Volumetric equation development and carbon storage estimation of urban forest in Daejeon, Korea

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\textbf{ABSTRACT}

This study was performed to develop equations which are suitable for estimating carbon storage of urban forest in Daejeon, Korea and to evaluate carbon storage and sequestration of urban forest using developed equations. Along the urban forest, we only concern about the major street tree species (\textit{Platanus occidentalis}, \textit{Ginkgo biloba}, \textit{Zelkova serrata}, \textit{Chionanthus retusa}, and \textit{Acer pseudo-sieboldianum}) which are planted alongside a road for vehicles as well as pedestrian in urban area. Developed equations showed \( R^2 \) of 0.93 (Z. serrata), 0.67 (\textit{P. occidentalis}), 0.96 (\textit{G. biloba}), 0.93 (\textit{C. retusa}), and 0.88 (\textit{A. pseudo-sieboldianum}) when they were derived from diameter at breast height (DBH). Using the DBH-volume equation, the five street tree species (\textit{P. occidentalis}, \textit{G. biloba}, \textit{Z. serrata}, \textit{C. retusa}, and \textit{A. pseudo-sieboldianum}), which account for 70% of total street trees in the Daejeon, stored about 4290 tons of carbon. Among the five street tree species, \textit{P. occidentalis} constituted more than 50% of total stored carbon and followed by \textit{G. biloba}. Based on the carbon storage, five street tree species can sequester 216 tons of carbon annually which means that 793 tons of carbon dioxide (\( \text{CO}_2 \)) removal from the air every year.

\textbf{Introduction}

The ideal method for measuring biomass and carbon storage of tree is physically cutting down and weighing the entire tree, but this method is time-consuming and destructive (Lefsky and McHale 2008; McHale et al. 2009). In addition, Kettnerings et al. (2001) explained that weighing tree biomass in the field is the most accurate and certain method to estimate tree biomass without damage, although this method is an extremely time-consuming and destructive. However, it is not easy to cut the urban trees down without official procedure following the regulation of the government. Urban trees were cut when they were old or too large and thus spoiled the sight of urban environment, which does not represent average form (McHale et al. 2009).

In 2006, Intergovernmental Panel on Climate Change (IPCC) provided internationally agreed methodologies that are able to be used for estimating greenhouse gas inventories in urban area (IPCC 2006). Up to date, many studies have been performed to develop biomass equations or volume equations for estimating carbon storage of forest tree species and published in North America (Smith and Brand 1983; Ter-Mikaelian and Korzukhin 1997), Europe (Zianis et al. 2005), as well as in Korea (Son et al. 2001, 2005, 2007). But most of the equations are questionable for applying to urban trees because there are big differences between urban environment and natural forest such as growth form of trees, management, condition of nutrients and water, and resistibility to stressful conditions in urban areas (Johnson and Gerhold 2001; McHale et al. 2009). Nowak (1994) found that allometric equation developed for forest trees overestimated tree biomass planted in urban area, and thus it is necessary to multiply 0.8 in order to adjust the estimation of biomass. Pillsbury et al. (1998) developed volume equations for 15 urban tree species in California, and McHale et al. (2009) also developed volume equations for 11 dominant species in Fort Collins, Colorado. Peper et al. (2014) described the development of allometric equations for urban ash trees (\textit{Fraxinus spp.}) in Oakville, Canada and Yoon et al. (2013) developed urban-specific allometric equations following the nondestructive approach for five common street tree species in Daegu, Korea. In addition, Kim and Lee (2016) tried to suggest regression functions as the most suitable volume model to predict the volume for major five street tree species in Gwangju, Korea.

Also, many studies about carbon storage and sequestration of urban trees have been accomplished in China, Australia, South Africa, Korea and United States (Fang et al. 2001; Brack 2002; Nowak et al. 2006a, 2006b, 2007a, 2007b, 2007c; Stoffberg et al. 2010; Yoon et al. 2013; Tang et al. 2016).

The objective of this paper is (1) to develop equations for estimating carbon storage of urban forest derived from diameter at breast height (DBH) and crown cover area (CCA) and (2) to evaluate carbon storage and sequestration by the urban forest in Daejeon.

\textbf{Materials and methods}

\textbf{Project site}

Daejeon is located in the mid-southern part of Korea and 167.3 km away from the capital city of Seoul. The latitude and longitude of an area is 36°10′50″N–36°29′47″N/
127°14′54″E–127°33′21″E (Figure 1). The average annual temperature is 12.3 °C and the coldest temperature is in January (−1.9 °C) and the hottest is in August (25.5 °C).

