MDPI

Article

Ecological Design and Construction Strategies through Life Cycle Assessment of Carbon Budget for Urban Parks in Korea

Hye-Mi Park [ID] and Hyun-Kil Jo *

Department of Ecological Landscape Architecture Design, Kangwon National University, Chuncheon 24341, Korea; phm2071@gmail.com
* Correspondence: jhk@kangwon.ac.kr; Tel.: +82-33-250-8345

Abstract: Although urban parks sequester carbon by vegetation growth, they emit carbon due to materials production, transport, construction, management, demolition, and disposal throughout their life cycle. This study estimated the carbon budget of urban parks over their life cycle according to land cover type and explored ecological design and construction strategies to maximize carbon reduction. After setting up the scope of the life cycle, the energy and material used for each stage were analyzed on the basis of field survey, design and construction details, and literature review of 30 study parks. The net carbon uptake per unit of park area averaged 8.51 kg/m^2, with urban parks playing an important role as a source of carbon uptake to mitigate the climate change. This study suggested ecological design and construction strategies including the expansion of tree planting spaces through the minimization of grass and impervious areas, the minimization of changes to existing topography, and the utilization of local materials. As a result of applying these strategies to study parks, the net carbon uptake increased approximately 9.2 times. These study results are expected to be useful as information for the implementation of carbon-neutral policies and greenspace establishment projects.

Keywords: climate change; low carbon; urban greenspace; landscape materials; planting; management

1. Introduction

Climate change, a major environmental issue that the whole world faces, negatively affects ecosystems and socioeconomic systems. In addition to signing the Kyoto Protocol, the international community signed the Paris Climate Agreement, which obliges most countries to reduce their greenhouse gas emissions to limit the increase in the global average temperature to 1.5 °C [1]. The Intergovernmental Panel on Climate Change (IPCC) reported that all countries around the world should strive for zero carbon emissions by 2050 to achieve this goal [2]. Recently, the EU, Korea, and Finland have actively set targets to realize such as carbon neutrality low emissions development strategies (LEDS) [3–5]. Carbon reduction can be achieved through the efficient use and saving of fossil fuels, the development of alternative energy sources, and the creation and conservation of greenspace [6–8].

Urban greenspace that includes trees and soil plays an important role as a source of carbon uptake in delaying or mitigating climate change because it sequesters atmospheric carbon during the process of growing trees and contributes to the accumulation of carbon in the soil. In reality, the creation of greenspace is considered a greenhouse gas reduction activity in carbon neutrality programs around the world [9,10]. In cities where carbon emissions are dominant, greenspaces are becoming more important as the only carbon uptake sources. In particular, among the types of greenspaces, urban parks are potential spaces that can create significant greenspace areas within the limited open space of cities and can thus greatly contribute to securing carbon uptake sources and carbon credits.

However, even if urban greenspace sequesters carbon by growing trees, the entire process of materials production, transport, construction, management, demolition, and

disposal emits carbon both directly and indirectly. In other words, direct carbon emissions occur when operating equipment such as excavators and grass mowers while indirect carbon emissions also occur when using facilities, paving materials, and fertilizers in the manufacturing process, which consumes fossil fuels. Such carbon emissions offset a part or more of the carbon uptake by urban greenspace. Life cycle assessment is a useful analytical methodology to quantify the carbon released and sequestered throughout the life cycle of goods or services ranging from production to disposal and is being used in various industries and study areas.

The life cycle assessment of the carbon budget of urban greenspace is very important for clarifying the carbon reduction effect and in devising policies, designs, and construction strategies that can minimize carbon emissions while maximizing carbon uptake. Low-carbon parks can contribute to improving the quality of an urban landscape and the health and well-being of citizens by providing a comfortable living environment in a city dominated by hardscapes. Therefore, the purpose of this study was to quantify carbon that is sequestered and released in the process of materials production, transport, tree growth, management, demolition, and disposal for 30 years of urban parks in Korea, focusing on vegetation and paving materials. Additionally, on the basis of the results of the carbon budget analysis, we explored ecological design and construction strategies to maximize the carbon reduction effect. The results of this study can contribute to the international sharing of carbon budget indicators, greenspace design, and construction-related basic information for carbon reduction according to the entire life cycle of urban parks.

Related Research

As the role of urban greenspaces as carbon uptake sources has become more important, numerous studies [8,11–17] have been conducted to estimate their carbon reduction effects worldwide. However, most of these studies only consider carbon uptake by trees, and due to the difficulty of data collection and the complexity of space, there are only a few studies that have perceived the carbon budget through the life cycle assessment of urban greenspaces as follows [18–21]. Strohbach et al. (2012) quantified the net cumulative carbon uptake of some urban greenspaces in Leipzig, Germany, and analyzed the carbon budget by comparing them according to four designs and management scenarios [18]. The net cumulative carbon uptake per unit area over the life cycle of urban greenspace was 37.4–44.2 t/ha, and the design with densely planted trees showed a better carbon reduction effect than the alternative design in which grass dominated. According to Kendall and McPherson (2012), five- and nine-gallon container trees produced on nurseries in California, USA, emit 1.3 and 4.2 kg of carbon, respectively, over their life cycle [19]. The major carbon emissions factor in the production of these trees was energy consumption in irrigation and greenhouse heating. McPherson and Kendall (2014) reported that some urban greenspace in Los Angeles, USA, sequester an accumulated total of 49.5 kt of carbon throughout their life cycle [20]. Carbon emissions were 46% of the cumulative carbon uptake and the major emissions factors were wood combustion and irrigation. Park et al. (2021) reported that the net carbon uptake of urban trees of stem diameter at breast height of 7, 10, and 13 cm produced in nurseries in Korea were 4.6, 12.2, and 24.3 kg/tree, respectively [21]. The above studies on the life cycle assessment of carbon budgets for urban greenspace have limitations in that they did not consider the carbon emissions of paving materials and facilities. In addition, except for McPherson and Kendall (2014), carbon budget calculations excluded carbon emissions from tree production. Quantifying the carbon budget accurately according to the entire life cycle of urban greenspace requires including carbon emissions from production, construction, management, removal, and disposal of trees; paving materials; and facilities.

