Estimating carbon storage and CO$_2$ absorption by developing allometric equations for Quercus acuta in South Korea

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ABSTRACT
This study was conducted to estimate C storage and CO$_2$ absorption by developing allometric equations for Quercus acuta in South Korea. Carbon content and CO$_2$ absorption were estimated according to climate change using data such as volume, stem density, and biomass expansion factor (BEF). Three kinds of BEFs were applied for this calculation: the national factor (NF, 1.22); the factor in this study (1.3275); and the biomass expansion regression equation (BRE) in this study. BRE among BEFs was developed to calculate BEF related to diameter at breast height (DBH) because BEF had a significantly positive relationship with DBH; the bigger DBH grew, the higher BEF increased. When applying the NF, C content and CO$_2$ absorption were the lowest as 64.0455 t C ha$^{-1}$ and 234.6840 t CO$_2$ ha$^{-1}$, respectively; whereas these were 69.6865 t C ha$^{-1}$ and 255.5165 t CO$_2$ ha$^{-1}$ for the factor in this study. The highest values of C content and CO$_2$ absorption were shown as 74.9280 t C ha$^{-1}$ and 274.7365 t CO$_2$ ha$^{-1}$ when using the BRE. Carbon content prediction equations were also developed using these BEFs. Thus, BRE is suitable for developing an allometric equation for C content prediction with the greatest R$^2$ adjusted of 0.9815.

Introduction
The industrial revolution of the last 150 years fostered excessive use of fossil fuels. Levels of CO$_2$ in the Earth’s atmosphere increased almost 50% between 1845 and 2010. The distribution of CO$_2$ varies by location and season, but the level of CO$_2$ is steady within 80 km of the aerosphere (Keeling et al. 1982; Cleveland et al. 1983; Komhyr et al. 1985).

Increasing CO$_2$ levels has become a major concern for climate change, and has caused problems such as global warming, rising sea level, desertification, and changes in weather. The effects of climate change produce unexpected and uncertain results in most societies and species throughout the world. For example, drought, flood, and negative effects on the drinking water supply and agriculture are caused by climate change. Many species in animal and plant communities have been confronted with the crisis of extinction, and it is difficult to maintain a safe water supply because of rising sea levels and the threat of salt immersion.

Climate change produced by increasing CO$_2$ levels in the atmosphere also affects forested areas. The flora of Korea has changed because of the rising annual mean temperature, and the northern limit line for plant growth has moved steadily northward. Furthermore, the biorhythms of plants are changing, and the time of flower blooms is getting earlier. Finally, trophic chains and overall biodiversity can be affected and changed. For these reasons, Tans et al. (1990) observed the global atmospheric CO$_2$ budget, Birdsey (1992) estimated the ability of C stock in the United States, McPherson and Simpson (1999) studied CO$_2$ reduction in urban forestry, and Kurz et al. (1992) reported methods to control atmospheric CO$_2$ increase using the forest ecosystem.

According to previous studies, forestation can be considered one of the most suitable methods for decreasing CO$_2$ levels in the atmosphere (Laclau 2003). Forests have been described as carbon sinks that absorb greenhouse gases from the atmosphere (Lee et al. 2008). In accordance with the 1997 Kyoto Protocol, all developed industrialized nations must cut back on their greenhouse gas emissions. The Kyoto Protocol took effect on 16 February 2005, and expired in 2012. During the first performance period (2008–2012), Korea still did not have to follow the Kyoto Protocol, but it will in the future. Thus, it is necessary to study forest carbon sinks in detail to protect the environment.

Much research has been done to estimate accurate C stock in forests on major species including: Pinus densiflora (Norisada et al. 2006; Kim 2008; Choi et al. 2009; Kim et al. 2009; Noh et al. 2010); Pinus thunbergii (Lee and You 2001; Son et al. 2013); Larix leptolepis (Nabeta 1994; Son and Hwang 2003; Umehara et al. 2004; Kim 2006); Liriodendron tulipifera (Jung et al. 2010; Kim et al. 2011; Kim et al. 2012); Chamaecyparis obtusa (Yokota and Hagihara 1996; Araki et al. 2010; Araki et al. 2015; Kim 2015); and Quercus serrata (Kitao et al. 2015), but studies on warm-temperate species are not enough. However, as the natural habitat of warm-temperate species might increase due to climate change, and those species would play a CO$_2$ sink role, it is considered that research on warm-temperate species must be expanded gradually. Therefore this study was conducted to estimate C content and absorption of CO$_2$ according to climate change, and to develop an allometric equation for Quercus acuta in Wando, Jeollanam-do, South Korea.

