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Carbon Offset Service of Urban Park Trees and Desirable Planting Strategies for Several Metropolitan Cities in South Korea

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Abstract: Urban parks are essential for offsetting high carbon emissions in cities, which are known to be high emitters. This study quantified carbon uptake and storage in Daejeon and Daegu, two major metropolitan cities in South Korea, and explored planting strategies to promote carbon offset services. Mean carbon uptake and storage per unit area in the study parks were 2.6 ± 0.1 t/ha/yr and 29.9 ± 1.7 t/ha, respectively. The urban park trees of a metropolitan city in South Korea were estimated to annually sequester and store 50 kt/yr and 572 kt of carbon, respectively. This carbon uptake equaled 1.5% of the total annual carbon emissions from residential energy consumption. The economic value of the carbon uptake was equivalent to $3.3 million/yr, which is 1.50% of the annual establishment budget of urban forests of the Korea Forest Service. Planting strategies included reducing unnecessary grass and pavement areas, the active planting of trees in the potential planting space, multilayered planting, and planting tree species with high growth rates. These results are expected to guide policies related to carbon credits, which have recently emerged as major concerns, and to provide useful information for quantifying carbon offset services in greenspace establishment projects.

Keywords: climate change; indicator; storage; uptake; tree planting structure

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1. Introduction

Fossil fuel consumption and greenspace degradation caused by industrialization continue to increase the average global CO_2 concentration. As of 2021, the average CO_2 concentration in the Earth's atmosphere was approximately 414.7 ppm, which is a 50% increase compared to pre-industrialization levels [1]. The accompanying greenhouse effect has caused environmental problems (such as climate change), with far-reaching implications on the global ecology and socioeconomic system. The international community has been promoting various international agreements to mitigate climate change impacts; the most notable example is the recent Paris Climate Change Agreement, which aims to limit the increase in global average temperature to below 1.5 °C (relative to pre-industrial levels) [2]. However, the Intergovernmental Panel on Climate Change (IPCC) reported that the 2030 reduction goals set by many countries are not sufficient to meet this goal, and all countries must achieve zero carbon emissions by 2050 [3]. In response, many countries globally (including South Korea, the United States, and the European Union) have set carbon neutrality as their main policy in a bid to achieve zero carbon emissions by 2050 [4–6].

Urban trees contribute to carbon reduction by directly sequestering the CO_2 through photosynthesis and avoiding carbon emissions by promoting building energy savings through wind protection, shading, and evapotranspiration [7–10]. In addition, urban trees offer

air purification, microclimate amelioration, rainfall collection, and noise reduction [11–17]. Therefore, planting urban trees is a vital carbon uptake strategy for mitigating climate change, in line with worldwide carbon-neutral programs, including the IPCC guidelines [18,19]. It is necessary to understand urban trees' carbon offset service to establish national greenhouse gas reduction targets by planting trees. Accordingly, since the 1990s, studies to identify carbon uptake and storage in urban trees have been actively conducted in various countries around the world, including the United States, Europe, China, South Korea, Bangladesh, and Africa [8,20–37].

Nowak and Crane [21] quantified the carbon offset service per unit of area and crown cover in urban trees. Annual carbon uptake per unit area and cover was 0.80 t/ha/yr and 0.29 kg/m^2/yr, respectively. Moreover, carbon uptake per unit of tree cover was used as a default carbon uptake coefficient by the IPCC [22]. Afterward, Nowak et al. [23] revised their estimates of carbon uptake and storage based on field data from 28 US cities to 0.28 kg/m^2/yr and 7.69 kg/m^2/yr per tree cover, respectively. Depending on the city, these values exhibited a difference of up to 4.5 times. Carbon storage per unit area of major European cities, such as Leicester, Boston, and Leipzig, were 49.3 t/ha, 28.8 t/ha, and 11.0 t/ha, respectively [24–26]. The carbon uptake per tree in Bolzano, Italy, ranged from 12.1 to 17.4 kg/tree/yr and was somewhat different depending on the methods such as CTCC, UFORE, and the European allometric model [27]. Carbon uptake per unit area in Beijing, Shenyang, and Hangzhou, China, were 2.2 t/ha/yr, 2.8 t/ha/yr, and 1.7 t/ha/yr, respectively [28–30].

Applying carbon uptake coefficients per tree cover developed in the United States, McGovern and Pasher [31] analyzed the changes in carbon uptake for urban trees in Canada from 1990 to 2012. They found that the crown cover of urban trees decreased by approximately 1.5% over the 22 years, whereas carbon uptake was similar. In major cities in Ethiopia and Nigeria, carbon storage per unit area was 33.2 t/ha and 39.7 t/ha, respectively [32,33]. Meanwhile, the carbon uptake and storage coefficient according to greenspace type has been continuously explored to quantify the carbon offset service of trees in all city environments. Urban trees on roadsides in Vadodara, India, were analyzed to offset 22% of the city's carbon emissions [34]. Jo et al. [8] reported that carbon uptake and storage per unit area in urban parks in Seoul were 3.5 t/ha/yr and 38.5 t/ha, respectively. In contrast, the carbon uptake per unit area of an urban park in Dhaka, Bangladesh, was 5.3 t/ha/yr [9]. In major cities in Germany, Finland, and Italy, carbon storage per unit area of an urban park was 60 t/ha, 28 t/ha, and 26 t/ha, respectively [35–37].