On the other hand, besides urban greenspace, many studies on the life cycle assessment of carbon budgets have been conducted in various industrial fields such as construction, civil engineering, and agriculture [22–29]. Carbon emissions per floor area according to the life cycle of a building were in the range of 0.9–18,409 t/m^2, depending on the country

such as the United States, Italy, Canada, and Finland, and the emissions associated with commercial buildings were generally higher than those of residential buildings [22]. The key factor in carbon emissions is energy consumption according to building operation, which constitutes 80–85% of the total emissions. In addition, the quantification of the carbon footprint in the production of building materials and studies on the creation of low-carbon buildings have been conducted [23–26]. Trovato et al. (2020) reported that public buildings can reduce their cooling and heating energy by 58.5% and 33.4%, respectively, through the use of wooden double-glazed windows, organic external wall insulation systems, and green roofs [27]. Sambito and Freni (2017) calculated the carbon footprint of the life cycle of the integrated urban water systems of Palermo, Italy, and proposed replacing old pumps with high-efficiency pumps to reduce their carbon emissions [28]. According to Diacono et al. (2019), carbon emissions per unit area of zucchini and lettuce production were about 0.8 t/ha and irrigation was the main factor in carbon emissions [29]. These fields analyze the impact of input materials or processes on energy consumption through life cycle assessment and strive to reduce carbon emissions below an appropriate level. However, urban greenspaces are still lacking in these efforts. Therefore, urban greenspaces also need to estimate clear carbon reduction effects through life cycle assessment and explore various ways to minimize emissions.

2. Materials and Methods

2.1. Selection of Study Parks

The study parks were selected by considering their type, size, and regional distribution to quantify the carbon budget of urban parks in Korea. To select study parks, this study requested that the government department in charge of urban parks in Korea as well as landscape design and construction companies provide design, construction, and management details of all parks constructed within the last 10 years. Urban parks that had been established for more than 10 years were excluded from this study because it was difficult to obtain data necessary for the life cycle assessment of the carbon budget. Among the 70 total obtained data, 30 parks were selected as study sites by considering the data validity, type, size, and regional distribution of the parks. Urban parks selected included small parks, children's parks, and neighborhood parks, as stipulated in the Urban Park and Greenspace Act; of these, children's parks and neighborhood parks are regulated to secure their scale to at least 1500 m^2 and 10,000 m^2, respectively [30]. The parks were distributed in Seoul, Incheon, Bucheon, and Namyangju in the northwest of the country; Chuncheon, Hongcheon, and Yangyang in the northeast; Daejeon, Sejong, and Jeungpyeong in the center; and Daegu in the south (Figure 1). Seoul, Daejeon, Daegu, Incheon, Bucheon, and Namyangju are large cities with a high population density, while Chuncheon, Hongcheon, Yangyang, and Jeungpyeong are small- and medium-sized cities with a lower population density.

2.2. Goal and Scope Definition

This study set the life cycle assessment scope of the urban parks through literature review [14,16,18–21], field surveys of study parks, interviews with working-level personnel, and inspections of design and construction details. The life cycle assessment scope of urban parks constitutes a cradle-to-grave carbon inventory that includes materials production, transport, construction, vegetation growth, management, demolition, and disposal. The main materials that constitute an urban park are vegetation, paving materials, facilities, and buildings. However, in the case of facilities such as benches, pergolas, slides, and storm water pipelines, the types and shapes were very wide, studies related to life cycle assessment were insufficient, and it was difficult to procure cooperation and data from companies. Buildings that contain management offices and restrooms also differed in terms of size and design by park and tended to be distributed only in large-scale neighborhood parks.
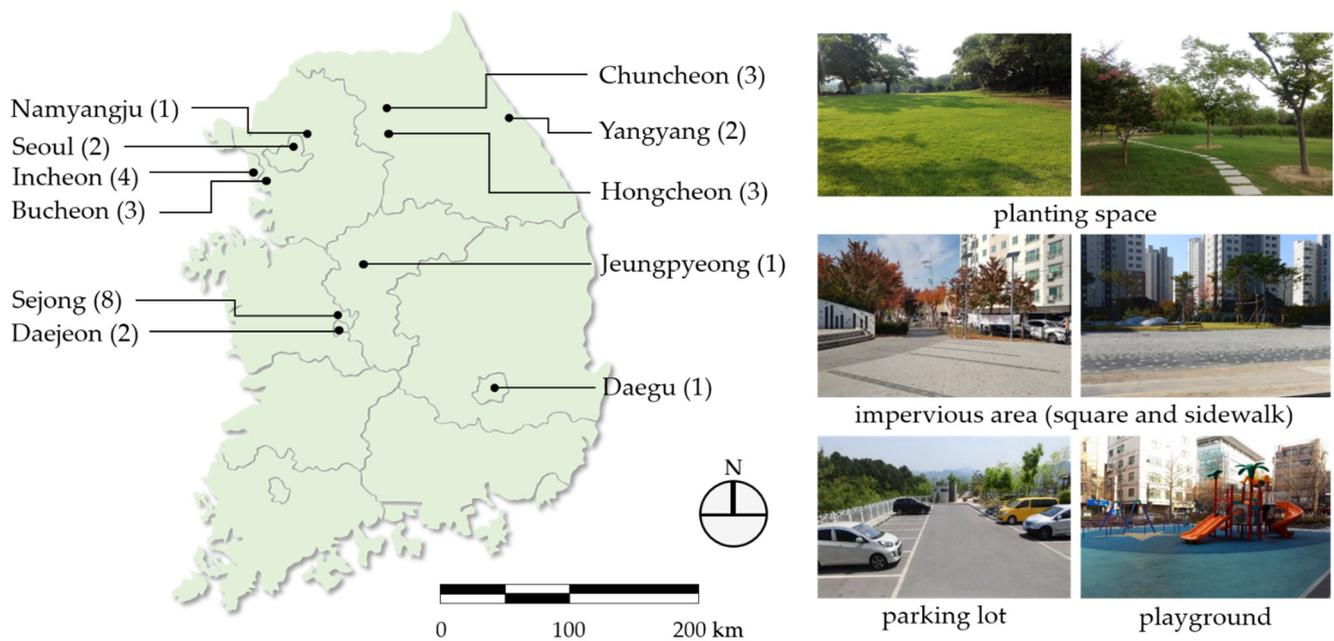
Figure 1. Location and landscape of study parks.

