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Root Biomass Allocation and Carbon Sequestration in Urban Landscaping Tree Species in South Korea

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Abstract: The quantification of urban tree biomass allocation has primarily relied on estimations using allometric equations (AEs) developed for nondestructive harvest methods. However, the lack of harvest-based AEs that account for belowground biomass, nutrient concentration, and annual growth rates poses challenges in accurately quantifying the greenhouse gas inventory for urban land uses. In this study, we aimed to develop AEs using a log-transformed linear model for eight urban landscaping tree species, taking into account belowground biomass. We purchased 117 urban landscaping trees from tree farms in South Korea and investigated their biomass fractions, carbon and nutrient concentrations, and annual growth rate using a destructive method. We also developed AEs for different tree compartments using diameter at breast height as an independent variable. The AEs obtained exhibited high suitability, as evidenced by their high R^2 values (0.853–0.982 and 0.806–0.923 for aboveground and belowground biomass, respectively). The mean belowground biomass fraction across the different species was approximately 30%, suggesting that urban trees could allocate more belowground biomass than forest trees. Conversely, carbon and nitrogen concentrations varied significantly across species and compartments, and the mean annual carbon sequestration rate was 3.96 kg C year^{-1} tree^{-1}. Therefore, the application of the AEs for urban trees may enhance the accuracy of the national greenhouse gas inventory for the settlement sector.

Keywords: belowground carbon fraction; LULUCF; nitrogen; root-shoot ratio; settlement

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1. Introduction

Estimating tree biomass is essential for the assessment of forest resources [1]. Tree biomass is crucial for evaluating timber production, ecosystem productivity, biomass energy resources, and carbon sequestration within forests. Although tree biomass can be directly measured via a process that involves harvesting trees and subsequently drying and weighing them, this practice is not always feasible. Thus, biomass allometric equations (AEs), based on the harvesting of sample trees, have been developed to facilitate the accurate estimation of the biomass of living trees [2]. These equations are based on consistent relationships between tree size parameters, such as diameter and height, and the biomass of various tree parts, including aboveground and belowground parts [3,4]. However, these proportions vary according to tree species, region, and growth environment characteristics [5,6]. Therefore, numerous studies on various species across different regions [7,8] have contributed to the establishment of generalized AEs that are applicable across taxa and regions. Additionally, in recent decades, significant advances have been made in the development and availability of AEs for assessing forest carbon storage and sequestration, particularly in response to climate change. However, AEs designed specifically for urban trees are lacking.

Despite occupying smaller areas and constituting a smaller proportion of biomass than forest trees, urban trees provide various ecosystem services that are closely connected to human life [9–11]. To evaluate and manage these ecosystem services, it is necessary to quantify urban tree biomass using AEs. However, owing to considerable differences in the growth environments of forest and urban trees, including factors such as microclimate, physical space, competing vegetation, nutrient availability, and management practices [12], AEs developed for forest trees are not directly applicable to urban trees [13,14]. Additionally, while AEs for urban trees have been developed for North America [15], their application to other regions, including South Korea, is limited.

The lack of AEs for urban trees has posed challenges in accounting for greenhouse gas emissions in the settlement sector. This sector encompasses all developed land uses, including residential, transportation, commercial, and industrial purposes, as defined in the Land Use, Land-Use Change and Forestry (LULULUCF) category according to the Intergovernmental Panel on Climate Change (IPCC) reporting guidelines [16]. For example, country-specific emission factors for settlements are provided in the national inventory reports of only a few countries, such as the USA, Canada, and Japan. In cases where such factors are not available, most national inventory reports estimate the carbon sequestration of urban trees by applying the forest-to-urban-tree conversion factor (0.8) to biomass estimates derived from AEs for forest trees [17]. Therefore, it is essential to address the limited availability of AEs for urban trees to support the accurate reporting of greenhouse gas inventory for settlement areas.

One of the challenges associated with the development of AEs for urban trees is the limited ability to harvest the trees. While it is easier and more common to harvest sample trees in managed or natural forests, urban trees are usually municipal or private assets. Thus, their complete removal is challenging owing to regulatory and property-related issues. Consequently, nondestructive methods, such as the use of laser dendrometers [18,19] and laser scanning [20–22], which reportedly exhibit high accuracies [23], have been employed to develop AEs for urban trees. However, these nondestructive methods do not adequately consider belowground and foliage biomass, nutrient concentration in tree compartments, or annual growth rates. Therefore, AEs for urban tree biomass estimation that consider both belowground and aboveground biomass are urgently required. Given that a key obstacle in obtaining such equations is the limited possibility of destructively harvesting urban trees, purchasing sample trees grown in urban areas may present a suitable strategy for overcoming this limitation.

Therefore, in this study, we aimed to develop biomass AEs for eight urban tree species in South Korea using over 100 urban trees by purchasing them from tree farms. The specific aims of the study are as follows: (1) investigate whether the biomass fractions of urban tree compartments and their carbon and nitrogen concentrations vary according to species and diameter class, and (2) quantify the amount of carbon sequestered by the sampled trees annually. We hypothesized that urban trees would allocate belowground biomass differently from forest trees, owing to differences in understory and belowground conditions. The findings of this study may provide AEs that can be employed to enhance the accuracy of urban tree biomass estimation and greenhouse inventory.

