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Carbon Reduction Services of Evergreen Broadleaved Landscape Trees for *Ilex rotunda* and *Machilus thunbergii* in Southern Korea

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Abstract

This study quantified carbon reduction services through direct harvesting of *Ilex rotunda* and *Machilus thunbergii*, which are the typical urban landscape tree species in southern Korea. A total of 20 open-grown tree specimens (10 specimens for each species) were selected reflecting various sizes of stem diameter at breast height of 1.2 m (DBH) at a regular interval. The study measured biomass for each part of the tree specimens including roots to compute total carbon storage per tree. Annual carbon uptake per tree was also calculated analyzing the DBH growth rate of stem disk specimens. Quantitative models were developed using DBH as an independent variable to easily estimate storage and annual uptake of carbon by tree growth for each species. All the models had a high goodness-of-fit with R^2=0.95-0.99. The difference in carbon reduction services between DBH sizes increased with increasing DBH. The storage and annual uptake of carbon from a tree with DBH of 10 cm were 13.5 kg and 2.4 kg/yr for *I. rotunda*, and 19.1 kg and 3.6 kg/yr for *M. thunbergii*, respectively. The tree of this size stored the amount of carbon equivalent to that emitted from a gasoline use of approximately 24 L for *I. rotunda* and 34 L for *M. thunbergii*, respectively. The study provides actual measurement data to quantify carbon reduction services of urban open-grown landscape trees for the warm-temperate species that have been little known until now.

Key Words: annual uptake, quantitative model, root digging, storage, urban open-grown

Introduction

Climate change from carbon emissions is one of worldwide environmental concerns. Landscape trees planted in urban lands such as gardens, parks, and streets contribute to carbon reduction through photosynthetic uptake and storage of atmospheric carbon (Piao and Jo 2018; Jo et al. 2018; 2019b; 2019c). There is internationally rising interest in planting of urban landscape trees as one of major carbon offset activities. Based on the 2005 Kyoto Protocol and the 2006 IPCC (Intergovernmental Panel on Climate Change) guideline (UNFCCC 2006; KFRI 2012), tree planting with a minimum area of 0.05 ha in urban settlements is recognized as an effective activity to enhance carbon stocks.

Concern about increasing carbon concentrations in the atmosphere has generated diverse studies of exploring carbon reduction effects of landscape trees at the urban scale (Nowak 1994; McPherson 1998; Jo 2002; Nowak and Crane 2002; Nowak et al. 2013; McGovern and Pasher

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2016). However, there exists the limitation that the majority of the past studies substituted, in quantifying carbon reduction by urban open-grown trees, data of carbon estimates from forest trees (especially below ground carbon). This limitation is attributed to the difficulty in cutting and root digging of landscape trees planted.

The substitution of carbon estimates from forest trees could cause a significant error in computing storage and annual sequestration of carbon by urban landscape trees, because of different growth environments including maintenances and competing conditions (Jo and Park 2017). Therefore, Jo and Ahn (2012) and Jo et al. (2013; 2014) measured, through a direct harvesting method, above ground and below ground biomass for open-grown landscape tree species frequently planted in the temperate region of the Republic of Korea. Based on the biomass measurement, they developed quantitative models to estimate storage and annual uptake of carbon by tree growth for each species.

However, there is no information on carbon reduction services of warm-temperate landscape tree species planted in urban settlements of the southern region such as Gyeongnam, Jeonnam, and Jeju provinces of the country, except Jo et al. (2019a)'s research for *Camellia japonica* and *Quercus myrsinaefolia*. The purpose of this study was to quantify storage and annual uptake of carbon for *Ilex rotunda* and *Machilus thunbergii* through direct harvesting including root digging, and to develop quantitative models to easily estimate their carbon reduction services. *I. rotunda* and *M. thunbergii*, which are evergreen broadleaved tree species, are the representative landscape plants growing in the southern region of the Korean Peninsula at 35° or lower North (KGLC 1979). This study could contribute to estimating carbon reduction of landscape trees planted in Korean southern cities and other countries for the same species or genera.