Noticeably, the carbon offset service of urban trees exhibits large differences depending on country, city, and greenspace type. Therefore, if the IPCC applies the carbon unit used in the United States to other countries, considerable estimation errors may result. To set accurate carbon reduction goals for urban trees and establish related policies, proper carbon uptake coefficients for each greenspace type that consider the unique city and country characteristics are required. Urban parks have potential as spaces for planting a considerable number of trees within the limited urban space (which is a carbon emitter) while facilitating carbon uptake. However, the carbon offset service of trees, considering regional characteristics and greenspace types per country, have not been sufficiently studied. Therefore, this study aims to quantify carbon uptake and storage by focusing on urban parks in Daejeon and Daegu (large cities in South Korea). In addition, planting strategies for maximizing the carbon offset service will be explored. The results of the study could contribute to highlighting the significance of urban parks as a source of carbon uptake and provide basic information related to carbon uptake indicators.

The definitions of carbon uptake, carbon storage, carbon indicator, and carbon offset service used in this study are as follows. In this study, carbon uptake refers to the carbon absorbed by trees in one year, and carbon storage indicates the total carbon accumulated over many years of tree growth. In addition, the carbon indicator refers to the carbon uptake and storage per unit greenspace area or per unit crown cover, and the carbon offset service indicates the rate at which the carbon uptake of trees offsets regional and national

carbon emissions. In this study, when the carbon uptake and storage are calculated, the carbon lost due to pest damage, pruning, and thinning is not reflected.

2. Materials and Methods

2.1. Selection of Study Cities and Parks

As of 2022, Korea comprised 17 metropolitan units, including 7 metropolitan cities, 9 provinces, and 1 special autonomous city, which together make up its administrative districts [38]. In Korea, a metropolitan city is defined as a large city with a population of over 1 million and well-developed education, transportation, and industry sectors [39]. Examples include Seoul, Daejeon, Daegu, Busan, Incheon, Gwangju, and Ulsan. Notably, approximately 43% (22 million people) of the total Korean population lives in metropolitan cities [40]. According to statistics, these cities occupy only 5.4% of Korea's total land area, but their park areas account for 32.7% of Korea's total park area [41]. Seoul was excluded from this study because research on carbon offset services for urban parks has already been conducted there. Accordingly, the cities to be studied were selected by considering their geographical distribution, park area, and administrative status. Daejeon, a transportation hub located in the central region of Korea with headquarters to many government agencies and public corporations, and Daegu, which is located in the southern region of Korea and occupies the largest park area, were selected as the study cities.

The total administrative area and population of the study cities are 1423.2 km^2 (539.5 km^2 for Daejeon and 883.7 km^2 for Daegu) and 3,823,707 people (1,448,401 for Daejeon and 2,375,306 for Daegu), respectively [42]. The population density in Daejeon and Daegu is 2,684.7 people/km^2 and 2,687.9 people/km^2, respectively, which is 5.3 times higher than the South Korean average. Regarding land use, forests (51% for Daejeon and 53% for Daegu) and building sites (13% of Daejeon and 10% of Daegu) were dominant in the study cities [43,44]. The urban parks in Daejeon and Daegu, excluding grave parks, were 5.9 km^2 and 15.6 km^2, occupying 1.8% and 1.1% of the total urban area, respectively [45,46].

For this study, sample parks were selected using systematic sampling from 1:1000 scale aerial photographs of the study cities (Figure 1). Radial lines were drawn on the photographs in eight directions, intersecting at the city center. Annular circles were then drawn at intervals of 40 cm for Daejeon and 30 cm for Daegu, considering the different sizes of the cities. Moreover, the parks in contact with the radial line and annular circle or closest within 500 m from the point of contact were selected as the study sites. This site sampling method was developed by Jo et al. [8] to fairly select study parks on a city-wide scale.

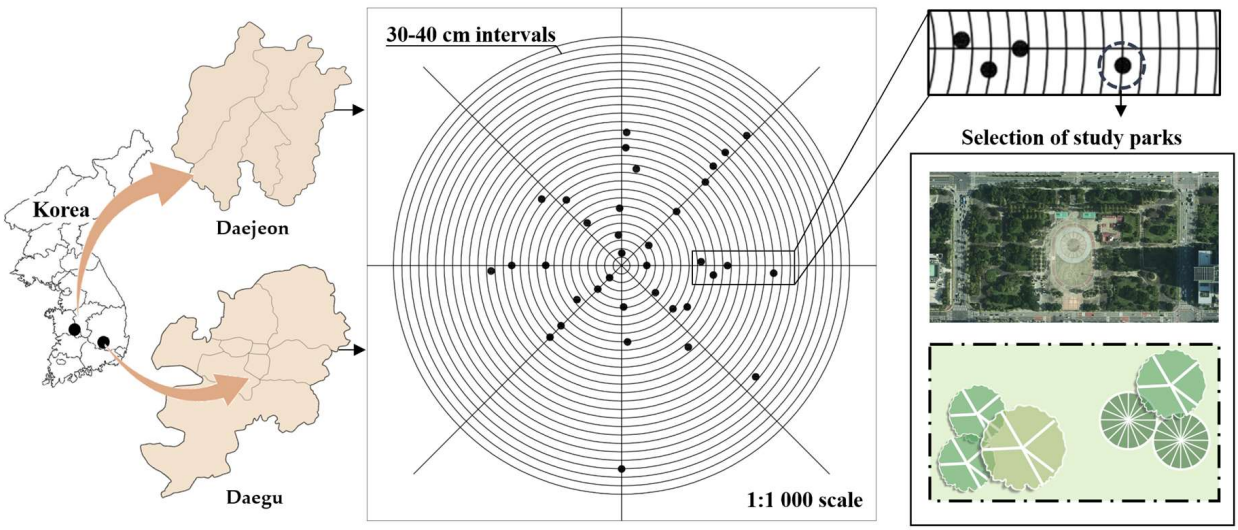

Figure 1. Depiction of systematic sampling method to select study parks.

