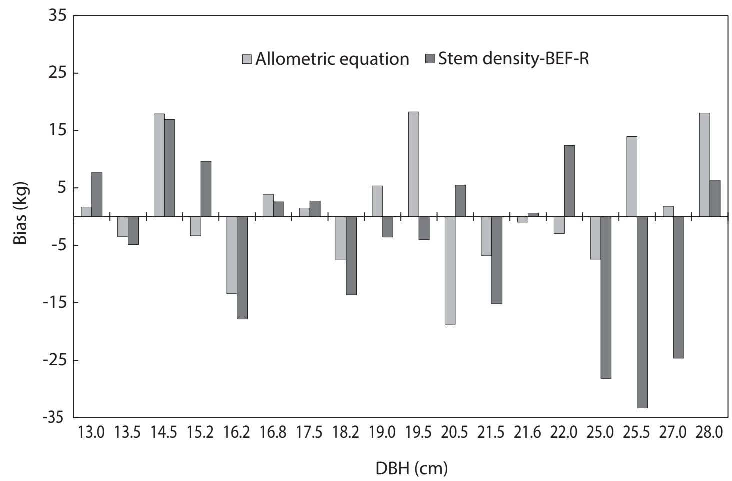

Fig. 4. Bias of the allometric equation and stem density-BEF-R in the biomass estimation of *Cryptomeria japonica* in Hannam experimental forest, Jeju Island, Korea. Stem density-BEF-R represents stem density, biomass expansion factor, and ratio of the root biomass to aboveground biomass, respectively.

study because in most forest inventories, such as the 5th NFI of Korea, only representative trees were measured for total height, due to the difficulty and high cost, while all the DBH of the trees in a plot were collected (Seo et al. 2013). Furthermore, Montagu et al. (2005) stated that DBH was considered as the best predictor variable in order to obtain a stable relationship. Various studies reported that DBH was sufficient to accurately estimate the tree biomass because of the difficulty to accurately measure the total height of the trees (Lim et al. 2013) and that adding total height as second variable did not significantly improve the biomass estimations of the models (Annighofer et al. 2012).

Stem density and biomass expansion factor

This study did not only estimate the biomass and develop allometric equations but it also determined the stem density, BEF, and the ratio of the root biomass to aboveground biomass (R) of the *C. japonica* in Hannam experimental forest. Results showed that the mean stem density of *C. japonica* was 0.37 g cm^{-3} (SD, 0.04; SD, standard deviation) that was comparable to the previous studies in Korea. Lim et al. (2013) determined that the stem density of *C. japonica* in the Gyeongnam and Jeonnam provinces was 0.40 g cm^{-3} while Seo and Lee (2013) reported that the stem density of this species were 0.38 g cm^{-3}, 0.34 g cm^{-3}, and 0.34 g cm^{-3} for the three age classes (<21 years, 21-40 years, and 41-60 years), respectively. In Japan, Fukuda et al. (2003) reported that the mean stem density of *C. japonica* was 0.35 g cm^{-3} that was comparable to the mean stem density of this study. The result of this study was also within range of the suggested basic wood density of the IPCC (2003) that was 0.32-0.44. This showed that there was no significant difference in the mean stem density between younger stands and older stands. Furthermore, there was also no significant correlation between stem density and age of the tree that were consistent with the study of Fujiwara et al. (2007) and Seo et al. (2013).

The estimated aboveground BEF of the *C. japonica* in Jeju Island was 1.28 g g^{-1} (SD, 0.10). This BEF is comparable to the results of the previous studies in Korea. Lim et al. (2013) reported that the BEFs of *C. japonica* were 1.37 g g^{-1} for the less than 30 age class, 1.30 g g^{-1} for the less than 40 age class, and 1.28 g g^{-1} for the less than 50 age class. Seo and Lee (2013) reported that the aboveground BEFs of this species were 1.30 for the 21 to 40 age class and 1.28 for the 41 to 60 age class. In Britain, Levy et al. (2004) studied the BEF of the different coniferous trees; the mean BEF was 1.43 ranging from 1.04 to 2.32. Furthermore, IPCC (2003) suggested a BEF value of 1.30, which was similar to the result of this study.

The R of *C. japonica* in this study was 0.32, and it was comparable to the result of the study of Lim et al. (2013). They reported that the mean R of *C. japonica* in Gyeongnam and Jeonnam in Korea was 0.28 with a range from 0.24 to 0.32. Seo and Lee (2013) reported that the R of the *C. japonica* stands were 0.20, 0.23, and 0.23 for the three age classes (<21 years, 21-40 years, and 41-60 years), respectively. In Japan, Fukuda et al. (2003) reported that the R values of the *Chamaecyparis obtuse* and *C. japonica* species were 0.23 and 0.20. The difference between the R values in this study to those in the previous studies might be attributed to the stand density and soil fertility as several researchers (Litton et al. 2003, Vanninen and Makela 2005, Peichl and Arain 2007) reported that stand density and soil fertility had an effect on R.

The total biomass that were predicted using both the allometric equation (method 1) and the stem density, BEF and R (method 2) were compared to the observed biomass of the 18 trees. The total biomass using method 2 was calculated as:

Total biomass = tree volume × stem density × BEF × R.

The biases of the two methods were determined as shown in Fig. 4. This comparison showed that the method 1 had a better predictive capability as compared to the method 2. A negative value in the bias indicates over prediction of total biomass while a positive value indicates under prediction of total biomass. The mean bias was also determined for the two methods. Method 1 had a mean bias of 1 kg while method 2 had a mean bias of -4.5 kg. Thus, the more suitable method to estimate the total biomass of *C. japonica* in Jeju Island was the allometric equation. This result was comparable to the study of Seo et al. (2013), which reported that the allometric equation also provided a better predictive capability than the stem density-BEF in the estimation of the aboveground biomass of *P. rigida* in Korea.

CONCLUSION

Allometric equation using DBH as predicting variable was developed, and the stem density, BEF, and R were determined to accurately estimate the biomass of *C. japonica* in Jeju Island. The performance of the allometric equation in estimating the total biomass of this species was compared to using the stem density-BEF-R. Based on the evaluation, it is recommended to use the allometric equation in order to have more accurate biomass estimation of *C. japonica* in Jeju Island. The results of this study provide forest managers a better tool for accurately assessment of the biomass and subsequently the carbon stocks in the *C. japonica* forests stand in Jeju Island, Korea which is considered as an international effort to address and mitigate climate change.

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