Materials and Methods

Selection of study species and trees

Of the tree species frequently planted as urban landscape trees in the warm-temperate southern region of the Republic of Korea, this study selected *I. rotunda* and *M. thunbergii*, based on the existing literature on the planting frequency of landscape tree species (Park et al. 2015; Yoon et al. 2017). A total of 20 tree specimens for digging (10 specimens for each species), which were normally open-grown with the typical form of the species, were chosen reflecting various stem diameter sizes at a regular interval from young trees to mature ones. The tree specimens were purchased at gardens in the city of Sacheon, Gyeongnam for *I. rotunda* and along streets in the county of Goseong, Gyeongnam for *M. thunbergii*. The decision on the tree sample size was a compromise between both conflicting concerns for the high cost and difficulty in tree purchase and the need for a sufficient number of specimens.

Tree digging and fresh weight measurement

The tree specimens were dug in late October 2018, and fresh weights of each part such as stem, branch, leaf, and root were measured (Fig. 1). Digging and fresh weight measurement were conducted applying the KFRI (2007)'s and Jo et al. (2014)'s standard methods for biomass survey and analysis. When digging the trees, the size of each specimen including stem diameter at breast height of 1.2 m (DBH), crown width, and tree height was measured with reference to Jo et al. (2014)'s methods. The soils under the

Fig. 1. Growing conditions and harvesting of study trees.

trees were sampled with a penta-repeat for each species, and physical and chemical characteristics of the soils were analyzed using the NIAST (2000)'s soil analysis methods.

Dry weight specimens and measurement

To compute dry weight of the trees compared to fresh weight, this study collected specimens of each part to convert to dry weight and measured the fresh weight of the specimens on site to an accuracy of 10 g. The stem was separated at 2 m intervals, and disks of 5-10 cm thickness were collected at the center of each separation. Branches of 1-2 kg were sampled with an even mixture of thick, medium, and thin branches. Roots were divided into stump and other parts, and 1-3 kg of these were collected. This study also randomly sampled 1 kg of leaf. The specimens for dry weight conversion were dried in an oven (US-1202 DH, Vision Scientific, Korea) at 85°C to constant weight, and the dry weight was measured to an accuracy of 0.01 g on an electronic scale (FX3200, AND, Japan). The ratio of dry weight to fresh weight of each specimen was computed to estimate the dry weight (hereafter referred to as biomass) for the part and tree total.

Development of quantitative models for carbon storage

Based on the biomass measurement of the tree specimens, quantitative models were developed to easily estimate carbon storage over the growth of a tree for the study species. That is, the above ground and below ground biomass of the trees was converted to carbon storage by multiplying by 0.5, because mean carbon content of wood and leaf was approximately 50% of biomass (Pingrey 1976; Chow and Rolfe 1989; Song et al. 1997; Jo 2002; Nowak and Crane 2002). The most suitable quantitative models and variables to estimate carbon storage were derived from repetitive linear and nonlinear approaches with DBH and tree height as independent variables.

Development of quantitative models for annual carbon uptake

Stem disks of 5-10 cm thickness of the tree specimens were collected from a breast height of 1.2 m to analyze their ages and annual DBH growth rates. The stem disks were immediately put into a double vinyl bag, and carried to the laboratory. The disk thickness was determined reflecting grinding efficiency and crack prevention for each stem diameter size. The DBH growth rate was obtained averaging the measurements from the four directions of each disk. Annual carbon uptake for each tree specimen was quantified analyzing the annual increase in biomass based on the DBH growth rate and converting it to the amount of carbon. That is, the DBH growth rate was used to identify the previous year's DBH, and this DBH variable was applied to the biomass equation to estimate the previous year's biomass. The previous year's biomass was subtracted from the present year's biomass to compute the annual biomass increment. Since leaf fall annually returns carbon to the atmosphere through collection and decomposition, 25% of leaf biomass was deducted for the evergreen species assuming three-year leaf retention (Rowntree and Nowak 1991; Dirr 2009). The most appropriate quantitative models were, through the above-mentioned linear and nonlinear approaches, developed to easily estimate annual carbon uptake according to the growth of a tree for the study species.