A minimum of 3and a maximum of 6 parks were selected from each of the 8 lines, and the total number of study parks was 71: 35 in Daejeon and 36 in Daegu (Table 1), which represented 4.4% and 6.2% of the total number of urban parks in Daejeon (579 parks) and Daegu (797 parks) [45,46]. Per Urban Park Law in South Korea, urban parks are divided into small-sized, children's, neighborhood, and theme parks. The law designates that the area of children's and neighborhood parks should be 1500 m^2 and 10,000 m^2 or above, respectively [47]. Notably, 19 neighborhood parks, 48 children's parks, 2 small-sized parks, and 2 theme parks were included in this study. The number of samples was determined based on the cost and time requirements for a field survey and the statistical reliability of the survey data. The area of the study parks ranged between 0.1 and 17.8 ha, with parks smaller than 0.5 ha accounting for 70% of the total parks. Field measurements were conducted on a total area of 87 ha (36 ha for Daejeon and 51 ha for Daegu), corresponding to 2% of the total park area.

Table 1. The number and area of study parks.

City	Neighborhood		Children's		Small-Sized		Theme	
	No.	A [1]	No.	A	No.	A	No.	A
Daejeon	10 (101)	26.2 (1305.1)	23 (314)	9.1 (75.5)	1 (93)	0.1 (16.3)	1 (71)	0.2 (543.9)
Daegu	10 (159)	27.2 (1330.1)	24 (477)	6.3 (76.1)	1 (122)	0.1 (18.7)	1 (39)	17.8 (560.5)

[1] A: Area (ha); Figure in parenthesis: Total number and area of urban parks in study city.

2.2. Field Survey and Analysis of Tree Planting Structure

In this study, the park area was measured in the field, and all trees and shrubs distributed within the study park boundaries were investigated. Notably, the species, stem diameter at breast height (DBH) for trees and at a height of 15 cm above ground for shrubs, height, crown width, and layering structure were considered. In addition, tree density, cover, distribution of stem diameter at breast height, importance value of species, layering planting structure, and potential planting space were analyzed for each study park based on the survey data. Tree cover was estimated by analyzing the ratio of the total crown area calculated based on crown width to the total park area. The importance values of species were calculated by using the formulas of Kerbs [48] and Miller and Winer [49]. Vertical structure was divided into three single-layered structures (tree, shrub, and grass) and three multilayered structures (tree+shrub, tree+shrub+herb, and tree+shrub+grass). Moreover, the types were noted on the aerial photograph of the park during the field survey. AutoCAD 2017 (Version 17, Autodesk, San Francisco, CA, USA) was then used to measure the single-layer planting area and multilayer planting area in each planting site, and the proportions according to vertical structure types were analyzed. Herein, potential planting space refers to an open space that is not occupied by existing tree crowns despite spaces being available for planting trees (i.e., 2 m width and 3 m height or larger) without obstruction to nearby structures such as overhead lines or manholes. In addition, the land cover type of all urban parks was analyzed by conducting field surveys and aerial photograph readings in parallel. Results from the field study and the analysis data were then utilized to quantify carbon uptake and storage of planted trees in urban parks and to explore planting strategies for enhancing carbon offset services.

2.3. Estimating Carbon Offset Service

To predict the carbon uptake and storage capacity of urban trees accurately, an appropriate quantitative model that considers the country, region, and growth environments should be applied. However, considering forest trees with different growth environments (such as management and growth competition) or using quantitative models that consider the conditions in other countries can cause numerous errors in the calculated carbon uptake

and storage capacity. Therefore, the carbon uptake and storage of all trees in urban parks were calculated in this study by applying the quantitative model per tree species developed for open-grown urban trees to the trees in each park (Table 2) [50–57]. In other words, the measured diameter of each tree was substituted as a main independent variable in the quantitative model developed through the direct harvesting method or seasonal CO_2 exchange rate measurement for urban trees. Several species without quantitative models were substituted for ones of the same genus or with the same properties. Existing studies on urban parks mainly developed the basic units for carbon offset service based on site area, crown cover, and basal area. Reflecting these research trends, this study also calculated carbon offset service per unit of park area, crown cover, and basal area. The carbon uptake and storage per unit of park area, crown cover, and basal area were averaged by reflecting area, tree cover, and stem diameter for each study park. The total carbon uptake and storage were calculated by applying the above criteria to the study cities and the total park area of a metropolitan city in South Korea. Furthermore, the carbon offset service of the urban parks was quantified based on 3746 kt/yr of carbon emissions [58] according to the annual residential energy consumption of a metropolitan city in South Korea.

Table 2. Regression equation sources of tree and shrub species used to calculate carbon uptake and storage in the study parks.