2. Materials and Methods

2.1. Study Location and Fieldwork

A total of 117 trees were purchased for approximately USD 40,000 and destructively harvested in the cities of Gongju (36°6′ N, 127°29′ E), Geumsan (36°6′ N, 127°29′ E), Nonsan (36°11′ N, 127°6′ E), and Wonju (37°20′ N, 127 °56′ E), central South Korea, between 2020 and 2023. These sample trees had been grown for periods ranging from several years to decades on tree farms located in peri-urban areas that supply trees for various urban green spaces. In the tree farms, the trees were grown in close proximity to other neighboring trees, conditions similar to those in city parks, rather than being isolated. These trees were maintained according to typical landscaping practices, such as pruning, watering during drought, and weeding. The sample trees were selected based on the following criteria: (1) the crown tree received full sun without notable suppression from nearby trees; (2) the crown shape represented the typical morphology of each species; and (3) there was no visible damage on the crown or stem of the tree. At least 10 and up to 20 trees were sampled for each species. The general recommendation for the number of sample trees in allometric studies is at least 30. However, a smaller sample size is deemed acceptable when it is not feasible to secure a sufficient number, as reported in previous studies [24,25], especially in urban environments [15,26,27]. Based on the locations of the sample trees, the samples represented urban trees in the temperate (*Cwa* based on the Köppen climate classification system) and continental (*Dwa*) climate regions in the Korean Peninsula, where two-thirds of the South Korean population resides.

Four gymnosperms (*Ginkgo biloba*, *Abies holophylla*, *Pinus densiflora*, and *Pinus strobus*) and four angiosperm species (*Prunus* × *yedoensis*, *Zelkova serrata*, *Quercus palustris*, and *Chionanthus retusus*) were selected based on their dominance in urban areas, preference for recent planting, availability for purchase, and the lack of relevant previous studies. *G. biloba*, *Pinus densiflora*, *Prunus* × *yedoensis*, and *Z. serrata* represent the top four dominant urban tree species, collectively accounting for 44% of total urban tree frequency (unpublished data), and have remained the most dominant species in various urban green spaces throughout South Korea for decades. The distribution of *Pinus strobus*, *C. retusus*, and *Q. palustris* has also increased in recent years. Although *A. holophylla* is not commonly grown nationwide, it has become a representative landscaping species in the continental climate region of South Korea. To minimize seasonal variations in biomass and nutrient concentrations in each tree compartment, the trees were harvested and examined in July or August of each year.

The trees were uprooted using an excavator. However, root biomass may be either underrepresented owing to uncollected roots in the soil, or overestimated owing to the attachment of soil to the root samples. To minimize these sampling errors, the following procedures were implemented: (1) the soil surrounding the excavated tree was collected as widely and deeply as possible; (2) all tap and lateral secondary roots that remained in the soil were manually excavated; and (3) the soil attached to the roots was carefully removed through shaking and scraping (Figure A1).

For each tree, the diameter at breast height (DBH)—diameter at 1.2 m above the ground according to the national standard of South Korea and Japan [28]—was measured after excavation. Subsequently, the stems, branches, leaves, and roots of each tree were collected and their green weights were measured. To convert green weight to dry biomass, samples representing the dry-to-green weight ratio for each tree compartment were also collected. Specifically, stem disks were sampled at heights of 0.2, 1.2, and 2 m, while branch and root samples were collected from each tree to represent the size distribution of each sample (Table 1). Depending on the field conditions, the measurement of green weight and sampling were performed either in situ or ex situ after transporting the excavated trees to the campus of Sangji University, Wonju.

Table 1. Descriptive statistics (mean (range)) for sampled trees for developing allometric equations of major urban landscaping trees in South Korea.

Species	*N*	Age (Years)	Diameter at Breast Height (cm)	Height (m)	Dry Biomass (kg)
Ginkgo biloba	16	16.9 (8–34)	10.8 (5.3–24.6)	8.5 (4.5–14.7)	47.2 (7.8–201.1)
Abies holophylla	20	20.3 (13–28)	11.4 (5.2–20.6)	5.7 (3.0–8.6)	51.3 (7.7–129.5)
Pinus densiflora	10	15.5 (12–20)	13.4 (7.2–19.0)	6.4 (2.9–8.2)	71.9 (19.8–165.2)
Pinus strobus	10	15.5 (7–26)	12.3 (7.1–20.3)	6.0 (4.3–7.7)	50.2 (9.5–150.5)
Chionanthus retusus	20	16.1 (9–24)	12.4 (5.1–22.5)	8.0 (5.6–12.9)	96.7 (12.3–241.4)

Table 1. *Cont.*

Species	*N*	Age (Years)	Diameter at Breast Height (cm)	Height (m)	Dry Biomass (kg)
Prunus × yedoensis	11	19.4 (14–28)	13.7 (7.0–22.2)	9.2 (4.9–12.6)	84.3 (13.9–200.2)
Quercus palustris	20	12.7 (10–15)	14.3 (6.8–23.4)	9.3 (7.2–11.6)	99.1 (19.9–213.4)
Zelkova serrata	10	18.5 (15–25)	13.4 (5.5–22.1)	7.3 (4.6–9.7)	116.4 (12.4–335.0)

2.2. Laboratory Analysis

The green weight of each root, stem wood, stem bark, branch, and foliage sample were measured immediately after collection, while dry weight was measured after oven drying at 85 °C for over 72 h. The dry biomass of each tree compartment was estimated by calculating the dry-to-green weight ratio of the samples. Further, a subsample from each tree compartment was ground into powder, and its carbon and nitrogen concentrations were determined using the Vario Macro CHN elemental analyzer (Elementar Analysensysteme GmbH, Langenselbold, Germany). A tree ring from the stem disk sampled at breast height (1.2 m above the ground) was examined following typical procedures for stem analysis [29]. The five-year growth rate of the trees was determined based on differences in bark diameter between the year of examination and five years prior.