Table 1. Physical and chemical characteristics of soils for study trees

Species	Soil texture	pH	OM (%)	TN (%)	Ava. P (mg/kg)	EC ($cmol^+$/kg)			CEC ($cmol^+$/kg)
						K^+	Ca^{2+}	Mg^{2+}	
Ilex rotunda	Loam	6.6 (middle)	1.9 (low)	0.14 (high)	271.2 (high)	0.81 (middle)	6.49 (high)	1.57 (middle)	9.5 (middle)
Machilus thunbergii	Clay loam	4.8 (low)	2.8 (low)	0.20 (high)	185.3 (middle)	0.20 (low)	1.71 (low)	0.40 (low)	3.0 (low)

OM, organic matter; TN, total nitrogen; Ava. P, Available P_2O_5; EC, exchangeable cation; CEC, cation exchange capacity; ( ), soil assessment rating based on KILA (2016)'s standards.

Results and Discussion

Growth environments of study trees

The city of Sacheon and the county of Goseong where the study trees grew are located in a warm-temperate zone in the southern inland (34°52′-35°09′North and 127°52-128°30′East) of the Korean Peninsula. The average annual temperature and precipitation in the last 10 years (2009-2018) were 13.9°C and 1,522.2 mm, respectively (KMA 2019). Soil texture was loam for *I. rotunda* and clay loam for *M. thunbergii* (Table 1). The chemical properties were as follows: pH 4.8-6.6, organic matter 1.9-2.8%, total nitrogen 0.14-0.20%, available phosphate 185.3-271.2 mg/kg, exchangeable K^+ 0.81-0.20 $cmol^+$/kg, and cation exchange capacity 3.0-9.5 $cmol^+$/kg. Based on the soil assessment standards provided by the KILA (2016), soil conditions for *I. rotunda* fell in the middle or high range in components other than organic matter, while those for *M. thunbergii* fell in the low range in most components except total nitrogen and available phosphate.

Growth rates and biomass changes

The DBH of the study trees ranged from 3.2-11.4 cm for *I. rotunda* and from 3.6-16.7 cm for *M. thunbergii* (Table 2). The age range of *I. rotunda* and *M. thunbergii* was 7-15 years and 5-14 years depending on the DBH sizes, respectively. Annual DBH growth rate of the trees averaged 0.62±0.05 cm/yr for *I. rotunda* and 0.82±0.08 cm/yr for *M. thunbergii* greater than that for *I. rotunda*. The DBH growth rate is directly associated with annual changes in biomass and carbon uptake. Jo and Park (2017) reported that the mean annual DBH growth rate of open-grown landscape trees in middle Korea was 0.72 cm/yr for deciduous broadleaved species and 0.83 cm/yr for evergreen coniferous species, while that of forest trees was 0.57 cm/yr for evergreen coniferous species. Thus, the DBH growth rate of the study species was greater than that of forest trees due to better maintenance and less competition, but lower than or similar to the case of open-grown landscape trees in a temperate zone from Jo and Park's study.

Total biomass of the trees tended to increase nonlinearly with DBH growth, and ranged from 1.4-37.0 kg/tree for *I. rotunda* and from 3.6-137.9 kg/tree for *M. thunbergii* (Fig. 2). The biomass allocation ratio per tree part varied more or less between the species. *I. rotunda* showed the highest rate in stem with approximately 41%, followed by root with 30%, branch with 21%, and leaf with 8%, while *M. thunbergii* showed the highest rate in root with 35%, followed by stem with 28%, branch with 19%, and leaf with 18%. The biomass expansion factor of the above ground parts (stem, branch, and leaf) compared to stem averaged 1.73±0.08 for *I. rotunda* and 2.34±0.08 for *M. thunbergii* (Table 3). The ratio of below ground biomass/above ground biomass (B/A ratio) was 0.45±0.05 for *I. rotunda* and 0.53±0.04 for *M. thunbergii*. The B/A ratio of the study species was greater than 0.23 (evergreen coniferous species)-0.40