	Species	Diameter Range (cm) [1]	Reference
Tree	Manchurian fir (*Abies holophylla*)	5–19	Jo et al., 2014 [50]
	Palmate maple (*Acer palmatum*)	7–27	Jo and Cho, 1998 [51]
		5–20	Jo and Ahn, 2012 [52]
	Camellia (*Camellia japonica*)	4–10	Jo et al., 2019a [53]
	Retusa fringetree (*Chionanthus retusus*)	3–11	Jo et al., 2014 [50]
	Japanese cornelian cherry (*Cornus officinalis*)	3–15	Jo et al., 2014 [50]
	Ginkgo (*Ginkgo biloba*)	6–31	Jo and Cho, 1998 [51]
		5–25	Jo and Ahn, 2012 [52]
	Round-leaf holly (*Ilex rotunda*)	3–12	Jo et al., 2019b [54]
	Crape myrtle (*Lagerstroemia indica*)	3–14	Jo et al., 2019a [53]
	Thunberg's bay-tree (*Machilus thunbergi*)	4-17	Jo et al., 2019b [54]
	Korean red pine (*Pinus densiflora*)	5–25	Jo et al., 2013 [55]
	Korean pine (*Pinus koraiensis*)	5–31	Jo et al., 2013 [55]
	Apricot (*Prunus armeniaca*)	4–14	Jo et al., 2014 [50]
	Korean flowering cherry (*Prunus yedoensis*)	5–23	Jo and Ahn, 2012 [52]
	Bamboo-leaf oak (*Quercus myrsinifolia*)	3–17	Jo et al., 2019a [53]
	Rigid-branch yew (*Taxus cuspidata*)	2–15	Jo et al., 2014 [50]
	Sawleaf zelkova (*Zelkova serrata*)	6–34	Jo and Cho, 1998 [51]
		5–28	Jo and Ahn, 2012 [52]
	General hardwoods	3–28	Jo, 2020 [56]
	General softwoods	5–31	Jo, 2020 [56]
Shrub	*Pinus* spp.	0.6–3.6	Jo, 2002 [57]
	Rhododendron spp.	0.4–3.4	Jo, 2002 [57]
	General hardwoods	0.4–4.0	Jo, 2002 [57]
	General softwoods	0.4–4.0	Jo, 2002 [57]

[1] Stem diameter at breast height (DBH) for trees and diameter at 15 cm above ground for shrubs.

2.4. Statistical Analyses

Using Microsoft Office Excel 2016 (Version 16, Microsoft Corporation, Redmond, WA, USA) and SPSS 26.0 for Windows (Version 26, International Business Machines Corporation, Armonk, NY, USA), the following statistical analyses were performed in addition to basic statistics like the mean and standard error. First, the t-test was used to determine whether any meaningful statistical differences existed between parks in Daejeon and Daegu in terms of tree planting structure, land cover types, and carbon offset service. To examine factors affecting carbon offset service, Pearson's correlation coefficient was used to identify the

relationship between carbon offset service and variables including tree planting structure and land cover types.

3. Results

3.1. Characteristics of the Study Parks

3.1.1. Land Cover Types in the Study Parks

Regarding the ratio of land cover types in the study parks, the pavements and facilities type was the highest, ranging between 16.6% and 82.5%, and an average of 54.6 ± 1.8% (Table 3). Areas composed of trees and shrubs presented the following outcome: a range between 11.1 and 75.5%, and an average of 41.1 ± 1.7%. The average grass area was 4.2 ± 0.9%, and comparisons of the percentage of land cover types of Daejeon and Daegu revealed that both cities were close to the mean value. Although the pavement/facility and grass in Daejeon were slightly higher than that in Daegu, the difference was not statistically significant ($p > 0.01$).

Table 3. Percentage of land cover types of urban parks sampled in the study cities.

Land Cover Types (%)	Daejeon	Daegu	Mean	*p*
Tree/Shrub	40.1 ± 2.6	42.1 ± 2.3	41.1 ± 1.7	0.574
Grass	4.5 ± 1.4	3.9 ± 1.1	4.2 ± 0.9	0.721
Pavement/Facility	55.3 ± 3.0	54.0 ± 2.1	54.6 ± 1.8	0.735
Other [1]	0.1 ± 0.0	0.0 ± 0.0	0.1 ± 0.0	0.335

[1] Including bare soil, ponds, wetlands, and streams.

3.1.2. Tree Planting Structures

The planting density of trees in the study parks was 3.0 ± 0.2 trees/100 m^2 in Daejeon and 3.8 ± 0.4 trees/100 m^2 in Daegu (Table 4). The overall average of the two cities was 3.5 ± 0.2 trees/100 m^2. Regarding tree density per park, 3 trees or fewer/100 m^2 accounted for 49.3%, followed by 3–5 trees/100 m^2 at 34.3%, and 6 trees or more/100 m^2 accounting for 16.4%. The basal area of the planted trees ranged from 347 to 1976 cm^2/100 m^2, with an average of 1019 ± 49.6 cm^2/100 m^2. Tree basal areas of 1000–1500 cm^2/100 m^2 in the study parks were the highest with 40.3%, followed by 500–1500 cm^2/100 m^2 with 31.3%, and 500 cm^2 or less/100 m^2 with 17.9%. The average DBH of planted trees was 18.4 ± 0.6 cm; the DBH distribution was 62.8% for 20 cm or less, 21.9% for 20–30 cm, and 15.3% for 30 cm or more (Figure 2). The cover of planted park trees and shrubs ranged between 12.1 and 76.4%, with an average of 43.1 ± 2.2%. The planting density, basal area, and cover of trees in Daejeon and Daegu did not exhibit a statistically significant difference ($p > 0.05$).

Table 4. Tree planting structures in the study parks.

Planting Structure	Daejeon	Daegu	Mean	*p*
Density (Tree/100 m^2)	3.0 ± 0.2	3.8 ± 0.4	3.5 ± 0.2	0.086
Basal Area (cm^2/100 m^2)	1046 ± 73.2	995 ± 68.2	1019 ± 49.6	0.611
Cover (%)	43.3 ± 3.6	42.9 ± 2.7	43.1 ± 2.2	0.938

A total of 174 species were found in the study parks, indicating a relatively diverse species composition. Among the top 10 species with high importance values per study city, the commonly planted species were *Zelkova serrata* (9.9%), *Pinus densiflora* (9.7%), *Pinus koraiensis* (6.8%), *Acer palmatum* (5.4%), *Prunus* spp. (5.2%), *Chionanthus retusa* (4.4%), *Rhododendron yedoense* var. *poukhanense* (3.6%), and *Ginkgo biloba* (3.0%). The top five species with high importance values in Daegu were *Z. serrata*, *P. densiflora*, *Prunus* spp., *A. palmatum*, and *C. retusa*. In Daejeon, the top dominant species were *Pinus strobus*, *P. densiflora*, *Z. serrata*, *A. palmatum*, and *Rhododendron* spp. Regarding the vertical planting structures of planted trees in the study parks, 64% of the total planted area consisted of single-layered structures with trees, shrubs, or grass, which was higher than the multilayered structures (36%) in

which trees, shrubs, and grass were planted simultaneously (Table 5). Among the single-layered structures, planted areas consisting of only shrubs or grass without trees accounted for approximately 25.2%.