Therefore, in this study, the life cycle assessment scope of urban parks was limited to vegetation and paving materials. In addition, the following items were excluded from this life cycle assessment: excavators, power sprayers, and grass mowers were considered infrastructure that could be used in the long term, and therefore their production was not considered. Energy consumption due to workers commuting to and from work and user visits were excluded due to the lack of relevant data and difficulties in data statistics. In addition, the recycling of removed trees and paving materials was excluded from this study because the amount of recycling was insignificant and related data were insufficient. Figure 2 shows the scope of this study set in consideration of the above items.

The lifetime of urban parks is set as 30 years, considering that the lifespan of urban trees is approximately 26–60 years [31] and the cycle of urban park remodeling projects conducted in Korea over the last five years has been 20–30 years. In the case of related prior studies [18,20], the lifetime of urban greenspaces was set to 40–50 years, but this study only considered the lifespan of trees. Considering the practical urban park remodeling cycle in Korea, which is accompanied by landscape materials removal, tree planting, and paving, it was judged that 30 years would be appropriate. In addition, considering that about 10-year-old trees are mainly planted in Korea's urban parks [32], trees older than 40 years were eventually removed 30 years after the park had been established.

2.3. Data Collection and Analysis

To analyze the carbon budget over the lifetime of study parks, we collected and investigated energy consumption or carbon emissions for each stage of the life cycle. In addition, to estimate the carbon uptake of study parks, we surveyed the species, stem diameter, crown width, and height of all trees for each park and simulated their annual growth changes during the life cycle. The detailed explanation of the data collection and investigation method for each stage of the life cycle assessment is as follows.
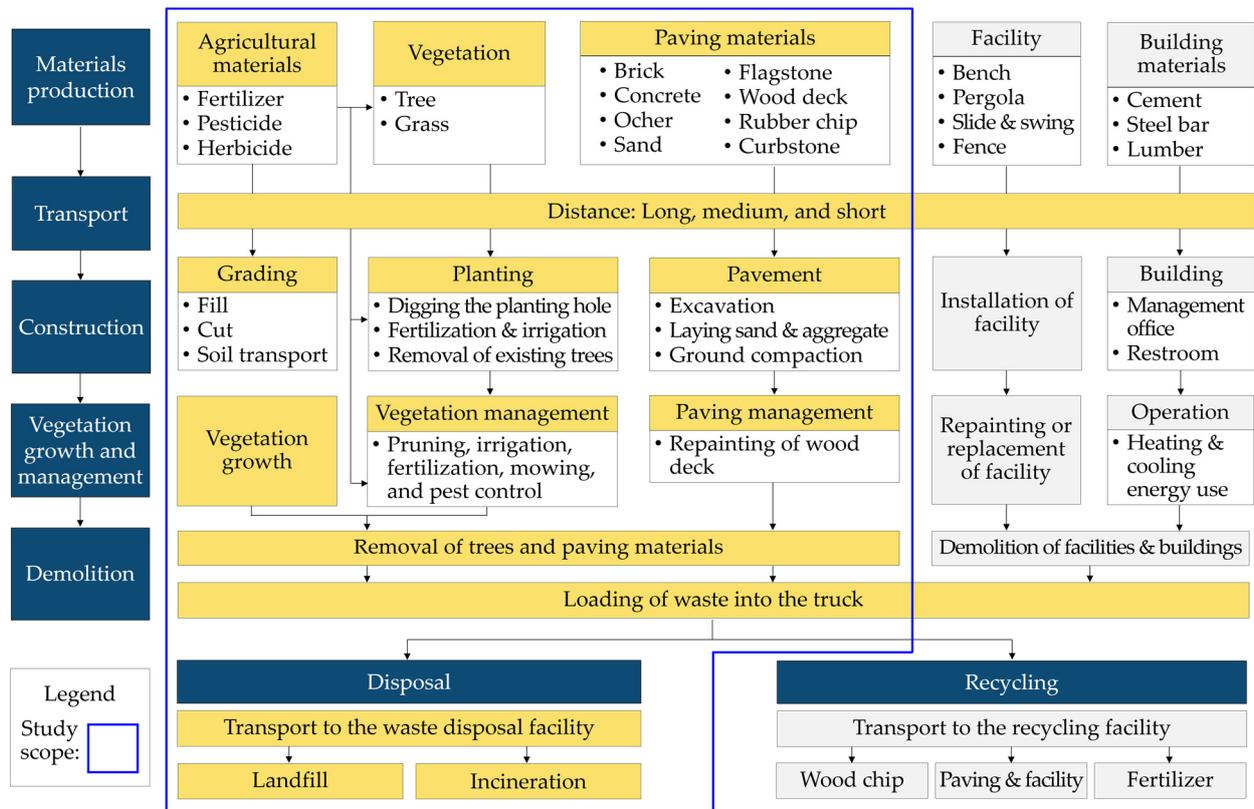
Figure 2. Life cycle assessment scope of study parks.