2.3. Data Analysis

Using DBH as an independent variable, AEs were developed for the dry biomass of each tree compartment. Among the various types of equations for fitting allometric models—such as polynomial, quadratic, exponential, logarithmic, and power functions—power function (Equation (1)) has been widely used in allometric studies. This is because power function can be easily linearized through a log transformation (Equation (2)), allowing it to be fitted using linear regression.

$$\text{Biomass} = a \times \text{DBH}^b \tag{1}$$

$$\log(\text{Biomass}) = \log(a) + b \times \log(\text{DBH}) \tag{2}$$

With the increasing accessibility of nonlinear fitting techniques, nonlinearly power fitting, which may offer better performance than log-transformed linear fitting, has been occasionally recommended in recent years for its statistical robustness [30,31]. However, log-transformed linear fitting is still preferred due to its conceptual and theoretical soundness foundations. Log transformation can represent the biological scaling law, and the coefficients from log-transformed linear regression can describe the magnitude of size scaling [32,33]. Therefore, in this study, a log-transformed linear regression analysis was selected for model fitting given its conventional and common use in biomass AE studies [34,35]. To minimize potential bias in the log-transformed linear regression analysis, a correction factor (CF) was determined (Equations (3) and (4)), as recommended by Baskerville [36] and Sprugel [37].

$$\text{CF} = e^{\left(\frac{\text{SEE}^2}{2}\right)} \tag{3}$$

where SEE represents the standard error of the estimate.

$$\text{SEE} = \sqrt{\sum(\ln y_i - \ln \hat{y}_i)^2 / (N - p)} \tag{4}$$

where y_i represents the measured value; $\hat{y}_i$ represents the estimated value calculated using the developed AEs; N represents the number of trees sampled; and p is the parameter coefficient. Biomass estimates were first calculated, and were then followed by the back-transformation of log-transformed values and correction using the CF. Further, the biomass of each compartment was subtracted from the whole tree biomass to obtain biomass fractions.

The p-value, coefficient of determination (R^2), and root mean square error (RMSE) were derived to confirm the goodness-of-fit of each AE. Further, the biomass distribution ratios and annual carbon sequestration rates in each compartment were investigated using analysis of covariate (ANCOVA), with DBH set as the covariance. Inter-species and inter-compartment differences in carbon and nitrogen concentrations were determined via two-way analysis of variance (ANOVA). When inter-species differences in the observed variables were confirmed, Tukey's honest significant difference (HSD) post-hoc test was performed to identify the mean difference between the species.

To identify the characteristics of underground biomass allocation in urban trees, root biomass fraction needs to be compared between urban trees. As we did not harvest comparable forest trees, we adopted published root biomass fractions from two sources: (1) the global biomass allometry dataset for more than 3500 tree species by Ledo et al. [38] and (2) the country-specific emission factors for South Korean forest trees by Son et al. [39]. When a root-to-shoot ratio (RSR) was reported, it was converted to root biomass fraction using the following equation.

$$\text{Root biomass fraction} = \frac{\text{RSR}}{1 + \text{RSR}} \quad (5)$$

The difference in root biomass fractions between this study and the previous studies was assessed using the t-test.

The carbon sequestration rates of the sampled trees were calculated by subtracting their carbon storage level five years ago from the current values using the AEs developed in this study as follows:

Carbon sequestration rate (kg C year^{-1}) =

$$\sum_{c=1}^{n} a_c \times \left(\text{DBH}_t^{b_c} - \text{DBH}_{t-5}{}^{b_c}\right) \times CF_c \times Cconc_c/5 \quad (6)$$

where a_c, b_c, and CF_c are the coefficients of AEs for each tree compartment (root, stem wood, stem bark, branch, and foliage); DBH_t and DBH_{t-5} is the DBH of the sampled year and five years ago (as determined using tree-ring analysis), respectively; and $Cconc_c$ is the carbon concentration for each tree compartment. Additionally, differences in annual carbon sequestration rate according to species were tested via ANCOVA with Tukey's HSD post-hoc test, as stated above.

All statistical analyses were performed using R software [40] and visualized using the *ggplot2* package in R [41].

3. Results

3.1. Developed AEs

Biomass AEs were developed for stem wood, stem bark, branch foliage, roots (i.e., belowground biomass), and aboveground dry biomass for each species (Figure 1, Table 2). Except for the foliage AEs for *G. biloba*, which exhibited marginal significance, all the other AEs were statistically validated, demonstrating a proportional increase in biomass across each tree compartment with increasing DBH ($p < 0.05$). Further, both root and aboveground AEs demonstrated high R^2 values greater than 0.85 (except for *Pinus densiflora*), with the aboveground AEs exhibiting slightly higher R^2 values than the root AEs. Specifically, the R^2 values of the aboveground AEs ranged from 0.853 for *Prunus* × *yedoensis* to 0.982 for *C. retusus*, and those for the root AEs ranged from 0.806 for *Z. serrata* to 0.923 for *Pinus strobus*. The accuracy of AEs for foliage varied considerably according to species. Specifically, the R^2 values of foliage AEs were >0.9 for *P. strobus*, *Q. palustris*, and *C. retusus*, whereas those for *G. biloba* and *Prunus* × *yedoensis* were <0.6.