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Materials and methods

Materials

Wando Warm-Temperate Forest Arboretum, where this study was carried out, is located in Wando-gun, Jellanam-do, South Korea (34°21′46.2″N, 126°39′38.4″E) (Figure 1). This arboretum is a total of 2050 ha in area, and provides habitat for about 750 rare plants, so it has high scientific value. The main distribution species are Quercus acuta, Camellia japonica, Dendropanax trifidus, and Castanopsis cuspidata. The Q. acuta stand types are classified into four groups such as pure Q. acuta community, Q. acuta–C. japonica community, Q. acuta–Carpinus tschonoskii community, and Q. acuta–Q. serrata community (Kim et al. 2002). This study was conducted in the pure Q. acuta community. Quercus acuta is a representative warm-temperate species, and is distributed throughout 60% of the Wando Arboretum area.

Four sample plots were randomly selected in the study area, and one of them was established within a young stand to ensure age and diameter classes were distributed evenly (Table 1). The mean age was the highest at 38 years in sample plot 1, 35 years in sample plot 2, 31 years in sample plot 3, and 22 years in sample plot 2. The mean height was the highest at 15 m in sample plot 1, and 13 m, 11 m, and 9 m in sample plots 4, 3, and 2, respectively. Sample plots 4, 1, and 3 showed similar mean diameter at breast height (DBH) with 17 cm, 16 cm, and 15 cm, respectively, while sample plot 2 was 7 cm mean DBH. Altitude was the highest, at 402 m, in sample plot 4, 292 m, in sample plot 3, 268 m, in sample plot 3, and 226 m, in sample plot 3. For all sample plots, slope was less than 15°, and aspect was southwest.

Statistical methods

We used a regression equation with DBH as an independent variable, as follows:

\[ Y = \alpha X^\beta \]  

This equation is changed into a logarithmic regression equation, and becomes a simple linear model. There are several forms of logarithmic regression equations to estimate biomass (Table 2).

Height and DBH are universally used as independent variables in volume growth models. Previous studies verified that the suitability of applying both DBH and height might be superior to that of applying only DBH. Therefore, if the second and third equations, which use DBH and height as independent variables, are used, results may be more accurate than those using the first equation with only DBH. On the other hand, it is truly difficult to measure height accurately. For this reason, making predictive estimations using these regression formulas, which apply only the DBH factor, might be more efficient. Therefore, the regression formula \( Y = \alpha X^\beta \) was utilized for this study, because only the first logarithmic regression equation uses DBH as the independent variable rather than height.

Carbon content and CO2 absorption

Five sample trees per plot (total 20 trees) were cut down and dissected into stem, branch, foliage, and root. Stem was divided into 2 m length logs, and volume was calculated using the Huber formula. Stem disks were gathered from the middle of each log, and dried at 85 °C using a forced convection programmable dry oven (FCPO560, Lab House, Dongseo Science Co., Ltd., Korea). Stem density (SD) and biomass expansion factor (BEF) were calculated with dry weight and volume, and then used to compute C content and CO2 absorption using the following equations:

\[ \text{Total biomass (kg)} = \text{Abov ground biomass (kg) × BEF + REF - 1} \]  

\[ C_{\text{content (kgC)}} = \text{Biomass (kg) × CCF} \]  

\[ \text{CO2 absorption (kgCO2)} = C_{\text{storage (kgC)}} \times CO2CF \]

where, \( V \) is the aboveground volume, SD is the species-specific stem density. For these calculations we used BEFs in three ways: the national factor (NF, 1.22); this study’s factor (1.3275); and this study’s regression formula (\( Y = 0.7535 \times X^{0.22} \)). Moreover, 0.5 and 1.26 were used as the C conversion factor (CCF) and root expansion factor (REF), respectively (IPCC 2003). 44/12 was used for the CO2 conversion factor (CO2CF), which is the molecular weight of CO2.

Results

Biomass expansion factor

Aboveground BEF for Q. acuta was slightly higher than the national factor (1.22) at 1.3275, with a range from 1.062 to 1.712 (Table 3). After classifying the sample trees into under 20, 21–40, and over 41 years-of-age classes, changes of BEF over time, aboveground BEF, and the total BEFs of each age class were estimated. For trees under 20 years-of-age, the mean aboveground and total BEFs were 1.2247 and 1.2750, respectively, whereas for trees over 41 years, the mean aboveground BEF was 1.5080 and the total BEF was 1.9070. Thus, BEF was proportional to tree age.
There was a noticeable distinction between young and mature stands in the previous studies. The greater the DBH, the bulkier the branch and leaf volume. Seo (2008) also found the same result with a negative correlation between DBH and BEF for *Pinus densiflora*; whereas the BEF of *Q. acuta*, a broadleaf tree, increased with increasing DBH (Figure 2). For these reasons, it is not enough to estimate BEF of whole-life trees using a simple factor. Thus, we considered the relationship between BEF and DBH, and analyzed it using the regression equation. We found that BEF gradually increased with DBH, and formulated an equation with \( a = 0.7535 \) and \( b = 0.22 \):

\[
Y = 0.7535 \times X^{0.22} \tag{6}
\]

The \( R^2 \) (coefficient of determination) value was 0.5035 because the total number of sample trees was not sufficient. Thus, further research should increase the sample trees to increase the \( R^2 \) value.