**Species selection and data collection**

Five major tree species including *Ginkgo biloba*, *Platanus occidentalis*, *Zelkova serrata*, *Chionanthus retusa*, and *Acer pseudo-sieboldianum* were selected for this study and those comprise about 70% of street trees in Daejeon (Table 1). The DBH was measured at a point 1.3 m using a diameter tape. If the stem separates at breast height or below, this tree was excluded as a sample. If stem forking occurred above the breast height, a DBH measurement was made. Sampled street tree species showed DBH distribution as in Figure 2.

Diameter outside bark (DOB), for developing volumetric equation, was measured from 0.2 m at intervals of 1 m by the laser dendrometer (Criterion RD 1000, Laser Technology, USA) and the laser distance meter (Leica Disco A5, Leica, USA). If butt was placed at the point, the measurement interval could be changed.

Total tree height, for developing volumetric equation, was measured from the ground level to the highest portion of the tree and it was measured by the laser dendrometer (Criterion RD 1000, Laser Technology, USA).

Crown diameter was measured by laser distance meter (Leica Disto A5, Leica, USA) from all directions. Sometimes, it was not able to measure the crown diameter due to the road condition. CCAs were calculated with averaged crown diameter and these were used to correlate with volume of trees.

**Tree volume calculation and equation development**

In other studies for volume measurement, sample trees were divided into several segments according to a few criteria. Height and diameter of each segment were measured using Spiegel Relaskop for calculating of total volume (Pillsbury and Reimer 1997; Pillsbury et al. 1998). In this study, we used criterion RD 1000 (Laser Technology, USA) for measuring height and diameter but sample trees were divided into several segments just as Pillsbury and Reimer (1997) did. In addition, we tried to separate as small as segment possible to be included.

Cubic foot volume of each tree was worked out with three equations. The base segment (from ground level to 0.2 m) was considered as a cylinder (Equation (1)), the highest portion of segment was considered as a cone (Equation (2)), and the rest was treated as a paraboloid frustum (Equation (3), which is Smalian’s formula).

\[
V_1 = A_b L, \quad (1)
\]
\[
V_2 = L / 3(A_b), \quad (2)
\]
\[
V_3 = L / 2(A_u + A_b), \quad (3)
\]

where \( V \) is the volume outside bark in cubic feet to 0-inch top, \( A_b \) is the cross-sectional area outside bark at base in square feet, \( A_u \) is the cross-sectional area outside bark at top in square feet, and \( L \) is the length of segment in feet. When we calculated volume of segment, we considered every segment as a cone, so that made easier to calculate the volume and reduce the time to measurement.

Volumetric equations used only one variable to predict tree volume. For the selected tree species, DBH and CCA are used as a variable. The relationship between (1) DBH and total volume, (2) CCA and total volume is described by Equations (4) and (5), respectively.

\[
V = b_0(DBH)^{b_1}, \quad (4)
\]
\[
V = b_0(CCA)^{b_1}, \quad (5)
\]

where \( V \) is the total volume of outside bark, \( b_1 \) is the regression coefficients. Simple regression analysis contributed to establish the volumetric equations of each urban tree species.

**Table 1.** Statistical information of major tree species in Daejeon.

| Species               | Other species | Total  |
|-----------------------|---------------|--------|
| Zelkova serrata       | 36,443        | 118,851|
| Platanus occidentalis |               |        |
| Ginkgo biloba         | 36,306        |        |
| Chionanthus retusa    | 14,558        |        |
| Acer pseudo-sieboldianum | 7662    |        |
|                       | 16,465        |        |
|                       | 7417          |        |
|                       | 30.7          |        |
| Rate (%)              | 12.2          |        |
| No. of trees          | 6.4           |        |
|                       | 13.9          |        |
|                       | 6.2           |        |

*Figure 1.* The location of study sites, Daejeon.
Biomass and carbon estimation using volumetric equations

The volumetric equations were used to calculate the volume of the tree. First of all, we calculated the volume of trees with DBH, and CCA and then converted volume to fresh weight (FW) biomass by multiplying the tree density factor which is species-specific value. Second, we added the belowground biomass by multiplying 1.28 so we got a total fresh weight biomass including the root portion. Third, we modified total fresh weight biomass to dry weight biomass by the constant 0.56, otherwise by the constant 0.48 for conifers. These conversion factors were from average species moisture contents (Young and Carpenter 1967; Nowak 1993, 1994). Finally, we converted dry weight biomass to stored carbon contents by multiplying 0.5 and then converted to absorbed carbon dioxide (CO₂) by multiplying the constant 44/12 (McPherson and Simpson 1999).