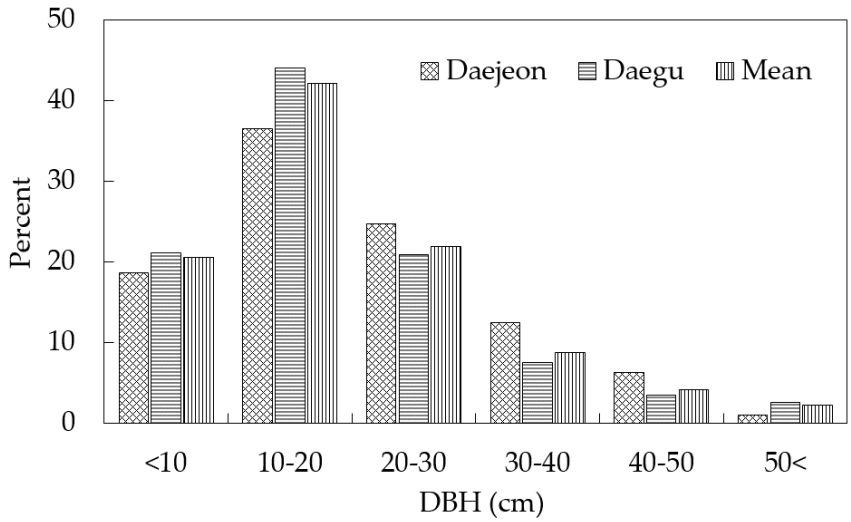

Figure 2. Distribution of study park tree DBHs.

Table 5. Vertical planting structures in the study parks.

Vertical Structure (%)		Daejeon	Daegu	Mean	*p*
Single-Layer	Tree	33.5	44.5	38.8	0.097
	Shrub	10.1	2.6	6.5	0.010
	Grass	14.6	23.0	18.7	0.009
Multilayer [1]	T+S	10.5	13.4	11.9	0.412
	T+S+H	2.8	4.7	3.7	0.331
	T+S+G	28.5	11.8	20.4	0.015

[1] T: tree; S: shrub; G: grass; and H: herbaceous plant.

3.2. Carbon Offset Service

The carbon uptake per unit area of the study parks ranged from 1.0 t/ha/yr to 5.4 t/ha/yr, with the average being 2.6 ± 0.1 t/ha/yr (Figure 3). The carbon storage ranged from 7.8 t/ha to 67.7 t/ha, with the average being 29.9 ± 1.7 t/ha. The carbon uptake per unit of basal area of planted trees and shrubs ranged from 1.1 kg/100 cm^2/yr to 3.4 kg/100 cm^2/yr depending on the park, with the average being 2.6 ± 0.1 kg/100 cm^2/yr. Meanwhile, the carbon storage ranged from 17.8 kg/100 cm^2 to 42.6 kg/100 cm^2, with the average being 28.7 ± 0.6 kg/100 cm^2. The average DBH of trees in the study parks, on the other hand, was approximately 18.4 cm, as stated above, and the basal area was 265.9 cm^2. If this carbon reduction unit is applied per unit of basal area, one tree of this specification will have a carbon uptake of 6.9 kg per year and carbon storage of 76.3 kg. The carbon uptake per crown cover is recognized as a Tier 2-level carbon uptake coefficient in the IPCC guidelines [22], but only a few studies have quantified it by city as a whole or by the type of greenspace. The carbon uptake per tree cover in the study parks ranged from 0.3 kg/m^2/yr to 1.2 kg/m^2/yr depending on the park, with the average being 0.6 ± 0.0 kg/m^2/yr. The carbon storage ranged from 2.8 kg/m^2 to 17.4 kg/m^2, with the average being 7.0 ± 0.4 kg/m^2.