### Carbon content and CO\(_2\) absorption

Three kinds of BEFs were applied, and C content and CO\(_2\) absorption were estimated with respect to each sample tree. As a result, the national factor (NF, 1.22) had the lowest values of 64.0455 t C ha\(^{-1}\) and 234.6840 t CO\(_2\) ha\(^{-1}\) for C content and CO\(_2\) absorption, respectively. When applying the biomass expansion regression equation (BRE) obtained from this study, the values of C content and CO\(_2\) absorption were the greatest at 74.9280 t C ha\(^{-1}\) and 274.7365 t CO\(_2\) ha\(^{-1}\), respectively (Table 4). For this reason, it is important to estimate BEF precisely, because the values of C content and CO\(_2\) absorption differ according to BEF. Consequently, the use of precise BEF estimates would enhance the value of the Korean forest in regard to carbon emission rights (CERs).

| BEF type | C content (t C ha\(^{-1}\)) | CO\(_2\) absorption (t CO\(_2\) ha\(^{-1}\)) |
|----------|----------------------------|------------------------------------------|
| NF\(^a\) | 64.0455                    | 234.6840                                 |
| BEF\(^b\) | 69.6865                    | 255.3165                                 |
| BRE\(^c\) | 74.9280                    | 274.7365                                 |

Notes: \(^a\)NF = national factor.  
\(^b\)BEF = biomass expansion factor obtained in this study.  
\(^c\)BRE = BEF regression equation developed in this study.

### Carbon content prediction equations by BEF type

| Coefficient | BEF type | \( \alpha \) | \( \beta \) | MSE | \( R^2 \) | Adjust \( R^2 \) | Pr > F |
|-------------|----------|--------------|-------------|-----|---------|----------------|--------|
| NF\(^a\)    | 0.1356   | 2.2489       | 89.7863     | 0.9711 | 0.9695 | 0.0001         |
| BEF\(^b\)   | 0.1475   | 2.2489       | 106.2985    | 0.9711 | 0.9695 | 0.0001         |
| BRE\(^c\)   | 0.0837   | 2.4689       | 85.6069     | 0.9825 | 0.9815 | 0.0001         |

Notes: \(^a\)NF = national factor.  
\(^b\)BEF = biomass expansion factor obtained in this study.  
\(^c\)BRE = BEF regression equation developed in this study.

![Figure 1. Location of the study area.](image1)

![Figure 2. Relationship between DBH and BEF of *Quercus acuta*.](image2)

Figure 3. Simple linear regression analysis of C contents predicted by NF, BEF, and BRE.
analysis, even though NF and BEF (at 1.22 and 1.3275, respectively) were similar with the same $R^2$ and adjust $R^2$ values (0.9711, 0.9695), MSE (89.7863) of NF was lower than that of BEF (106.2985). On the other hand, in the case of BRE, there was a higher exponent of C content prediction equation than for others, so the C content of this equation is more accurate with the increase of DBH. In addition, using BRE could predict more accurate C content as the adjusted $R^2$ value is higher than the other BEFs, 0.9815 as compared to 0.9695. Thus, it is true that all forecasting C content had a $P$ value of $>0.05$ and adjusted $R^2$ of $>0.96$, so the created models are really useful. In particular, the model developed by using BRE was the best one with the highest C content (Figure 4).

**Simulation of three different predictable models**

Carbon content and CO₂ absorption were simulated with respect to a virtual tree of *Q. acuta* using BEFs and BRE models (Table 6). When a tree reached 25 cm DBH, the values of C content and CO₂ absorption showed the highest values at 221.07 t C ha⁻¹ and 810.60 t CO₂ ha⁻¹, respectively, when applying BRE. These figures were higher than using NF (1.22) and BEF (1.3275). The main reason was because BEF of *Q. acuta* increases relative to the rising DBH if using the biomass regression equation. In addition, the more DBH increases, the greater the gap of predicted C content and CO₂ absorption between BRE and the other two different BEFs would occur. Thus, the economic and public value of forests will increase in terms of large-scale forest management using BRE.