Carbon sequestration

Annual carbon sequestration by urban trees depends on the measurement of radial growth increment (Nowak 1994). It is well known that average DBH growth was 0.38 cm/year for the forest tree species (Smith and Shifley 1984; Nowak 1994; Nowak and Crane 2002) and average DBH growth was 0.61 cm/year for the urban tree species (Smith and Shifley 1984; Nowak 1994). Nowak and Crane (2002) mentioned that growth rates of the tree were affected by tree condition, so it is not considered when the trees showed bad condition physically in this study.

The difference in the amount of carbon storage between year $x$ and year $x + 1$ is the total amount of carbon sequestration per year (Nowak and Crane 2002; Nowak et al. 2008).

Data analysis

For each species, we evaluated the relationship between volume of stems and DBH or CCA. Data was transformed using the natural log function and using linear regression.

$$\ln(y) = \ln(a) + b \cdot \ln(x),$$

where $y$ is the volume of stem, $x$ is the DBH or crown cover, $a$ and $b$ are parameters (Sit and Poulin-Costello 1994). All regressions were developed by PROC REG in SAS (Systat 9.2, Systat Software Inc., Richmond, USA).
Result and discussion

Tree volume equation

Many studies are found in relation to volume equation derived from DBH as a predictor of forest tree species all around world such as Zianis et al. (2005) which had been conducted in Europe. He reviewed 230 equations for major species in Europe. On the other hand, few studies are found on the development of volumetric equations for urban forest. Pillsbury and Reimer (1997) developed tree volume equations for 10 urban species such as Blue gum, acacia, and Holly oak in California and Pillsbury et al. (1998) extended volume equations for 15 urban tree species.

We evaluated the relationship between volume of stems and DBH for each street tree species. The logarithmic linear regressions for volume versus DBH were highly significant (p < 0.0001) and the coefficient of determination (R²) value displayed 0.88–0.96 except P. occidentalis which showed the lowest value of R² (R² = 0.67) and also showed the highest value of root mean square error (RMSE) values. However, G. biloba showed the highest value of R² which is 0.96 and the lowest value of RMSE (Table 2).

Figure 3 indicated the relationship between volume of stems and DBH of each species. A. pseudo-sieboldianum showed the smallest range of DBH (Table 2). P. occidentalis showed the widest range of DBH and the biggest difference of volume when they have the same DBH (Figure 3). This may be one of the reasons that P. occidentalis showed the lowest value of R² and the highest value of RMSE as compared to other species.

We also evaluated the relationship between volume and CCA (Table 3). Apart from the equations derived from DBH, these equations showed relatively lower R² value and higher RMSE. The R² values for G. biloba and A. pseudo-sieboldianum were 0.70 and 0.74, respectively (Table 3).

Figure 4 showed the relationship between volume of stems and CCA for each species but variance of volume had mostly a big difference with the same CCA.

Equations accuracy and reliability

We examined reliability and accuracy of equations with several statistics methods such as coefficient of determination (R²), adjusted R², RMSE, average percent deviation (APD), and percent aggregate difference (PAD) (Pillsbury and Kirkley 1984; Pillsbury et al. 1998).

R² is provided in Tables 2 and 3 to show the variation about the average sample volumes. DBH-volume equations developed for the street trees had R² between 0.67 and 0.96. CCA-volume equations developed for the street trees had 0.53–0.74. Street trees showed that DBH-volume equations had higher R² values than CCA-volume equations. Pillsbury et al. (1998) developed 15 volume equations for 15 urban species and these equations showed R² values between 0.90 and 0.98.

RMSE (another measure of the residual variation) is the root of the mean squared difference between the predicted and actual values of volume (Pillsbury and Kirkley 1984). This value is expressed as a percent of the mean volume as shown in Tables 2 and 3. DBH-volume equations for street trees ranged from 14 to 36 but CCA-volume equations ranged from 36 to 41 for street trees. These range were similar (or even less) to the range of equations which developed by Pillsbury and Kirkley (1984).

In addition to the reliability tests previously discussed above, we conducted several other tests. Average percentage deviation (APD) gave an idea of the amount by which any single calculated volume by developed equation in this study will differ from the actual volume. DBH-volume equations of only G. biloba, Z. serrate, and C. retusa had a similar value of APD with Pillsbury et al. (1998) which ranged from 9% to 19% (Table 4).

The aggregate difference is considered as a better indicator of reliability because most of the users or researchers are interested in the accuracy of a larger number of trees than individual trees (Pillsbury et al. 1998). PAD of equations derived from DBH was between 0.7% and 6.6% for street tree species (Table 4). In previous study, Pillsbury and Kirkley (1984) showed between 2.1% and 5.8% of PAD for redwood trees and Pillsbury et al. (1998) showed between −4.5% and 1.9% of PAD.