2.3.1. Vegetation Production

Urban parks around Korea mainly plant trees with a stem diameter at breast height (DBH) of 8–10 cm [32]; these emit carbon due to production in a nursery before being transported to their target sites. According to Park et al. (2021), trees with a DBH of 7, 10, and 13 cm resulted in emissions of 1.6, 2.5, and 3.3 kg of carbon per tree during the production process [21]. Therefore, this study calculated the carbon emissions due to tree production by applying the above carbon emissions coefficient to all trees planted in the study parks. However, this study did not consider carbon emissions from shrub production due to the lack of related studies.

Like trees, grass, which is the main land cover material for urban parks, emits carbon during production processes to the target site until it is applied to the park. Figure 3 presents the grass production process considered for this study, which includes four steps: (1) soil preparation, (2) sowing, (3) management, and (4) harvest. Since there is no carbon emissions coefficient that can be directly applied to grass production, KFRI (2015)'s grass cultivation and management technology and Jo's (1999) and Park et al.'s (2021) study results related to greenspace management and tree production were applied to calculate the carbon emissions [21,33,34]. That is, soil preparation was quantified by applying 5.4 mL/m^2 of diesel consumption per square meter according to tractor operation and soil improvement in Korean landscape tree nurseries [21]. The energy consumption from grass mowing was quantified by applying 10.1 mL/m^2 of gasoline consumption per grass area according to the use of mowers in recreational lands [34]. In addition, the energy consumption and pesticide application amount for grass production were based on the study results of KFRI (2015) [33].
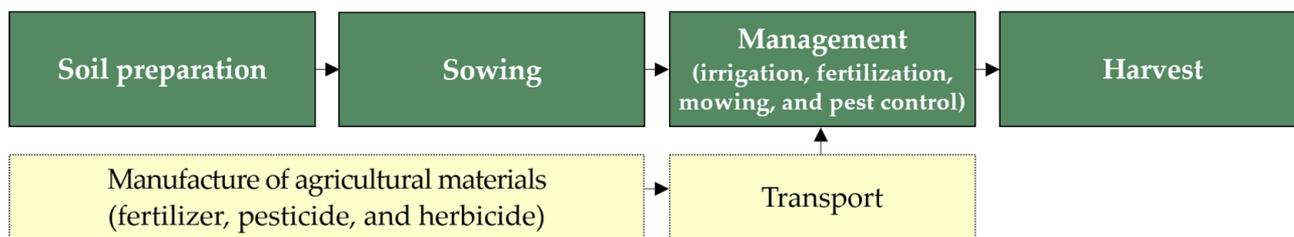
Figure 3. Overview of landscape tree production process.

2.3.2. Paving Materials Production

The life cycle of paving materials production can be divided into stages such as raw material extraction and transport, manufacturing, packaging, and transport to the target location. The major paving materials applied to the study parks were bricks, ocher, flagstones, wood deck, concrete, rubber chips, and curbstones. Carbon emissions due to paving materials production were calculated by applying energy consumption units (Figure 4) [35–37] for each paving material due to the lack of cooperation with the relevant company. In other words, the types of materials used for each pavement and their input amounts were identified, and the basic unit of energy consumption for each material was applied here. As an exception, in the case of rubber chips, the basic unit of energy consumption of brick was used instead because the input material had no energy consumption unit. Brick occupied the largest area among paving types of the study parks, and therefore it was used as a substitute for the energy consumption of rubber chips.

Figure 4. The calculation process of energy consumption per square meter by paving materials. [1] The unit of curbstone is piece instead of square meter [35–37].

2.3.3. Transport

The carbon emissions of transporting construction materials such as trees, grass, and paver to the park were calculated by considering the energy consumption reflecting the one-way transport distance for each material, truck fuel efficiency, and loading capacity [38–40]. Thus, the total amount of diesel used for transport was calculated based on the total number of trucks required to transport the materials required for construction, the transport distance, and the truck's fuel efficiency (8 t: 9.3 L/h, 15 t: 15.9 L/h, and 24 t: 23.0 L/h) [39,40]. On the other hand, the transport distance is a major variable that determines the level of energy consumption in the transport stage; it can differ greatly

depending on the location of the company and the urban park. In Korea, the transport distances for materials are at least approximately 20 km (inside the jurisdiction) and can be >400 km (transport distance between the southern and northern regions). Therefore, in this study, the transport distance was divided into long, medium, and short distances, and the carbon emissions in each of these three scenarios were analyzed by comparison. In this analysis, the long, medium, and short distances were assumed to be 400, 200, and 20 km, respectively, considering Korea's maximum and minimum transport distances and their median values.

2.3.4. Construction

The carbon emissions in the construction stage of urban parks, such as grading, planting, and installation of paving materials, were estimated by considering energy consumption on the basis of field survey, construction details, construction standard production unit, operational cost of construction equipment, and estimation standard of landscape architecture (Figure 5) [38–41]. As a result of reviewing the above data, we found that grading included fill, cut, soil transport, and mounding, and planting included loading, unloading, planting, fertilization, irrigation, removal of existing trees, and transplanting. Pavement construction included work such as excavation, ground compaction, laying sand and aggregate, and disuse of residual soil. In this study, the type of equipment used for these works, working hours, fuel efficiency by equipment, and amount of fertilization and irrigation were identified for each park, and the energy consumption was estimated.