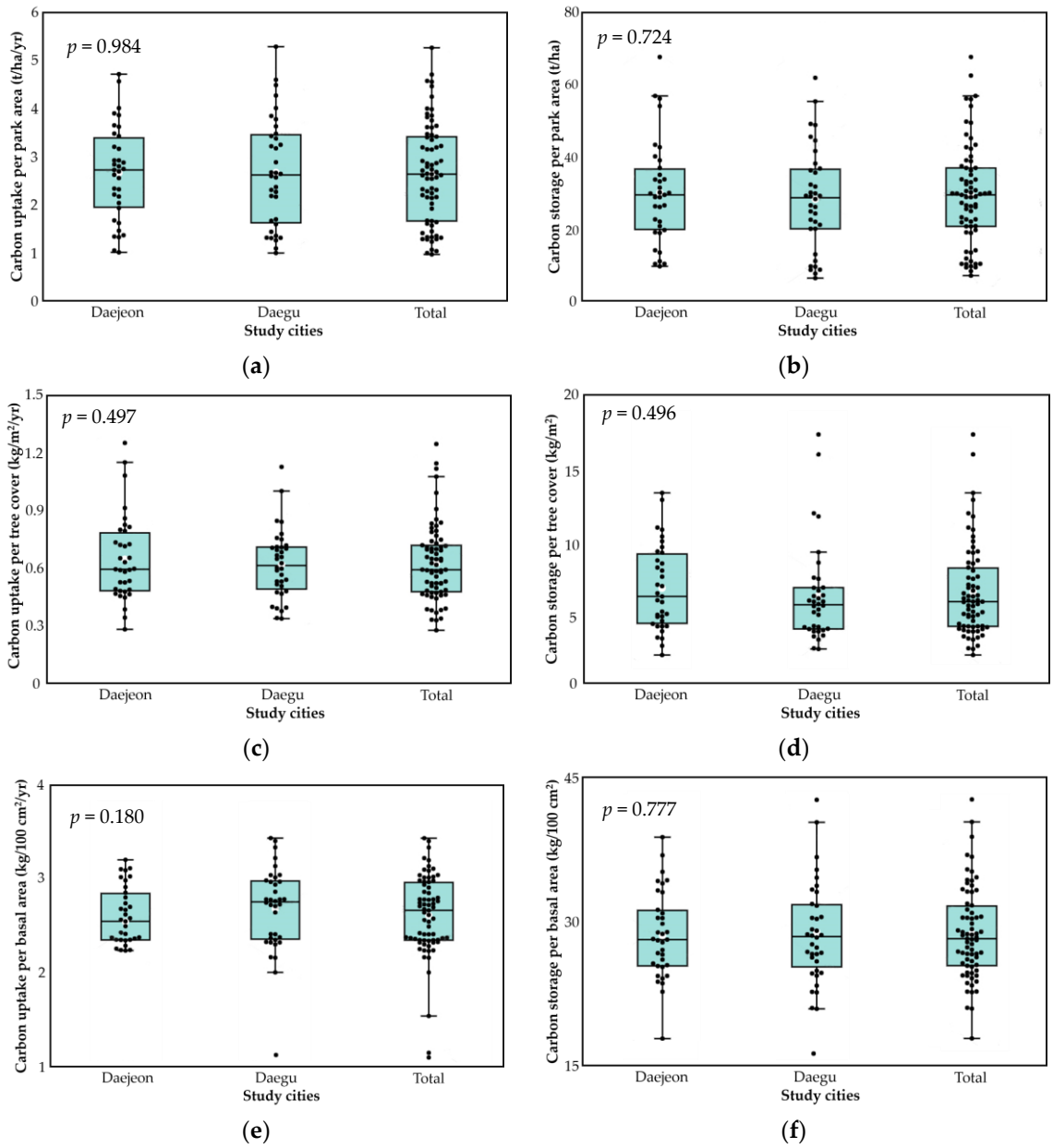

Figure 3. Carbon uptake and storage by trees and shrubs in study parks: (**a**) carbon uptake per park area; (**b**) carbon storage per park area; (**c**) carbon uptake per tree cover; (**d**) carbon storage per tree cover; (**e**) carbon uptake per basal area; (**f**) carbon storage per basal area.

3.3. Correlation between Carbon Offset Service and Tree Planting Structure

The correlation between the carbon offset service and tree planting structure was analyzed to determine the factors affecting the level of carbon offset service in the study parks. Accordingly, the correlation coefficients between carbon uptake and tree density, average DBH, and crown cover in the study parks were 0.445, 0.486, and 0.699, respectively, exhibiting significant positive correlations ($p < 0.01$) (Table 6). Carbon storage was also analyzed to have a positive correlation with tree density, average DBH, and crown cover. Therefore, the higher the planting density of trees, the larger the size of the planted trees, and the higher the crown cover, resulting in a greater carbon offset service by the urban parks. In addition, analysis of the correlation coefficient between land cover types and carbon offset service in the study parks demonstrated a significant positive correlation (0.404) between tree/shrub with the carbon uptake ($p < 0.01$). On the other hand, the correlation coefficients of carbon uptake with grass and pavement/facility demonstrated

negative correlations at −0.239 and −0.265, respectively. In other words, the carbon offset services in the study parks tended to decrease as the share of grass or pavement/facility in the total park area increased.

Table 6. Pearson correlation coefficients between carbon offset service and factors.

Factors		Carbon Uptake	Carbon Storage
Planting structure	Tree density	0.445 **	0.081 **
	Avg. DBH	0.486 **	0.717 **
	Crown cover	0.699 **	0.547 **
Land cover type	Tree/shrub	0.404 **	0.262 *
	Grass	−0.239 **	−0.124 *
	Pavement/facility	−0.265 **	−0.186 *

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

4. Discussion

4.1. Carbon Indicator of Urban Parks

A carbon indicator that can easily quantify carbon uptake and storage is required to develop a carbon-neutrality policy that leverages urban parks. Existing studies on urban parks have established a carbon indicator for carbon offset services mainly based on park area or tree cover [8,9,19–22]. The carbon uptake per unit of park area and crown cover of urban parks in Seoul was 3.5 t/ha/yr and 0.7 kg/m^2/yr, respectively, which was higher than the estimates of this study (2.6 t/ha/yr and 0.6 kg/m^2/yr) [8]. The carbon uptake per unit area of urban parks in Dhaka was 5.3t/ha, which was twice higher than these study parks [9]. The carbon storage per unit area of the urban parks in Hamburg and Helsinki was 59.8 t/ha and 28.1 t/ha, respectively [36,37], which were similar to, and approximately double, the estimate from this study (29.9 t/ha). The carbon uptake and storage per tree cover in urban greenspaces in the United States were 0.28 kg/m^2/yr and 7.69 kg/m^2, respectively [23]. In Korea, the carbon uptake per unit area of multifamily residential gardens was 1.1 t/ha/yr [59]. Noticeably, the carbon indicator in urban parks differs greatly between countries. These differences are attributed to differences in geographic and natural growth environments, quantitative models that have been applied, sampling methods, and tree planting structures. Furthermore, even within the same country, the carbon uptake and storage for each type of greenspace, such as parks, gardens, and street trees, exhibited a difference of up to four times. This demonstrates that a reasonable carbon indicator by country, city, and type of greenspace needs to be developed to quantify the carbon reduction service of urban greenspaces. Meanwhile, the carbon uptake and storage per unit of park area, crown cover, and basal area for the study parks were similar by city. This is presumably due to the tree planting structures in Daejeon and Daegu being similar. Specifically, as described above, no statistically significant difference in the tree cover and basal area between Daejeon and Daegu was observed.