**Discussion**

To compare our results with those of the previous studies (Table 7), BEFs of *Pinus densiflora* for. *erecta* were 1.432 for trees under 20 years of stand age and 1.200 for trees between 40 and 60 years of stand age. Those of *Pinus densiflora* in the central regions of Korea were 2.377 and 1.362, respectively (Park et al. 2005). Moreover, *Pinus rigida* BEFs were 1.278–1.355 and 1.082–1.004 for trees under 20 years and between 40 and 60 years of stand age classes (Seo et al. 2006). BEFs of trees under 20 years, between 21 and 40 years, and between 40 and 60 years of age for *Chamaecyparis obtusa* were 2.664, 1006, and 1.002, respectively (Lee et al. 2006). Aboveground BEFs of the result from the previous research on *Q. acuta* ranged from 1.168 to 1.324 according to the age classes (Lee et al. 2007). There was a single difference between *Q. acuta* and other species; that is, BEFs of *Q. acuta* increased over time while those of other species decreased. For *Q. acuta*, the amount of leaf and branch growth was proportionally greater than stem growth, whereas other species had low rates of growth for both leaf and branch in proportion to stem growth. Also, there might be a noticeable relationship between BEF and the number of trees because *Q. acuta* stand of this study with 1000N ha⁻¹ had BEF values higher than those of the previous study at 2000 N ha⁻¹ (Lee et al. 2007).

Lee et al. (2005) conducted a similar study to estimate aboveground C contents in the same study area using the functional model ($\text{Biomass} = \alpha \times \text{DBH} + \beta \times \text{DBH}^2$) with 0.9685 $R^2$. As can be seen from the predicted C content over DBH in Figure 5, these curves are quite similar to each other.

**Table 6.** Carbon contents and CO₂ absorption for simulating a virtual tree which has 25 cm DBH, by biomass expansion factors gathered from previous and this study (aboveground only).

| BEF type | DBH (cm) | Volume (m³ ha⁻¹) | Carbon content (t C ha⁻¹) | CO₂ absorption (t CO₂ ha⁻¹) |
|----------|----------|------------------|--------------------------|-----------------------------|
| NF²      | 25.0     | 278.5            | 176.30                   | 646.44                      |
| BEF³     | 25.0     | 278.5            | 191.83                   | 703.39                      |
| BRE⁴     | 25.0     | 278.5            | 221.07                   | 810.60                      |

Notes: *NF = national factor.*

²BEF = biomass expansion factor obtained in this study.

³BRE = BEF regression equation developed in this study.

**Table 7.** BEFs of previous studies by both species and stand age.

| Species                        | Stand age (years) | BEF   | Source                  |
|-------------------------------|-------------------|-------|-------------------------|
| *Pinus densiflora* for. *erecta* | ≤ 20              | 1.432 | Park et al.             |
|                               | 21–40             | 1.235 | 2005                    |
|                               | 41–60             | 1.200 |                         |
| *Pinus densiflora* in the middle of Korea | ≤ 20              | 2.377 | Park et al.             |
|                               | 21–40             | 1.721 | 2005                    |
|                               | 41–60             | 1.362 |                         |
| *Pinus rigida*                | ≤ 20              | 1.278– | Seo et al. 2006        |
|                               | 20–40             | 1.235 |                         |
|                               | 41–60             | 1.324 |                         |
| *Quercus acuta*               | ≤ 20              | 1.168 | Lee et al. 2007        |
|                               | 20–40             | 1.255 |                         |
|                               | 41–60             | 1.324 |                         |
| *Chamaecyparis obtusa*        | ≤ 20              | 2.664 | Lee et al. 2006        |
|                               | 21–40             | 1.006 | 2006                    |
|                               | 41–60             | 1.002 |                         |

![Figure 5. Comparison of aboveground C content of Quercus acuta between this study and a previous study (Lee et al. 2005) conducted at the same place with different sample plots.](image-url)
The C content of trees in this study is slightly higher than that of the previous study, but not significantly so. Also, they reach up to approximately 250 t C ha$^{-1}$ when DBH is 25 cm.

The purpose of this study was to provide basic information to help increase the public value of forests. As a result, forest carbon sink function can be reinforced by adding C storage of $Q.\ acuta$ species to the national carbon stock inventory. Thus, the results of this study will be useful to plan large-scale forest works and evaluate forests’ public value or function.

**Conclusion**

This study was conducted to estimate C content and CO$_2$ absorption of $Q.\ acuta$ in Wando Warm-Temperate Forest Arboretum in South Korea by developing the C content models, and three BEFs (NF, BEF, and BRE) as coefficients for biomass expansion factor. As a result, BEF was changed according to stand age classes and DBH; BEF of biomass expansion factor. As a result, BEF was changed according to stand age classes and DBH; BEF of $Q.\ acuta$ was increased, whereas that of coniferous species was decreased. This result emphasizes that the growth of root, branch, and foliage is greater than that of stem in the case of $Q.\ acuta$ species. Furthermore, this study provides evidence confirming that the C storage model developed using BRE is more accurate than using BEFs. The BRE model showed slightly higher R$^2$ and lower MSE than BEF models. Consequently, $Q.\ acuta$ has the competitive advantage of high biomass production and C storage related with DBH, and enhances forest carbon sink function.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

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