Field survey		Construction standard production unit [38, 39]
Construction detail		Operational cost of construction equipment [40]
		Estimation standard of landscape architecture [41]

Construction		Input equipment and material	Working hours (hr)	Fuel efficiency (L/hr)	Energy consumption [2]
Type	Work				
Grading	Mounding	Excavator (0.6 m²)	2	10.2	20.4
	⋮	⋮	⋮	⋮	⋮
Planting	Unloading	Crane (10 t)	5	3.8	19.0
	Digging the planting hole	Excavator (0.6 m²)	20	10.2	204.0
	Fertilization	Compost	600 [1]	-	600.0
	Irrigation	Sprinkler truck (5500 L)	3	9.4	28.2
	⋮	⋮	⋮	⋮	⋮
Pavement	Cut	Excavator (0.7 m²)	2	11.6	23.2
	Ground compaction	Plate compactor (1.5 t)	3	1.0	3.0
	Disuse of residual soil	Excavator (0.7 m²)	2	11.6	23.2
	⋮	⋮	⋮	⋮	⋮

Figure 5. The process of energy consumption calculation in the construction stage [38–41]. [1] Amount of compost used (kg). [2] Diesel consumption (L) for excavator, crane, and sprinkler truck, and gasoline consumption (L) for plate compactor.

On the other hand, trees of urban parks in Korea require supplementary planting if their mortality rate is >10% within two years after planting. According to a previous study [42], the mortality rate among trees in urban parks was about 10.4%. Therefore, in this study, it was assumed that 10% of planted trees were supplementary within two years after planting and the energy consumption according to this was included in the construction stage.

2.3.5. Tree Growth

To calculate the carbon uptake that can be sequestered during the life cycle of planted trees in the study park, we identified the species, size, and density of the planted trees on the basis of field survey, design details, and drawings for each park. By substituting the annual diameter growth rate into this tree inventory data, we simulated the growth change of the stem diameter over the life cycle. On the basis of the above studies, we found that the applied annual diameter growth rates were 0.72 cm/year for deciduous trees, 0.83 cm/year for evergreen trees, 0.42 cm/year for deciduous broad-leaved shrubs, and 0.26 cm/year for evergreen coniferous shrubs [43,44]. The inferred stem diameter was used to quantify the cumulative carbon uptake of trees during their life cycle.

2.3.6. Management

To promote the normal growth of vegetation, urban parks conduct annual management activities such as pruning, irrigation, fertilization, grass mowing, and pest control. To quantify the carbon emissions according to vegetation management, we investigated annual management status through interviews with officials in charge, the acquisition of maintenance statements, and actual measurements. This study examined the materials and types of equipment input, frequency, amount, and energy consumption in each stage in the management of study parks (Table 1).

Table 1. Survey inventory used to calculate the carbon emissions of management in study parks.

Component	Survey Inventory	
Pruning	Annual frequency	
	Annual prunning biomass (t/year)	
	Tool	Type (e.g., electric secateurs)
		Energy consumption
	Disposal method of pruned branches	
Irrigation	Annual frequency	
	Amount of water per year (L/year)	
	Tool	Type (e.g., spinkler)
		Energy consumption
Fertilization	Type (e.g., compost)	
	Annual frequency	
	Amount of fertilizer per year (t/year)	
	Tool	Type (e.g., power sprayer)
		Energy consumption
Mowing	Annual frequency	
	Annual mowing biomass (kg/year)	
	Tool	Type (e.g., mower)
		Energy consumption
Pesticide	Type (e.g., fungicide)	
	Annual frequency	
	Amount of pesticide per year (L/year or g/year)	
	Tool	Type (e.g., power sprayer)
		Energy consumption

On the other hand, data on fertilization and grass mowing were reinforced through field measurements. The actual amount of fertilizer used and grass mowed was measured

up to 10 g at 10 study parks that allowed field measurements to be taken. The mowed grasses were randomly sampled 3–6 for each site and dried completely in an oven (US-1202 DH, Vision Scientific, Daejeon, Korea) at 85 °C to constant weight, and then the dry weight was measured up to 0.01 g with an electronic scale (FX3200, AND, Tokyo, Japan).

The paving may be partially damaged during the life cycle but predicting the rate of damage is very difficult. In particular, bricks, which are most often used as a land cover type in urban parks, are semi-permanent materials. Most are not replaced and only repaired when damaged parts can be found. The guidelines for sidewalk installation and management in Korea recommend replacing paving materials after at least 10 years [45]. Therefore, the management of the paving only includes the energy consumption according to the repainting of the deck, excluding the part for reinstallation.

2.3.7. Demolition and Disposal

According to some remodeling details of urban parks in Korea, we found that urban parks were remodeled by removing pavements, facilities, and trees 20–30 years after construction. Most of the paving materials were completely demolished, and the equipment used at this stage was an excavator and crane. Only about 10–30% of planted trees were removed; the rest were preserved. Removed paving materials and trees were transported to a waste disposal facility near the site and then buried and incinerated, respectively. Of course, some removed trees and paving materials were recycled by nearby farms or companies, but this amount is insignificant and thus not included in this study.

To quantify the carbon emissions from demolition and disposal of study parks, this study assumed the following: (1) demolishing all paving materials; (2) removing 20% of all trees; (3) transport distance to the waste disposal facility was 20 km; (4) waste disposal method (trees: incineration, paving materials: landfill). In addition, the energy consumption and waste were calculated on the basis of estimation standard of landscape architecture [41]. Carbon emissions according to the landfilling of paver were calculated by applying a carbon emissions coefficient of 1.9 kg/C/t from landfilling of waste concrete to the weight of each paving material due to the lack of relevant data [36]. Carbon emissions from wood incineration were calculated by applying a carbon emissions coefficient of 3.2 kg/C/t per weight of waste wood from KEITI (2019) [36].