The estimated carbon uptake and storage per unit area for the study parks, considering the total urban park area (191 km^2) of a metropolitan city in South Korea [60], revealed that the total planted trees and shrubs in the urban parks had a carbon uptake and storage of 50 kt/yr and 572 kt, respectively. For the reported cost of carbon capture and storage of approximately \$67/t [61], the economic value in carbon uptake of planting trees and shrubs in all urban parks in metropolitan cities in South Korea was approximately \$3.3 million/yr. This is equivalent to approximately 1.5% of the annual establishment budget for urban forests of the Korea Forest Service. Given that the carbon emissions from residential energy consumption in a metropolitan city were approximately 3,746 kt/yr, the urban parks offset 1.5% of carbon emissions from residential energy consumption annually. The annual residential energy consumption per capita in South Korea can be calculated as 0.17 t/yr, implying that the urban parks in a metropolitan city offset the annual carbon emissions of approximately 293,000 people.

4.2. Factors Affecting the Level of Carbon Offset Service

As mentioned in Section 4.1, the annual carbon uptake per unit area of the urban parks in Daejeon and Daegu was 74% of that of Seoul, which was attributed to differences in tree planting structure and land cover type [8]. Specifically, the tree planting density and basal area of the study parks were 85% and 78% of the parks in Seoul, respectively, and the tree and shrub cover was 7.8% lower than that of Seoul. Moreover, the ratio of grass and pavement surfaces, which exhibited a negative correlation with the carbon offset services in the study parks, was 0.8% and 7.6% higher, respectively, than that for the urban parks in Seoul.

Even among the study parks, those with high tree density, tree cover, and average DBH but low ratio of grass and pavement exhibited relatively high carbon offset services. The study park with the highest carbon uptake level (5.2 t/ha/yr) had approximately 4 times higher planting density, crown cover, and basal tree area than the park with the lowest value (1.0 t/ha/yr). For each increase of 1 tree/100 m^2 in planting density, 10% in crown cover, and 5 cm in average DBH, the carbon offset service increased by 1.1, 1.2, and 1.5 times, respectively. Some parks have promoted carbon offset services by planting tree species with large diameters, high growth rates, and high carbon uptake capacity, even if the tree density, tree cover, and tree size are small. These species include *Z. serrata*, *P. koraiensis*, and *P. yedoensis*. According to Jo and Park [62], a 15-year-old *Z. serrata* exhibited 3.3 and 3.0 times higher carbon uptake capacity than *G. biloba* and *A. palmatum*, respectively. In study park "A," for example, although the tree cover was approximately 12% lower than that in study park "B," 2.3 times more plant species with a high carbon uptake capacity were planted, resulting in the amount of carbon sequestered per unit area being similar. The carbon indicator per unit area in this study reflected not only the areas covered by trees but also those covered by grass and pavement/facility. In the study parks, a higher pavement/facility or grass area among the land cover types resulted in a lower carbon uptake capacity. Hence, reducing grass and pavement/facility areas can enhance the carbon offset service. When the ratio of pavement/facility of the study park was 10% higher, the carbon uptake per unit area was approximately 11% lower. Thus, the tree planting structure and land cover type were the main factors determining the level of the carbon uptake capacity of the study parks. To maximize the carbon offset service of urban parks, planting design strategies should be established while considering these factors.

4.3. Planting Strategies

The urban parks of representative urban greenspace type are an important resource for enhancing carbon offset service through intensive tree planting in cities, which are known for their high carbon emissions. However, the carbon offset service of trees planted in urban parks is limited by large unused grass areas, the dominance of small trees, and single-layered structures in which only trees, shrubs, or grass are planted. Therefore, planting strategies can enhance the carbon offset service of urban parks by addressing the aforementioned problems.

Large grass areas consume considerable amounts of energy due to repeated mowing annually. According to previous studies, the annual carbon emission per unit area due to mowing was approximately 126.5 g/m^2 [63], which was more than 2.7 times the carbon uptake of grass (47.1 g) [64]. Quantifying the annual carbon emissions from mowing revealed that the carbon emissions due to mowing were 11.7% of the carbon uptake by trees of the study parks. These results suggest that planting strategies that allot a significant percentage to grass areas are undesirable in terms of energy savings and carbon reduction. Therefore, it is desirable to reduce large grass areas except for essential purposes and to expand the planting space for trees.

The total amount of potential planting space for trees with a crown width of 2 m and height of 3 m or higher in the study parks was 17.0 ha. Utilizing potential planting space can substantially expand the planting tree quantity while minimizing the waste of planting space. Specifically, it is possible to plant approximately 27,000 more trees of the above size

in the study parks. Active tree planting in the potential planting space can result in an additional annual carbon uptake of approximately 51 t/yr. This is equivalent to 33% of the carbon uptake of the study parks. These results suggest that prior to the expansion of new parks, carbon can be effectively reduced by actively utilizing the plantable space in existing parks.