Table 2. Coefficients and goodness-of-fit of biomass allometric equations (log(Biomass [dry kg]) = log(a) + b × log(DBH [cm])) for the different compartments of major urban landscaping tree species in South Korea. The asterisks indicate the statistical significance of the model (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Species	Tree Component	Coefficients			R^2	RMSE	p Value
		a	b	CF			
Ginkgo biloba	Aboveground	0.160	2.144	1.023	0.954	6.672	***
	Foliage	0.174	0.834	1.267	0.230	1.001	0.06
	Branch	0.007	2.827	1.111	0.886	4.036	***
	Stem bark	0.018	2.048	1.054	0.890	1.306	***
	Stem wood	0.129	2.023	1.022	0.950	4.600	***
	Root	0.238	1.783	1.051	0.893	7.317	***
Abies holophylla	Aboveground	0.236	2.035	1.034	0.924	9.212	***
	Foliage	0.126	1.791	1.078	0.808	3.993	***
	Branch	0.051	2.103	1.106	0.812	5.646	***
	Stem bark	0.032	1.819	1.034	0.906	0.431	***
	Stem wood	0.047	2.258	1.011	0.979	2.011	***
	Root	0.095	1.908	1.064	0.854	4.019	***
Pinus densiflora	Aboveground	0.130	2.239	1.039	0.901	15.765	***
	Foliage	0.022	2.060	1.076	0.802	1.876	***
	Branch	0.025	2.375	1.136	0.755	8.190	**
	Stem bark	0.021	1.988	1.098	0.746	1.578	**
	Stem wood	0.065	2.247	1.042	0.896	9.458	***
	Root	0.071	2.100	1.199	0.629	11.513	**
Pinus strobus	Aboveground	0.048	2.588	1.019	0.957	5.616	***
	Foliage	0.008	2.625	1.050	0.900	2.459	***
	Branch	0.003	3.230	1.048	0.934	4.383	***
	Stem bark	0.001	2.769	1.431	0.575	1.523	*
	Stem wood	0.071	2.049	1.026	0.913	1.554	***
	Root	0.076	2.066	1.033	0.923	3.264	**
Chionanthus retusus	Aboveground	0.353	2.050	1.009	0.982	11.790	***
	Foliage	0.075	1.698	1.026	0.928	1.419	***
	Branch	0.130	2.016	1.051	0.904	8.077	***
	Stem bark	0.031	1.861	1.040	0.911	1.713	***
	Stem wood	0.129	2.177	1.011	0.980	5.446	***
	Root	0.240	1.900	1.061	0.857	9.843	***
Prunus × yedoensis	Aboveground	0.202	2.132	1.052	0.853	18.357	***
	Foliage	0.023	1.882	1.182	0.578	3.502	**
	Branch	0.013	2.659	1.096	0.833	8.529	***
	Stem bark	0.073	1.497	1.064	0.699	1.311	**
	Stem wood	0.145	2.058	1.088	0.765	12.501	***
	Root	0.095	2.073	1.033	0.894	6.508	***
Quercus palustris	Aboveground	0.271	2.077	1.008	0.973	10.367	***
	Foliage	0.018	2.027	1.024	0.916	0.853	***
	Branch	0.035	2.409	1.044	0.894	6.599	***
	Stem bark	0.136	1.425	1.009	0.935	0.767	***
	Stem wood	0.144	2.072	1.004	0.984	4.468	***
	Root	0.211	1.736	1.025	0.886	6.203	***
Zelkova serrata	Aboveground	0.173	2.237	1.021	0.955	9.439	***
	Foliage	0.145	1.292	1.051	0.753	1.341	**
	Branch	0.022	2.619	1.052	0.925	5.323	***

Table 2. *Cont.*

Species	Tree Component	Coefficients			R^2	RMSE	*p* Value
		a	*b*	CF			
	Stem bark	0.017	2.103	1.048	0.896	1.292	***
	Stem wood	0.102	2.173	1.013	0.971	4.751	***
	Root	0.100	2.288	1.122	0.806	18.078	***

CF = correction factor to eliminate the bias introduced by back log-transformation; RMSE = root mean square error.

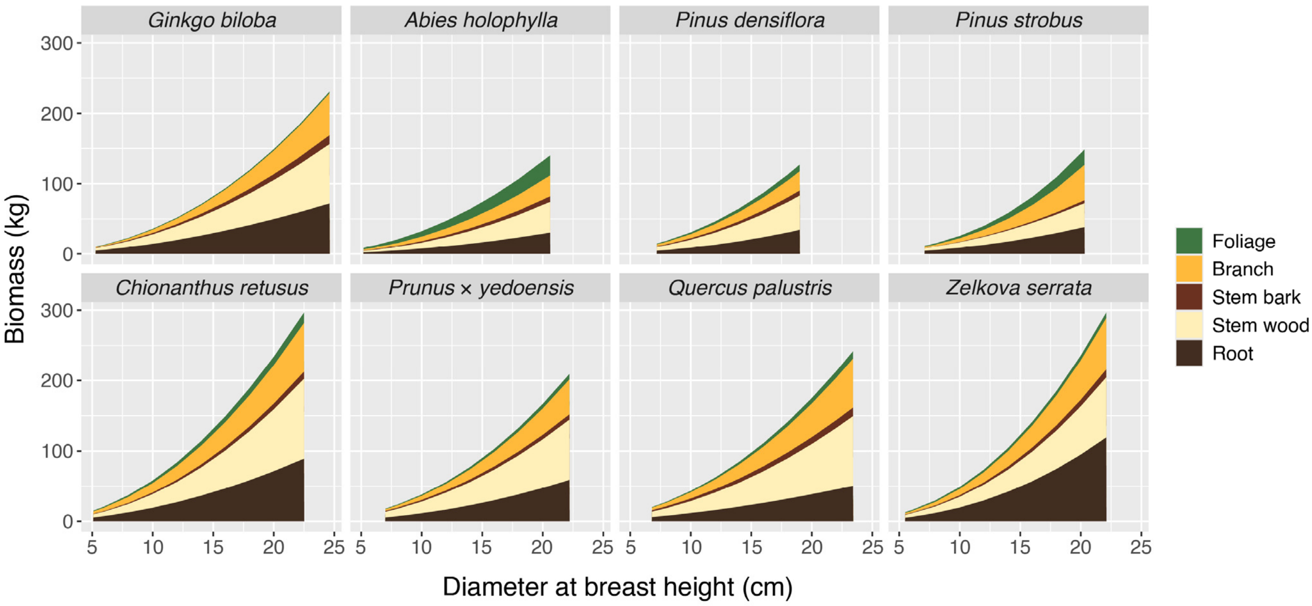

Figure 1. Biomass allometric equations for the compartments of eight urban landscaping tree species in central South Korea.

3.2. Biomass Fraction

Overall, the order of distribution of biomass in the tree compartments was as follows: stem wood (34.3%), roots (30.5%), branches (20.8%), foliage (8.7%), and bark (5.6%) (Figure 2). Inter-species differences were also observed in this distribution (Figure 2, Table A1). Specifically, *P. densiflora*, *P. strobus*, *C. retusus*, and *Prunus* × *yedoensis* allocated approximately 30% of their biomass to roots. This was higher than the mean values for *G. biloba* and *Z. serrata* (41.3% and 39.8%, respectively), but lower than those for *A. holophylla* and *Q. palustris* (24.2% and 24.6%, respectively) ($p < 0.05$, Table A1). The distribution fraction of stem biomass was the highest for *Prunus* × *yedoensis* (42.7%) followed by *Q. palustris* (39.7%), and the lowest for *P. strobus* (26.1%) followed by *A. holophylla* (27.6%). Additionally, the distribution ratios of foliage biomass were considerably higher for *A. holophylla* (22.7%) and *P. strobus* (13.0%) than for the other species (3.5–7.9%).