Table 2. Size and DBH growth of study trees for each species

Species	Growth place	Dbh (cm)	Height (m)	Crown width (m)	Age (yr)	Dbh growth (cm/yr)
Ilex rotunda	Garden (Sacheon)	3.2-11.4	3.0-4.7	1.2-2.6	7-15	0.62±0.05
Machilus thunbergii	Street (Goseong)	3.6-16.7	3.0-7.7	1.6-4.0	5-14	0.82±0.08

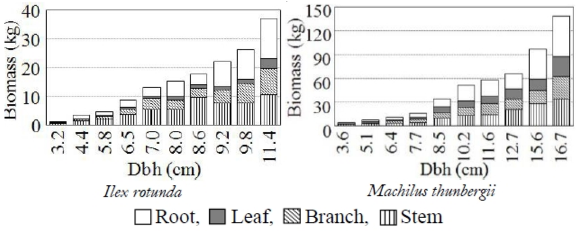


Fig. 2. Changes in biomass by DBH growth of study trees for each species.

Table 3. Biomass expansion factor (BEF) and ratio of below ground/above ground biomass (B/A) for study species*

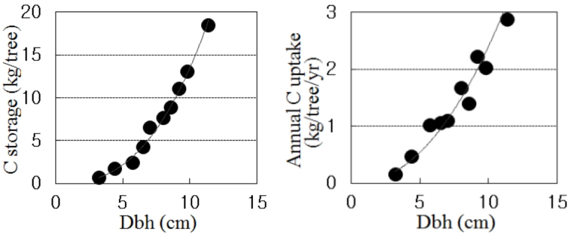
Species	BEF*	B/A ratio
Ilex rotunda	1.73±0.08	0.45±0.05
Machilus thunbergii	2.34±0.08	0.53±0.04

*Ratio of above ground (stem, branch, and leaf)/stem biomass.

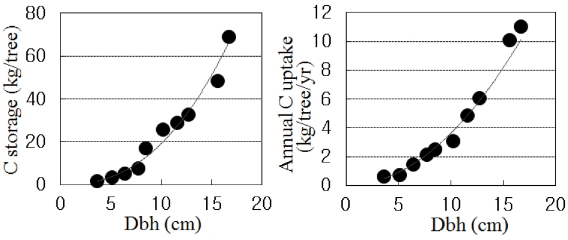
(deciduous broadleaved species) reported for open-grown landscape trees in a temperate zone of middle Korea (Jo and Park 2017). Thus, the biomass allocation rate including the B/A ratio was variable with tree species and growth environments, and especially could be useful in understanding the root biomass allocation on which little is known.

Carbon storage and quantitative models

Changes in carbon storage per tree with varying DBH for the study species are shown in Fig. 3, and Table 4 includes quantitative models developed to estimate carbon storage by DBH growth. The quantitative models for the study species were statistically significant ($p < 0.0001$) through F test, and had a high goodness-of-fit with $R^2 = 0.98\text{-}0.99$. The model coefficients were also significant at a 1% level. This study attempted to derive quantitative models including not only DBH but also tree height as independent variables. However, the R^2 for tree height was 0.88-0.89 lower than that for DBH. Although the quantitative models for tree height were statistically significant, the difficulty of accurately measuring tree height in the field could cause the larger error of estimation than that for the models using only DBH (Whittaker and Marks 1975; Park and Lee 1990). The quantitative models developed in this study can be easily used to estimate the carbon storage of the study species, as they require only DBH measurement.



Ilex rotunda



Machilus thunbergii

Fig. 3. Changes in storage and annual uptake of carbon per tree by DBH growth of study species.