Carbon storage

For the street tree species in Daejeon, overall, five species (Z. serrata, P. occidentalis, G. biloba, C. retusa, and A. pseudo-sieboldianum) stored 4290 tons of carbon. In terms of borough, Yusung-gu and Seo-gu stored 1076.1 and 1000.7 tons of carbon, respectively. The lowest was in Daeduk-gu where the carbon storage was 531.7 tons (Table 5 and Figure 5).

Nowak (1993) explained that the most important parameters in determining tree carbon storage is species and diameter distributions and Nowak and Crane (2002) noticed tree density and diameter distribution is the dominant factor that affects tree carbon storage. In this study, the differences in carbon estimate are likely due to (1) differences in number of planting trees, for example, street trees (we investigated) were planted more than 20,000 in both Yusung-gu and Seo-gu, and (2) differences in species distribution. Comparison with Daedeok-gu, Jung-gu and Dong-gu had less number of street trees but total carbon storage was higher (Figure 5), because P. occidentalis which were planted in Jung-gu and Dong-gu took a large portion of species distribution (Figure 5).

In terms of species, carbon storage of P. occidentalis was about 2457 tons in Daejeon and that of G. biloba was 1162 tons. Relatively, A. pseudo-sieboldianum stored only 123.7 tons.
tons of carbon (Table 5). We assumed that DBH was 25 cm and estimated carbon storage of each species, and the amount of carbon stored by *P. occidentalis* was 65 kg/tree and that by *G. biloba* was 33 kg/tree (Figure 6).

**Carbon sequestration and CO2 removal**

We computed carbon sequestration and CO2 removal by applying urban tree DBH growth which is 0.61 cm/year developed by previous study (Smith and Shiley 1984; Nowak 1994).

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**Table 3.** Parameters of CCA-volume equations of major tree species in Daejeon, Korea (*N*: number of trees; CCA: crown cover area; RMSE: root mean square error).

| Species            | N  | Crown cover area (m²) | a      | b     | \(R^2\) | RMSE  | Pr > F   |
|--------------------|----|-----------------------|--------|-------|---------|-------|----------|
| *Zelkova serrata*  | 89 | 15.2–110.8            | 0.000437| 1.445 | 0.530   | 0.356 | <0.0001  |
| *Platanus occidentalis* | 65 | 39.3–142              | 0.000914| 1.389 | 0.544   | 0.413 | <0.0001  |
| *Ginkgo biloba*    | 81 | 5.7–107.1             | 0.0031   | 1.013 | 0.704   | 0.406 | <0.0001  |
| *Chionanthus retusa* | 195 | 3.8–87.1              | 0.000744| 1.208 | 0.664   | 0.552 | <0.0001  |
| *Acer pseudo-sieboldianum* | 190 | 3.4–63.6              | 0.001473| 1.207 | 0.741   | 0.408 | <0.0001  |
Calculation showed that potentially 216.31 tons of carbon could be sequestrated by the 82,408 street trees in Daejeon (Table 6). Often emission reduction was reported as the full molecular mass of CO₂ than atomic mass carbon. In applying

**Table 4.** Results on the accuracy and reliability test for DBH-volume equations and CCA-volume equations of major tree species in Daejeon, Korea (APD: average percentage deviation; PAD: percent aggregate difference).

| Species             | Equations      | APD (%) | PAD (%) | Adj. $R^2$ |
|---------------------|----------------|---------|---------|------------|
| *Ginkgo biloba*     | DBH-volume     | 9.3     | 0.7     | 0.96       |
|                     | CCA-volume     | 33.4    | 5.9     | 0.70       |
| *Platanus occidentalis* | DBH-volume   | 32.8    | 6.6     | 0.67       |
|                     | CCA-volume     | 35.5    | 8.1     | 0.54       |
| *Zelkova serrata*   | DBH-volume     | 17.6    | 1.9     | 0.92       |
|                     | CCA-volume     | 29.3    | 4.9     | 0.81       |
| *Chionanthus retusa* | DBH-volume    | 20.1    | 4.3     | 0.93       |
|                     | CCA-volume     | 50.6    | 18.9    | 0.66       |
| *Acer pseudo-sieboldianum* | DBH-volume | 23.4    | 3.7     | 0.88       |
|                     | CCA-volume     | 34.1    | 8.0     | 0.74       |

**Figure 4.** Relationship between volume of stems and crown cover area for selected street tree species.

**Figure 5.** Total carbon storage of each borough of street tree species in Daejeon.
this conversion factor, potentially 793 tons of CO2 were removed every year by the same street trees above (Table 6). Based on the result, we are able to predict the capabilities of carbon sequestration and CO2 removal by street trees in the next 10 years.