To increase the carbon uptake per unit area within the limited planting space of urban parks, the current single-layer structure, which accounts for approximately 64.1% of the existing tree planting structure, should be converted into a multilayered structure composed of upper trees, middle trees, and lower shrubs. Multilayered planting is advantageous for enhancing tree density and crown cover per unit area, which are positively correlated with carbon uptake capacity. In addition, tree species such as *Z. serrata*, *P.* yedoensis, *P. koraiensis*, *Machilus thunbergi*, and *Quercus myrsinaefolia* are desirable due to their good annual growth rate and carbon uptake capacity. Moreover, relatively large trees are preferable for planting over small ones. Wang et al. [65] also proposed planting tree species with good carbon uptake capacity and the mixed planting of small, medium, and large trees to improve the carbon uptake of urban parks in Beijing, China. This planting strategy can not only promote carbon offset services, but also ecological services including air purification, microclimate amelioration, and wildlife inhabitation.

4.4. Limitation and Future Study Direction

Urban parks sequester carbon during the photosynthetic process in trees but emit carbon directly and indirectly during the life cycle of material production, transportation, construction, management, logging, and disposal. These carbon emissions offset some or exceed the carbon uptake by urban greenspaces.

The net cumulative carbon uptake per unit area in the entire process of some urban green spaces in Leipzig, Germany, was 37.4–44.2 t/ha [66]. According to Park and Jo (2021) [63], the carbon emissions per unit area generated due to material production, construction, and management during the life cycle of some urban parks in Korea was 9.3 kg/m^2, which was 52% of the cumulative carbon uptake by the vegetation. The 50-year net cumulative carbon uptake of an urban park in Milan, Italy, was 1.5 times higher in afforestation areas than in tree rows, even in the same location [67]. As a limitation, only the carbon uptake of trees in urban parks was quantified without considering the tree production, planting, irrigation, and mowing mentioned in the previous studies. However, most previous studies also had fewer samples or did not reflect the carbon emissions caused by the production and construction of pavements or facilities. Therefore, the actual carbon budget should be examined from all aspects of urban parks in the future.

Soils in urban greenspace continuously accumulate carbon annually through the inflow of litterfall [36,68–74]. Carbon storage per unit area (1 m depth) in the soils of some parks in Ohio, United Sates, reached 163–211 t/ha [69]. The carbon storage per unit area of soil (90 cm depth) in Helsinki urban parks was 104 t/ha, which was 3.7–5.0 times higher than that of trees [36]. As such, soils in urban parks have been reported to possess higher carbon storage than trees. The studies on carbon in the soils of urban parks generally focused on storage without quantifying the annual fixed amount of carbon by inflow and decomposition of litterfall. To calculate carbon storage and the annual fixed amount of carbon in the soil, the soil should be repeatedly excavated to a depth of 1 m or the inflow and outflow of the soil should be continuously analyzed every 15 or 30 d, which is difficult. In this study, soil excavation was not permitted by the study parks, so the carbon offset service of soils was not considered. Therefore, additional studies are required to quantify the actual carbon uptake and storage of urban parks considering not only trees but also soils. Moreover, this study did not quantify carbon offset services for all metropolitan cities in South Korea, so it is necessary to increase the reliability of the study results by securing the number of sample cities and parks in the future.

5. Conclusions

Urban parks are representative greenspaces in cities with potential spaces for significantly increasing the amount of greenspace. Thus, they can greatly contribute to securing a source of carbon uptake. However, the carbon offset service of urban parks has not been sufficiently explored. This study quantified carbon uptake and storage in Daejeon and Daegu, two major metropolitan cities in South Korea, and explored planting strategies to promote carbon offset service.

The carbon uptake and storage per unit area of the study parks were 2.6 ± 0.1 t/ha/yr and 29.9 ± 1.7 t/ha, respectively, which were higher than the estimates for other types of greenspaces, such as streets and multifamily residential gardens. The aforementioned carbon uptake indicators of the study parks reveal that planted trees in urban parks in metropolitan cities play an important role in offsetting approximately 1.5% of carbon emissions from residential energy consumption every year. Moreover, the economic value of carbon uptake was equivalent to $3.3 million/yr, which was 1.5% of the annual establishment budget for urban forests of the Korea Forest Service.

The representative factors that influenced the carbon offset service of the study parks were planting density, tree size, vertical structure, and land cover type. However, the study parks were found to have less carbon offset service compared to the estimates from previous studies, due to the wide distribution of large grass and pavement areas, the dominance of small trees, and the use of single-layered structures. Planting strategies such as reducing unnecessary grass and pavement areas, actively planting trees in the potential planting space, utilizing high-density multilayered structures, and planting tree species with high growth rates are proposed to enhance the carbon offset service of urban parks in South Korea.

On the other hand, since urban greenspace provides various services such as wildlife inhabitation and esthetic improvement in addition to carbon uptake, it is necessary to also consider these services when selecting tree species for planting. Even if the carbon uptake capacity is high, planting only a few species is very unfavorable for providing seasonal habitat and food for various wild animals as well as creating insufficient species diversity of the trees themselves. Therefore, it is necessary to improve biodiversity and esthetics by planting various tree species that provide food and habitat in addition to tree species with high carbon uptake capacity. In addition to this, it is desirable to secure the normal growth of trees and the landscape identity of the region through the planting of local species rather than exotic species that do not fit the environment of the region.

This study is meaningful because the tree planting structure of urban parks that lack relevant information is analyzed and carbon uptake and storage indicators are established. The carbon uptake and storage indicators as well as planting strategies proposed in this study are useful for establishing policies related to carbon credits (which have recently become major concerns) and for quantifying the role of carbon offset in greenspace development projects. However, this study has limitations in that it did not consider the carbon offset service of soil nor carbon emissions from management measures, such as pruning, irrigation, and lawn mowing. Hence, further studies are required to quantify the actual net carbon uptake of urban parks by incorporating soil and management. In addition, it is necessary to comprehensively quantify the carbon offset service of urban greenspaces and devise an optimal planting strategy by including more samples and performing supplementary studies on other types of greenspaces, including urban parks.

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