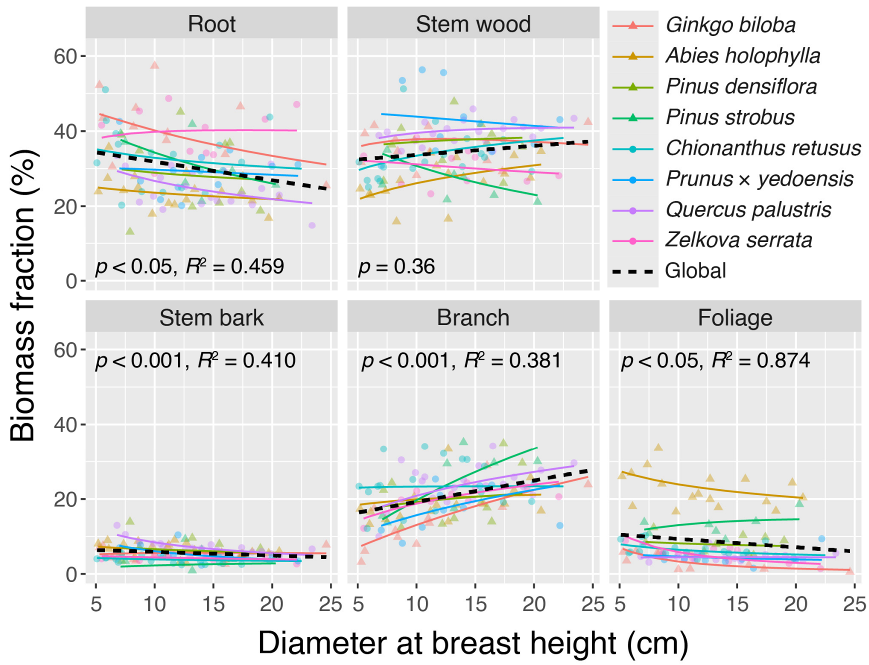

Figure 2. Biomass fractions in different tree compartments. The effect of the diameter at breast height (DBH) on the biomass distribution ratio was tested using a mixed-effect model (*Biomass ratio ~ DBH + Species*). The p and R^2 values of the model are presented in each panel. Table A1 provides descriptive statistics for biomass distribution ratios according to tree species.

With increasing DBH, the distribution ratio of branch biomass increased significantly ($p < 0.001$), whereas those of root ($p < 0.05$), stem bark ($p < 0.001$), and foliage ($p < 0.05$) biomass decreased significantly. Changes in the distribution of biomass in stem wood were insignificant ($p = 0.36$) and inconsistent across the species (Figure 2).

When compared with previous studies, the mean root biomass fraction of our study (30.5%) was significantly greater than that of 22 forest tree species in South Korea (23.6%) [35] and that from the global forest tree dataset (23.5%) [34] (Figure 3; *t*-test, $p < 0.001$). Moreover, the root biomass fraction values observed in this study remained significantly higher than those in the global tree dataset for trees with a DBH between 5 and 25 cm (19.4%) after accounting for covariate effects of tree size (*t*-test, $p < 0.001$).

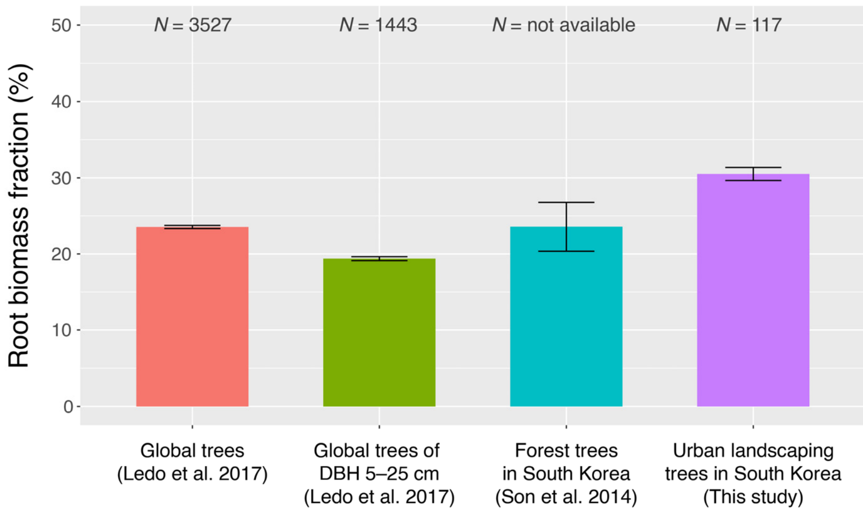

Figure 3. Root biomass fraction distribution between urban and forest trees. The values obtained in the present study, which investigated urban landscaping trees in South Korea, were compared to those

reported based on a global tree dataset (Ledo et al. [38]) and a South Korean forest tree dataset (Son et al. [39]). Data from the global tree dataset and this study were analyzed at the individual tree level, whereas data from forest trees in South Korea were available at the species level. Trees from the global dataset with a diameter at breast height (DBH) between 5 to 25 cm were extracted to account for the size-dependent variation in root biomass allocation. An error bar indicates a standard error.

3.3. Annual Carbon Sequestration Rates

The mean annual carbon sequestration rates (kg C tree^{-1} year^{-1}) during the last five years for *G. biloba*, *A. holophylla*, *P. densiflora*, *P. strobus*, *C. retusus*, *Prunus* × *yedoensis*, *Q. palustris*, and *Z. serrata* were 1.90 ± 1.53, 2.28 ± 1.45, 3.93 ± 2.41, 3.90 ± 2.92, 5.06 ± 3.51, 2.98 ± 1.73, 5.62 ± 3.24, and 5.82 ± 4.36, respectively (Table 3). In general, the annual carbon sequestration rate was higher for trees with a larger DBH than for those with a smaller DBH (Figure 4b). Further, when the covariance effect of tree size was considered ($p < 0.001$), significantly higher annual carbon sequestration rates were observed for *Z. serrata* and *Q. palustris*, whereas significantly lower rates were observed for *G. biloba* and *A. holophylla* ($p < 0.001$, Figure 4a).