2.4. Estimation of Carbon Budget

The carbon budget is a useful indicator to determine the accurate carbon reduction effect of urban parks and can be determined mathematically from the following Equation (1):

$$C = CU - CE \tag{1}$$

In this equation, C is the carbon budget over an urban park's life cycle; CU is the cumulative carbon uptake of vegetation; and CE is the carbon emissions from materials production, transport, construction, management, demolition, and disposal. The carbon budget was calculated by subtracting emissions from the cumulative carbon uptake. The cumulative carbon uptake refers to the amount of carbon continuously sequestered while growing during the life cycle of vegetation until it is removed from the urban park. In this study, the cumulative carbon uptake was estimated by applying Equation (2):

$$CU = \sum_{i=1}^{n} GU_i + \sum_{i=1}^{n} TU_i \tag{2}$$

In this equation, GU is the annual carbon uptake of grass and TU is the carbon sequestered annually by trees as they grow. According to the work of Jo and McPherson (1995), the annual carbon uptake of grass was calculated by multiplying the total grass area per park by 47.1 g/m^2 [46], sequestered by the roots. On the other hand, the grass mown each year was converted into carbon by multiplying the dry weight by 0.43 [43] and then excluding this from the uptake. The study related to the carbon uptake of grass

was conducted in the United States, and it is necessary to compare and verify the results through the development of a basic unit suitable for the growth environment of Korea in the future. The annual carbon uptake of trees was quantified by applying the quantitative model for each tree species developed for Korea's open-growing urban trees and the annual diameter growth rate as in Equation (3).

$$TU = (D \times T) \times Q \tag{3}$$

In this equation, D is the annual stem diameter growth rate of trees [43,44] (Section 2.3.5), T is the age of the trees, and Q is the carbon uptake quantitative model by tree species developed by measuring the CO_2 exchange rate measurements or direct harvesting methods including root digging targeting popular urban landscape tree species in Korea (Table 2) [47–56]. In other words, to calculate the annual carbon uptake of trees, we substituted the annual diameter growth rate for all trees in the urban park and then calculated the stem diameter for the corresponding year. The carbon uptake by trees was calculated by applying the quantitative model with the stem diameter as an independent variable. For certain species for which no quantitative model could be obtained, the average value was calculated by substituting equations for the same genus or group. The cumulative carbon uptake of trees was calculated by summing the annual carbon uptake on the basis of the tree growth coefficient throughout their life cycle.

Table 2. Quantitative model sources used to calculate carbon uptake of landscape trees.

	Species	**Diameter Range (cm)** [1]	**Reference**
Tree	*Abies holophylla*	5–19	Jo et al., 2014 [47]
	Acer palmatum	7–27	Jo and Cho, 1998 [48]
	"	5–20	Jo and Ahn, 2012 [49]
	Camellia japonica	4–10	Jo et al., 2019a [50]
	Chionanthus retusus	3–11	Jo et al., 2014 [47]
	Cornus officinalis	3–15	Jo et al., 2014 [47]
	Ginkgo biloba	6–31	Jo and Cho, 1998 [48]
	"	5–25	Jo and Ahn, 2012 [49]
	Ilex rotunda	3–12	Jo et al., 2019b [51]
	Lagerstroemia indica	3–14	Jo et al., 2019a [50]
	Pinus densiflora	5–29	Jo and Ahn, 2001 [52]
	"	5–25	Jo et al., 2013 [53]
	Pinus koraiensis	5–33	Jo and Ahn, 2001 [52]
	"	5–31	Jo et al., 2013 [53]
	Prunus armeniaca	4–14	Jo et al., 2014 [47]
	Prunus yedoensis	5–23	Jo and Ahn, 2012 [49]
	Quercus myrsinaefolia	3–17	Jo et al., 2019a [50]
	Taxus cuspidata	2–15	Jo et al., 2014 [47]
	Zelkova serrata	6–34	Jo and Cho, 1998 [48]
	"	5–28	Jo and Ahn, 2012 [49]
	General hardwoods	3–28	Jo, 2020 [54]
	General softwoods	5–31	Jo, 2020 [54]
Shrub	*Pinus* spp.	0.6–3.6	Jo, 2002 [55]
	Rhododendron spp.	0.4–3.4	Jo, 2002 [55]
	General hardwoods	0.4–4.0	Jo, 2001; 2002 [55,56]
	General softwoods	0.4–4.0	Jo, 2001; 2002 [55,56]

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

The carbon emissions generated during the life cycle of study parks was calculated by summing the emissions on the basis of both direct and indirect energy consumption. This concept can be represented by the following formula (4):

$$CE = CE_{direct} + CE_{indirect} \tag{4}$$

In this equation, CE_{direct} and $CE_{indirect}$ refer to carbon emissions from direct and indirect energy consumption, respectively. The direct carbon emissions were calculated by applying the following carbon emissions coefficients: 0.59 kg/L for gasoline, 0.71 kg/L for diesel, and 0.127 kg/kWh for electricity [57,58]. Indirect carbon emissions were calculated by multiplying the total amount of irrigation, fertilizer, compost, pesticide, fungicide, herbicide, and oil stain used during the life cycle by each emissions coefficient (Table 3) [59–64] in addition to the carbon emissions from the production, demolition, and disposal of urban parks' materials (Sections 2.3.1, 2.3.2 and 2.3.7). Meanwhile, the carbon budget according to the life cycle of study parks was converted into area units by reflecting the park area.

Table 3. Carbon emission coefficients used to estimate the carbon budget of study parks.