*P. occidentalis* showed the biggest potential to sequestrate carbon among five species because *P. occidentalis* has the largest average DBH and stored large amount of carbon rather than other species. *P. occidentalis* and *G. biloba* comprised 76% of carbon sequestration and CO2 removal of street trees in Daejeon (Table 6).

In a previous study, Brack (2002) predicted that urban forest in Canberra will sequestrate a total of 30,200 tons of carbon (street trees: 13,000, and park trees: 17,200) between 2008 and 2012. Stoffberg et al. (2010) estimated that urban forest will sequestrate 54,630 tons of carbon in the city of Tshwane, South Africa by 2032. Nowak et al. evaluated gross carbon sequestration by urban trees of several cities in United States. Gross sequestration by trees in Washington, DC and Casper and San Francisco, Philadelphia, and New York was about 16,200 tons (Nowak et al. 2006a), 1200 tons (Nowak et al. 2006b), 5200 tons (Nowak et al. 2007a), 16,100 tons (Nowak et al. 2007b), and 42,300 tons (Nowak et al. 2007c) per year, respectively. In addition, Tang et al. (2016) quantify carbon sequestration of urban street trees in Beijing district as about 3100 tons in 2014 which is equivalent to 0.2% of its annual CO2 emissions from total energy consumption.

### Table 5. Total carbon storage of each street tree species in Daejeon.

| Species          | Dong-gu | Jung-gu | Seo-gu | Yusung-gu | Daeduk-gu | Total   |
|------------------|---------|---------|--------|-----------|-----------|---------|
| Zelkova serrata  | 38.7    | 5.7     | 117.4  | 92.5      | 79.2      | 333.4   |
| Platanus occidentalis | 686.7  | 562.0   | 495.4  | 564.7     | 148.2     | 2457.0  |
| Ginkgo biloba    | 124.0   | 193.3   | 326.5  | 252.7     | 265.4     | 1162.0  |
| Chionanthus retusa | 26.1    | 16.4    | 33.2   | 128.6     | 9.9       | 214.2   |
| Acer pseudo-sieboldianum | 16.2    | 12.7    | 28.3   | 37.6      | 29.0      | 123.7   |
| Total            | 891.7   | 790.1   | 1000.7 | 1076.1    | 531.7     | 4290.3  |

### Table 6. Prediction on carbon sequestration and CO2 removal by major tree species in Daejeon, Korea.

| Species          | N      | DBH (cm) | Carbon sequestration (ton/year) | CO2 removal (ton /year) |
|------------------|--------|----------|--------------------------------|--------------------------|
| Zelkova serrata  | 7,662  | 11.5–39.0| 19.05                          | 69.8                     |
| Platanus occidentalis | 14,558 | 17.1–55.0| 91.76                          | 336.4                    |
| Ginkgo biloba    | 36,306 | 9.5–37.2 | 72.91                          | 267.3                    |
| Chionanthus retusa | 16,465 | 5.4–29.9 | 21.53                          | 78.9                     |
| Acer pseudo-sieboldianum | 7,417  | 6.5–28.0 | 13.07                          | 40.6                     |
| Total            | 82,408 |          | 216.31                         | 793                      |

### Figure 6. Carbon storage per tree of each street tree species.

**Conclusion**

Equations derived from DBH and CCA using laser dendrometer were developed for estimating carbon storage and sequestration of urban forest in Daejeon. Volumetric equations of street trees derived from DBH were significant, although they were composed of different species. However, equations derived from CCA showed lower $R^2$ value due to the relatively less accurate estimation of the CCA as compared to DBH.

Based on equations we developed before, carbon storage of urban forest was evaluated in Daejeon. It was calculated that *P. occidentalis* stored about 2500 tons of carbon and *G. biloba* stored about 1200 tons of carbon. On the other hand, *Z. serrata*, *C. retusa*, and *A. pseudo-sieboldianum* stored about 330, 210, and 120 tons of carbon, respectively. This is the reason that *P. occidentalis* and *G. biloba* have larger DBH values and those species are planted more than other species. In addition, it is possible to expect that 216.31 tons of carbon is sequestrated at least in every year by street tree species and 793 tons of CO2 is able to be removed from the atmosphere every year in Daejeon.

These kinds of study have a time and space limit. In order to estimate more accurate carbon storage or urban forest in Daejeon, further study should be performed. For example, for developing more trustworthy equation, variables should be estimated more accurately such as through measuring CCA using aerial photographs or satellite images.

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### Disclosure statement

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