Table 3. Carbon concentrations (%) of the compartments of major landscaping tree species in South Korea. The different letters represent significant mean differences, determined via Tukey's HSD test. The asterisks indicate the statistical difference among species (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Species	Root	Stem Wood **	Stem Bark ***	Branch ***	Foliage ***
Ginkgo biloba	46.98 (0.45)	49.57 (2.02) ab	45.21 (4.08) bc	50.39 (0.84) ab	52.98 (0.77) a
Abies holophylla	46.18 (1.83)	48.52 (5.33) ab	49.50 (1.63) a	51.31 (0.81) a	52.01 (0.51) a
Pinus densiflora	45.85 (2.37)	49.12 (0.82) ab	46.11 (3.50) cd	49.86 (0.70) abc	48.01 (2.41) ab
Pinus strobus	47.86 (3.09)	51.26 (2.84) a	48.22 (3.10) ab	50.74 (1.20) a	50.48 (3.02) bc
Chionanthus retusus	45.48 (2.58)	47.38 (1.16) b	44.14 (1.65) cd	48.34(0.45) bc	48.07 (0.44) ab
Prunus × *yedoensis*	47.80 (0.99)	48.33 (1.23) ab	44.75 (3.71) bcd	48.08 (2.00) c	46.58 (1.65) cd
Quercus palustris	45.31 (3.27)	48.16 (0.74) b	41.05 (1.68) d	51.65 (0.24) a	46.52 (1.02) cd
Zelkova serrata	46.67 (2.07)	48.00 (1.89) b	43.82 (3.39) cd	48.42 (0.77) bc	44.74 (2.46) d

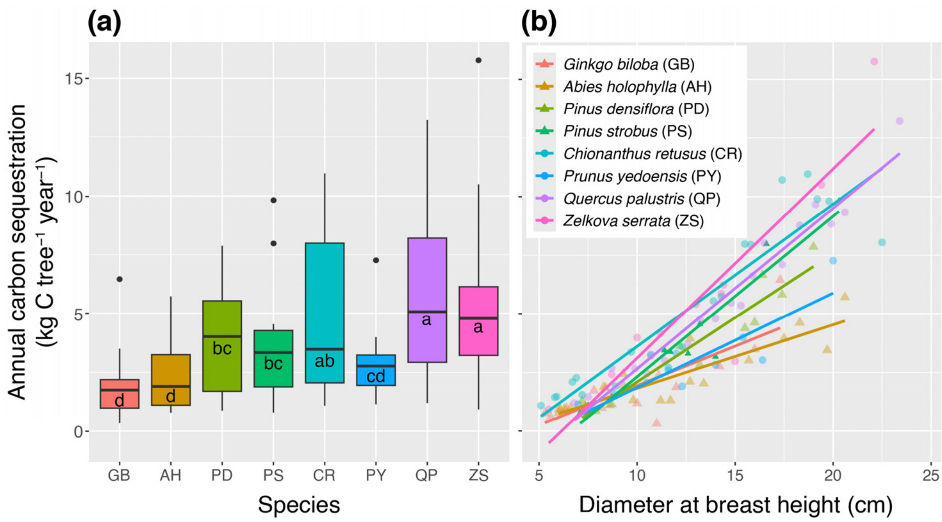

Figure 4. Annual carbon sequestration rates during the last five years according to species (**a**) and diameter at breast height (**b**). Inter-species differences in annual carbon sequestration rate were tested via analysis of covariance (*Annual carbon uptake rate ~ Species + DBH*). The different letters in the box represent significant mean differences, determined via Tukey's HSD test.

3.4. Carbon and Nitrogen Concentrations

The mean carbon concentrations of the tree compartments of the sampled species varied in the range of 41.05 to 52.98%. Statistically significant differences in carbon concentrations were analyzed according to tree species ($p < 0.001$) and compartment ($p < 0.001$). We observed that the mean carbon concentration across species for root, stem wood, stem bark, branch, and foliage were 46.7 ± 2.0%, 48.6 ± 2.5%, 45.4 ± 4.0%, 50.2 ± 1.6%, and 48.7 ± 3.2%, respectively (Table 3).

The nitrogen concentrations of the tree compartments varied to a greater extent (0.14–2.30%) than the carbon concentration for all species. Specifically, the coefficients of variation for carbon and nitrogen concentrations were 7.7% and 86.0%, respectively. Considering all species investigated, foliage exhibited relatively high mean nitrogen concentrations (1.71 ± 0.49%), several fold higher than those observed for woody compartments (0.57 ± 0.22%, 0.20 ± 0.09%, 0.61 ± 0.21%, and 0.41 ± 0.14% for root, stem wood, stem bark, and branch, respectively), and the differences were statistically significant ($p < 0.001$). Significant inter-species differences in nitrogen concentrations were also observed ($p < 0.001$). In general, angiosperms demonstrated higher nitrogen concentrations in all compartments than gymnosperms (Table 4).