Component	Carbon Emission Coefficients (kg/C/kg)	Reference
Compost	0.058	NAS, 2017; Lee, 2020 [59,60]
Fertilizer	0.221	Lee et al., 2018 [61]
Fungicide	3.38	Pitt, 1984; Lal, 2004 [62,63]
Herbicide	5.29	NAS, 2017; Lee, 2020 [59,60]
Irrigation	0.024	Pitt, 1984 [62]
Oil stain	3.06	Lee and Yang, 2009 [64]
Pesticide	3.79	Pitt, 1984; Lal, 2004 [62,63]

Ecological design and construction strategies to enhance the carbon reduction effect of urban parks are very important for mitigating climate change and creating a healthy living environment. Although some studies suggest general guidelines related to this, quantitative proof of how beneficial they are for carbon reduction is lacking. Therefore, to explore strategies that can actually enhance the carbon reduction effect, this study identified which materials and processes affect the release and uptake on the basis of quantitative analysis methods such as life cycle assessment of the carbon budget. In addition to solving the major factors causing carbon emission of urban parks, ecological design and construction strategies were proposed to maximize carbon uptake. These strategies were applied to 30 study parks, and their effectiveness was comparatively verified.

3. Results and Discussion

3.1. Land Cover Types and Tree Planting Structures

The areas of the study parks were in the range 0.1–4.9 ha, and parks <0.5 ha accounted for about 56.7% of the total. The distribution ratio by type of study park was 16.7% for small parks, 40.0% for children's parks, and 43.3% for neighborhood parks. As shown in Table 4, the ratio of land cover type in the study parks was the highest for grass with an average of $40.6 \pm 3.5\%$. As the second-highest, pavement was $37.5 \pm 2.9\%$, and the trees and shrubs were analyzed as $19.6 \pm 2.0\%$. The paving material with the highest occupancy ratio among pavement areas was brick at 65.3%, followed by ocher and sand at 16.1%, concrete at 8.3%, flagstones at 4.0%, rubber chips at 2.3%, wood deck at 0.5%, and curbstones at 3.5%. In other words, it was found that the study parks were dominated by grass, bricks, and concrete. Considering that the paved area of a park located in Toronto, Canada, was about 10% of the total park, it was found that the paved area of the study park was about threefold higher [65]. On the other hand, park names were termed by numbers consideration of the requests of some local governments and companies.

Table 4. The ratio of land cover types in study parks.

Study Parks	Area (m²)	Tree	Grass	Brick	Concrete	Ocher and Sand	Rubber Chip	Flag Stone	Wood Deck	Curbstone	Etc. [1]
							Paving				
1	1315	26.1	-	71.3	-	-	-	1.9	-	0.7	-
2	1003	41.1	7.9	23.7	-	25.3	-	0.3	-	1.7	-
3	1996	26.7	25.4	31.3	-	14.6	-	-	-	1.0	1.0
4	1006	16.5	30.7	33.1	13.7	-	-	3.1	-	2.9	-
5	22,546	23.5	47.4	7.4	0.1	15.9	-	3.6	1.2	0.9	-
6	18,681	30.1	44.3	19.2	-	3.7	0.7	-	0.2	0.2	1.6
7	1054	18.2	30.1	48.8	-	-	-	-	-	2.9	-
8	1897	21.5	23.6	26.6	18.0	1.0	8.0	-	-	1.3	-
9	1531	31.7	50.4	9.2	-	8.5	-	-	-	0.2	-
10	3789	11.2	53.0	20.9	-	7.9	3.5	0.8	-	2.7	-
11	3460	9.2	52.0	21.3	3.0	12.8	-	-	-	1.7	-
12	1897	30.0	30.6	22.3	1.7	8.1	1.2	5.3	-	0.8	-
13	49,251	5.7	10.6	67.6	10.3	-	2.5	1.2	-	2.1	-
14	17,653	28.5	34.6	32.1	-	1.5	0.4	1.6	-	1.3	-
15	23,365	10.1	59.5	24.7	-	2.3	2.0	0.4	-	1.0	-
16	21,776	8.0	60.2	26.8	-	2.3	0.4	1.3	-	1.0	-
17	27,171	8.2	64.5	20.5	-	3.2	0.2	2.1	-	1.1	0.2
18	14,625	8.8	57.8	30.4	-	2.2	-	-	-	0.8	-
19	10,482	8.6	66.8	17.0	1.1	2.2	-	3.8	-	0.5	-
20	17,846	10.3	56.9	27.0	-	2.8	2.0	-	-	1.0	-
21	18,513	9.0	54.9	32.7	-	2.4	-	-	-	1.0	-
22	2354	48.7	18.3	9.5	-	14.8	-	1.1	-	1.0	6.6
23	1006	33.6	42.5	-	-	13.3	-	4.4	-	1.2	5.0
24	1887	23.3	16.8	2.2	23.8	7.2	-	0.4	3.9	1.9	20.5
25	1000	21.3	28.2	17.3	-	12.2	-	6.2	-	3.0	11.8
26	14,111	20.1	43.6	6.5	6.3	3.7	-	0.1	-	0.3	19.4
27	4300	20.1	35.0	21.0	13.6	-	5.0	1.4	-	2.6	1.3
28	2793	15.7	31.0	48.2	-	-	-	3.3	-	1.8	-
29	3101	15.8	71.6	-	-	12.6	-	-	-	-	-
30	37,951	6.8	70.5	16.3	1.7	1.1	-	2.4	-	1.1	0.1
Mean		19.6 ± 2.0	40.6 ± 3.5	24.5 ± 3.1	3.1 ± 1.0	6.0 ± 1.2	0.9 ± 0.3	1.5 ± 0.3	0.2 ± 0.1	1.3 ± 0.2	2.3 ± 1.0

[1] Including the buildings, ponds, wetlands, and streams.