Carbon storage by DBH estimated with the above-mentioned quantitative models increased with increasing DBH growth for the DBH range studied (Table 5). As the DBH increased by 2 cm, carbon storage of the study species increased by 2.2 (*M. thunbergii*)-2.9 (*I. rotunda*) times on average. Carbon storage of *M. thunbergii* was greater than that of *I. rotunda* for the same DBH. For example, carbon storage for DBH of 10 cm was 13.5 kg for *I. rotunda* and 19.1 kg for *M. thunbergii* greater than that of *I. rotunda* by 1.4 times. Compared with other open-grown landscape trees for the same DBH (Table 5), carbon storage of the study species was lower than that of *Q. myrsinaefolia* planted in the warm-temperate southern region of the Republic of Korea (Jo et al. 2019a), and similar to or greater than that of evergreen coniferous species in the temperate middle region of the country (Jo et al. 2013; 2014). A gasoline consumption of 10 L releases about 5.7 kg of carbon into the atmosphere (GIR 2019). *I. rotunda* and *M. thunbergii* with the DBH of 10 cm stored the amount of carbon equivalent to that emitted from a gasoline use of approximately 24 L and 34 L, respectively.

Annual carbon uptake and quantitative models

Fig. 3 and Table 4 show changes in annual carbon uptake per tree by DBH growth for the study species and quantita-

Table 4. Quantitative models to estimate storage and annual uptake of carbon per tree of study species

Species	Carbon[a]	Quantitative model[b]	R^2	p
Ilex rotunda	Storage	$\ln Y = -3.4312 + 2.6207 \ln X$	0.9867	< 0.0001
	Annual uptake	$\ln Y = -4.0651 + 2.1464 \ln X$	0.9510	
Machilus thunbergii	Storage	$\ln Y = -2.6239 + 2.4213 \ln X$	0.9765	
	Annual uptake	$\ln Y = -3.3291 + 2.0051 \ln X$	0.9730	

[a] Storage: kg/tree, Annual uptake: kg/tree/yr.

[b] X: Dbh (cm).

Table 5. Differences in carbon storage (kg) per tree by DBH growth of study trees and other open-grown landscape trees

Species	n	Dbh range (cm)	Dbh (cm)								
			2	4	6	8	10	12	14	16	18
Ilex rotunda	10	3.2-11.4	0.2	1.2	3.5	7.5	13.5	21.8	-	-	-
Machilus thunbergii	10	3.6-16.7	0.4	2.1	5.6	11.1	19.1	29.7	43.2	59.7	79.4
Quercus myrsinaefolia[a]	10	3.1-16.6	0.5	2.5	6.8	13.9	24.0	37.6	54.9	76.2	101.8
Deciduous broadleaved[b]	51	3.1-23.0	0.4	2.0	5.5	11.7	19.8	29.4	40.9	55.3	70.7
Evergreen coniferous[c]	31	5.0-30.9	0.3	1.3	3.4	6.7	11.6	18.0	26.3	36.6	49.0

[a] Planted in the warm-temperate southern region of Korea (Jo et al. 2019a, the same with Table 6).

[b] Averaged across *Acer palmatum*, *Chionanthus retusus*, *Prunus armeniaca*, *Prunus yedoensis*, and *Zelkova serrata* planted in the temperate middle region of Korea (Jo and Ahn 2012; Jo et al. 2014, the same with Table 6).

[c] Averaged across *Abies holophylla*, *Pinus densiflora*, and *Pinus koraiensis* planted in the temperate middle region of Korea (Jo et al. 2013; 2014, the same with Table 6).

Table 6. Differences in annual carbon uptake (kg/yr) per tree by DBH growth of study trees and other open-grown landscape trees

Species	n	Dbh range (cm)	Dbh (cm)								
			2	4	6	8	10	12	14	16	18
Ilex rotunda	10	3.2-11.4	0.1	0.3	0.8	1.5	2.4	3.6	-	-	-
Machilus thunbergii	10	3.6-16.7	0.1	0.6	1.3	2.3	3.6	5.2	7.1	9.3	11.8
Quercus myrsinaefolia	10	3.1-16.6	0.2	0.8	1.8	3.0	4.5	6.3	8.4	10.7	13.3
Deciduous broadleaved	51	3.1-23.0	0.2	1.0	1.7	2.3	3.3	4.4	5.7	5.9	7.1
Evergreen coniferous	31	5.0-30.9	0.1	0.4	0.8	1.3	2.0	2.8	3.7	4.7	5.8

tive models developed to easily estimate the annual carbon uptake, respectively. The quantitative models for the study species were statistically significant ($p < 0.0001$) through F test, and had a high goodness-of-fit with $R^2=0.95$-0.97. The model coefficients were also significant at a 1% level. This study derived quantitative models including tree height as well as DBH as independent variables. However, the R^2 for tree height was 0.74-0.83 much lower than that for DBH. As mentioned in the quantitative models for carbon storage, using only DBH as an independent variable can be more desirable because it is possible to simplify field measurements and to reduce an estimation error from tree height.