Table 4. Nitrogen concentrations (%) of the compartments of major landscaping tree species in South Korea. The different letters represent significant mean differences, determined via Tukey's HSD test. The asterisks indicate the statistical difference among species (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Species	Root ***	Stem Wood ***	Stem Bark ***	Branch *	Foliage ***
Ginkgo biloba	0.60 (0.08) ^{a}	0.16 (0.09) ^{bc}	0.65 (0.08) ^{b}	0.34 (0.11) ^{ab}	1.39 (0.28) ^{cd}
Abies holophylla	0.53 (0.19) ^{a}	0.14 (0.08) ^{c}	0.63 (0.11) ^{b}	0.42 (0.12) ^{ab}	1.27 (0.29) ^{d}
Pinus densiflora	0.75 (0.10) ^{a}	0.14 (0.03) ^{c}	0.28 (0.06) ^{d}	0.37 (0.07) ^{ab}	1.35 (0.14) ^{d}
Pinus strobus	0.25 (0.08) ^{b}	0.18 (0.12) ^{bc}	0.47 (0.09) ^{c}	0.33 (0.12) ^{b}	1.30 (0.11) ^{d}
Chionanthus retusus	0.58 (0.06) ^{a}	0.31 (0.07) ^{a}	0.84 (0.10) ^{a}	0.33 (0.21) ^{b}	2.06 (0.10) ^{ab}
Prunus × yedoensis	0.75 (0.24) ^{a}	0.19 (0.04) ^{bc}	0.78 (0.11) ^{ab}	0.57 (0.15) ^{a}	1.91 (0.21) ^{b}
Quercus palustris	0.76 (0.16) ^{a}	0.23 (0.03) ^{b}	0.46 (0.05) ^{c}	0.28 (0.01) ^{b}	2.30 (0.11) ^{a}
Zelkova serrata	0.52 (0.15) ^{ab}	0.19 (0.09) ^{bc}	0.77 (0.30) ^{ab}	0.43 (0.19) ^{ab}	1.72 (0.25) ^{bc}

4. Discussion

4.1. Belowground Biomass Fraction of Urban Landscaping Trees

The belowground biomass fraction (or the RSR) varies substantially across vegetation type (grass, shrub, tree, etc.), region, climate [42], and in response to various environmental factors, such as water and nutrient availability and temperature [43]. Accordingly, it has received considerable attention in forest biomass and carbon cycle studies. However, its direct measurement is challenging, as the root system is hidden below the ground. Since the establishment of the belowground biomass fraction for global use by Cairn et al. [44], numerous field studies and meta-analyses have been conducted to investigate its value, not only in the comprehensive assessment of whole-tree biomass but also in understanding belowground adaptation and function (including root, soil, and rhizosphere) with respect to plant growth and the carbon cycle.

To the best of our knowledge, the present study is the first to suggest greater biomass allocation to belowground fraction for urban trees than for forest trees (Figure 3). Given that the belowground biomass fraction has likely never been determined for urban environments, our findings require further validation and explanation through additional studies. Nevertheless, based on current knowledge of biomass allocation, it is hypothesized that urban trees allocate more biomass to belowground structures as a result of potential deficiencies in underground resources (e.g., water stress, nutrients, soil pore space) in contrast to the abundant aboveground resources such as solar radiation. For example, a meta-analysis on southern temperate forests indicated that belowground biomass allocation increased with a lower precipitation-to-temperature ratio [45]. This previous finding supports our hypothesis, suggesting that urban environments, which are more prone to water and heat stress than forest environments, may lead to greater belowground biomass allocation.

The range of species, locations, and DBH of the studied trees may be insufficient to fully represent the entire urban tree population of South Korea. Thus, it may be premature to generalize the greater belowground allocation of biomass observed in this study to all urban trees. Given this limitation, further research is needed to better understand and quantify belowground biomass allocation in urban trees.

4.2. Carbon and Nitrogen Concentrations

In general, the carbon concentration of plant tissues is assumed to be half of their biomass (50%). Therefore, the National Greenhouse Gas Inventory guidelines of IPCC recommend a standard carbon conversion factor of 0.5 [16]. Considering the effort and cost associated with measuring the carbon concentration of each plant tissue and for different species, applying a carbon conversion factor of 0.5 is considered to be a cost-effective strategy. Nevertheless, the results of the present study confirmed the existence of a statistically significant difference in carbon concentrations between tree species and compartments, although the difference was not large. The mean carbon concentration of the studied trees was 47.5%. Therefore, the use of the prescribed carbon conversion factor can result in the overestimation of carbon storage and sequestration by up to 5.2%. This discrepancy in carbon concentrations should be considered in carbon inventory monitoring.

4.3. Challenges for Developing Biomass AEs for Urban Trees

In this study, landscaping trees were purchased and harvested from tree farms to develop AEs for biomass allocation by urban trees. While aboveground biomass of urban trees has been frequently determined using field surveys and remote sensing techniques, belowground biomass has not received similar attention. Destructive harvesting is advantageous in that it secures the underground biomass and allows the determination of biomass allocation fractions, nutrient concentrations, and annual carbon sequestration rates for different tree compartments. Although purchasing a sufficient number of trees for this purpose is cost-intensive, such an investment is necessary to ensure accurate reporting of greenhouse gas inventories in the settlement sector. Notably, the data from this study have been applied to design a country-specific emission factor for the settlement sector of South Korea in 2024. Securing appropriate funding to cover the costs of harvesting urban trees will be essential in countries aiming to improve their reporting of settlement-related greenhouse gas emissions.

Urban trees are exposed to heterogeneous growing conditions depending on their specific environments, such as parks, street alleys, or remnant and abandoned forest patches. For example, trees planted in isolated locations such as street alleys may experience restricted root growth due to limited belowground space, whereas their crown growth may be promoted by the sufficient gaps between isolated trees. In a meta-analysis, Poorter et al. [46] examined the effects of neighboring trees on biomass allocation, revealing that stem and root biomass fractions varied with plant density. This suggests that allometry and biomass allocation can exhibit significant variability even within urban environments. Given the growing conditions of the tree farms where sample trees of this study were sourced, the findings of this study may be limited to urban trees growing in proximity to neighboring trees, rather than isolated street trees. Furthermore, it is reasonable to question whether the studied trees from tree farms grew in conditions identical to those of urban trees and whether they can accurately represent the allometry of urban trees. In this context, obtaining harvestable urban trees remains a challenge, despite our efforts to acquire them from tree farms.