Annual carbon uptake by DBH estimated with the aforementioned quantitative models increased along with DBH growth, and the difference in annual carbon uptake between DBH sizes also tended to increase with increasing DBH (Table 6), similarly to carbon storage. As the DBH increased from 4 to 6 cm, the carbon uptake increased from 0.5 to 0.7 kg/yr and as the DBH increased from 10 to 12 cm, the carbon uptake increased from 1.2 to 1.6 kg/yr. Annual carbon uptake of *M. thunbergii* was greater than that of *I. rotunda* for the same DBH. For example, the carbon uptake for DBH of 10 cm was 2.4 kg/yr for *I. rotunda* and 3.6 kg/yr for *M. thunbergii* 1.5 times greater than that of *I. rotunda*. Compared with other open-grown landscape trees for the same DBH (Table 6), annual carbon uptake of the study species was lower than that of *Q. myrsinaefolia* planted in the warm-temperate southern region of the Republic of Korea (Jo et al. 2019a), and similar to or greater than that of evergreen coniferous species in the temperate middle region of the country (Jo et al. 2013; 2014). Thus, the carbon uptake of tree species was variable with different biomass for each DBH size and annual growth rates. The study species with the DBH of 10 cm acted as a carbon sink annually offsetting carbon emissions from a gasoline consumption of 4.2 L for *I. rotunda* and 6.3 L for *M. thunbergii*.

Conclusion

Urban greenspace enlargement through landscape tree planting is one of effective ways to contribute to atmospheric carbon reduction. Carbon reduction services of urban landscape trees are directly associated with their growth rates, sizes, and density. The information on storage and annual uptake of carbon by tree growth for each species is essential to not merely carbon estimation per unit area of urban landscapes, but also planting design and policy including appropriate species selection and planting techniques. However, little has been known regarding carbon reduction of urban landscape trees planted in the warm-temperate southern region of the Korean Peninsula. This study computed, through a direct harvesting method, storage and annual uptake of carbon for *I. rotunda* and *M. thunbergii*, which are the representative landscape tree species in the warm-temperate region.

Carbon reduction services of the study species increased with DBH growth, and the difference in carbon reduction between DBH sizes also increased with increasing DBH. Storage and annual uptake of carbon from a tree with DBH of 10 cm were 13.5 kg and 2.4 kg/yr for *I. rotunda*, and 19.1 kg and 3.6 kg/yr for *M. thunbergii*, respectively. The tree of this size annually offset the amount of carbon equivalent to that emitted from a gasoline consumption of 4.2 L for *I. rotunda* and 6.3 L for *M. thunbergii*. Carbon reduction services of *M. thunbergii* were greater than those of *I. rotunda* for the same DBH. Carbon reduction of the study species was also compared with that of other landscape tree species planted in cities of middle and southern Korea. The comparison revealed that carbon reduction services varied with different species and growth regions. Quantitative models for the study species were developed to easily estimate storage and annual uptake of carbon by tree growth by applying DBH as an independent variable. This study also acquired actual measurement data regarding growth characteristics of open-grown trees for the study species on which there has been little information, such as DBH growth rate, biomass expansion factor, and B/A ratio. The study findings could be useful in estimating carbon reduction services of open-grown landscape trees in the warm-temperate cities.

The major challenges in this study were the difficulty in purchasing tree specimens for logging, the digging of the specimens and the fresh weight measurement of each part, and the long-term drying of various fresh weight specimens and the complexity in quantitative analysis. The difficulty and high cost in tree purchase limited the obtainment of larger tree specimens and the sample size for digging. Additional experimental research on carbon reduction services of landscape tree species in the warm-temperate cities is required to verify the study findings and to build relevant data.

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