The limited range of tree diameter classes for which AEs have been developed remains an issue that needs to be addressed. In this study, AEs were developed for trees with DBHs up to 25 cm. Therefore, there are limitations to applying these AEs to larger urban trees. Fortunately, trees with DBHs below 25 cm are dominant in urban areas in South Korea, owing to the short history of urbanization and the establishment of urban green infrastructure in the country. For example, Lee et al. (unpublished) examined trees on a

50-year-old university campus in South Korea and estimated carbon storage and sequestration by the campus trees; the number of trees with a DBH < 25 cm accounted for approximately 75% of all the trees in the campus tree inventory. Therefore, considering that in South Korea, the range of the diameter of urban trees is not as wide as that of general forest trees, the AEs obtained in this study will be highly useful. Nevertheless, there are limitations to directly using them to estimate the biomass of larger-sized trees. To overcome this issue, Lee et al. (unpublished) proposed a hybrid approach for integrating AEs into urban trees using destructive and nondestructive methods. Harvesting large trees has long been a challenge in biomass allometry studies, and additional effort, investment, and innovation are required to overcome this challenge.

5. Conclusions

In the present study, we developed biomass AEs for eight common urban landscaping trees in South Korea. Using the destructive method, which is less favored in biomass studies involving urban trees, we found that urban trees allocate more belowground biomass than forest trees. In addition, we quantified the carbon and nitrogen concentrations in each tree compartment (root, stem wood, stem bark, branch, leaf, and aboveground) and the annual carbon sequestration rates. Overall, this study provides AEs for urban trees, which can be used to improve the accuracy of the national greenhouse gas inventory and the assessment of ecosystem services in the settlement sector.

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Data Availability Statement: The datasets generated and/or analyzed in the current study are available from the corresponding author upon reasonable request.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Biomass allocation fractions of tree compartments. Different letters represent the mean of significant inter-species differences, determined via the analysis of covariance followed by Tukey's HSD post-hoc test ($p < 0.05$).

	Root ***	Stem Wood ***	Stem Bark ***	Branch ***	Foliage ***
Ginkgo biloba	41.3 (9.3) [a]	35.7 (5.1) [ab]	5.4 (1.8) [abc]	14.1 (7.7) [b]	3.5 (2.2) [d]
Abies holophylla	24.2 (4.6) [c]	27.6 (6.1) [c]	6.8 (1.7) [a]	18.8 (4.9) [ab]	22.7 (4.7) [a]
Pinus densiflora	28.9 (10.8) [bc]	36.4 (6.7) [ab]	6.6 (3.3) [ab]	20.3 (7.5) [ab]	7.9 (2.6) [c]
Pinus strobus	31.6 (7.8) [abc]	26.1 (4.9) [c]	4.9 (2.6) [abc]	24.4 (8.6) [a]	13.0 (3.0) [b]
Chionanthus retusus	32.7 (8.4) [ab]	33.0 (6.6) [bc]	3.6 (0.9) [c]	24.2 (6.7) [a]	6.5 (1.9) [cd]

Table A1. *Cont.*

	Root ***	Stem Wood ***	Stem Bark ***	Branch ***	Foliage ***
Prunus × yedoensis	29.2 (6.4) [bc]	42.7 (8.9) [a]	5.4 (2.2) [abc]	18.0 (6.0) [ab]	4.7 (2.2) [cd]
Quercus palustris	24.6 (4.9) [c]	39.7 (3.0) [a]	7.1 (1.9) [a]	24.0 (5.4) [a]	4.6 (1.1) [d]
Zelkova serrata	39.8 (6.7) [a]	30.3 (4.8) [bc]	4.2 (0.8) [bc]	20.6 (3.4) [ab]	5.2 (2.2) [cd]
Mean	30.5 (9.2)	34.3 (7.7)	5.6 (2.3)	20.8 (6.9)	8.7 (7.1)

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

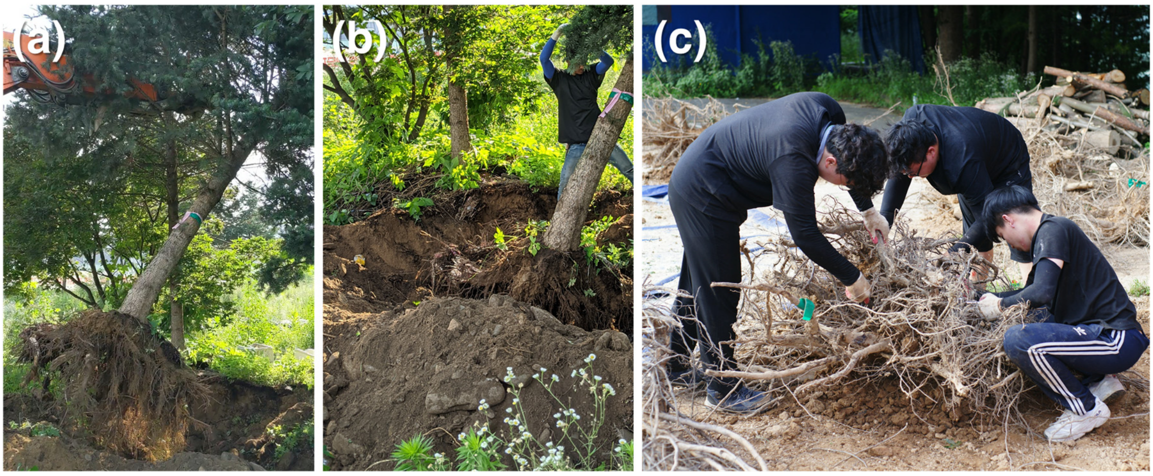

Figure A1. (**a**) The trees were uprooted using an excavator. Roots can be either underharvested due to uncollected roots remaining in the soil or overmeasured due to attached soil on the root samples. To minimize these sampling errors, (**b**) the soil around the excavated tree was excavated as widely and deeply as possible, and all tap and lateral secondary roots that remained in the soil were manually excavated; (**c**) the soil attached to the roots was removed by shaking and scraping as thoroughly as possible.

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