The density of planted trees in the study park was in the range of 1.4–17.2 trees/100 m², with an average of 5.8 ± 0.6 trees/100 m². Reportedly, the tree density in riparian greenspace in Korea is about 16 trees/100 m². In comparison, the tree density of the study park was one-third of that of the riparian greenspace. The DBH of the planted trees was 7.0–12.6 cm, with an average of 9.0 ± 0.3 cm. Most of the vertical planting structures in the study park were single-layered structures in which only grass, trees, or shrubs had been planted; in most cases, the same species were planted together. This greenspace structure has limited capacity for the improvement of various benefits of urban greenspace including carbon uptake. According to the results of previous studies, the carbon uptake of multi-layered plantings in which trees, shrubs, and herbs were planted in overlapping layers was up to 60 times better than that of single-layered plantings [66].

3.2. Life Cycle Assessment of Carbon Budget
3.2.1. Vegetation and Paving Materials Production

The carbon emissions per unit of park area from vegetation production averaged 2.61 ± 0.14 kg/m² (tree: 0.94 ± 0.14 kg/m², grass: 1.67 ± 0.15 kg/m²) (Table 5). This indicates that the vegetation of study parks is dominated by grass rather than trees, and the carbon emissions of grass production is considerable. According to this study, the carbon emissions per grass area from grass production were about 4.81 kg/m², which was 1.6 times higher than that of producing a tree with a DBH of 10 cm (2.5 kg/tree) [21].

Table 5. Carbon emissions per unit of park area by vegetation and paving production (kg/m²).

Vegetation			Paving
Tree	Grass	Total	
0.94 ± 0.14	1.67 ± 0.15	2.61 ± 0.14	3.30 ± 0.36

The carbon emissions per unit pavement area by paving material production was 14.6 kg/m² for concrete, which was the highest, followed by brick at 10.2 kg/m², flagstones and wood deck at 0.9 kg/m², and ocher at 0.6 kg/m² (Table 6). In particular, the carbon emissions of concrete were up to 24 times higher than that of other paving materials; reducing the carbon emissions of urban parks requires the application of pervious paving materials with low emissions. According to these emissions coefficients, the average carbon emissions per park area according to the paving production of the study park was 3.30 ± 0.36 kg/m² (Table 5), and the higher the occupancy ratio of impervious pavement, the higher the emissions tended to increase.

Table 6. Carbon emissions per unit pavement area by paving materials production (kg/m²).

Brick	Concrete	Flagstone (Granite)	Ocher	Wood Deck	Curbstone (15 × 15 × 100 cm) [1]
10.2	14.6	0.9	0.6	0.9	2.2

[1] Unit: kg/piece.

3.2.2. Transport

The average carbon emissions per unit of park area according to the transport scenario for each study park was 1.22 ± 0.08 kg/m² for long distance, 0.61 ± 0.04 kg/m² for medium distance, and 0.06 ± 0.00 kg/m² for short distance, with emissions from long distance being twofold higher than that of medium distance and 20 times higher than that of short distance. The main factor determining the high or low carbon emissions due to material transport was the transport distance; as the distance reduced, the carbon emissions decreased proportionally. In other words, reducing carbon emissions due to transportation requires applying local vegetation and materials that have been produced as close to the study park as possible. The application of local vegetation provides a similar growth environment even after planting in urban parks and thereby promotes the survival of trees and the reduction of defects. The carbon emissions from the transport of trees tend to increase as the sizes of the trees increase. When analyzed for each paving material, concrete, which must be transported as ready-mixed concrete, aggregate, and wire mesh together, emitted the most carbon.

3.2.3. Construction

The average carbon emissions per square meter of planting, grading, and pavement area for construction types in the study parks were 0.89 ± 0.04 kg/m² for planting, 0.71 ± 0.12 kg/m² for grading, and 0.27 ± 0.02 kg/m² for pavement (Table 7). The major factors in carbon emissions from planting construction were irrigation for trees and grass, digging the planting holes, and equipment use according to the loading and unloading of trees. Strohbach et al. (2012) reported that the major carbon emissions factors of planting construction are the use of equipment according to the establishment of planting holes and the movement of trees [18]. In addition, some parks have been shown to increase their carbon emissions by removing existing trees and planting new trees of the same size. When removing existing trees with DBH of 20 and 30 cm, the carbon emitted by the chainsaw operation was 0.4 kg/tree and 1.1 kg/tree, respectively. Considering the carbon that these trees have fixed thus far and the carbon they will sequester as they grow in the future, we found that the indiscriminate removal of existing trees further decreases the carbon reduction effect of the park.

Table 7. Carbon emissions per square meter of planting, grading, and pavement area for construction in the study parks (kg/m^2).

Construction Types		
Planting	**Grading**	**Pavement**
0.89 ± 0.04	0.71 ± 0.12	0.27 ± 0.02

Carbon emissions from grading construction tends to increase as the number of topographic changes such as fill and cut increases. In other words, filling and cutting emitted about $0.1\ kg/m^3$ of carbon per unit earthwork volume by using an excavator within the site and the emissions increased as the earthwork volume increased according to the topographic change. In addition, carbon was emitted in the process of bringing in and taking out soil, and when the transport distance was about 5 km, the carbon emissions per unit earthwork volume were about $0.9\ kg/m^3$. This indicates that the carbon emissions due to bringing in and taking out can be reduced if the fill and cut amounts are equal or if cut soil is used for filling.

Carbon emissions from pavement construction increased as the proportion of impervious pavement such as concrete increased. The carbon emissions per unit pavement area according to construction were about $0.5\ kg/m^2$ for concrete, $0.3\ kg/m^2$ for bricks, $0.2\ kg/m^2$ for wood and flagstones, and $0.1\ kg/m^2$ for ocher. In other words, the carbon emissions per unit pavement area of concrete were up to five times higher than those of other paving materials. The pavement construction emits carbon through excavation, ground compaction, and residual soil treatment. In general, residual soil is taken out to a nearby spoil bank, and if it is utilized for grading and planting construction, the carbon emissions due to its loading and transport can be reduced. It was determined that the carbon emissions per unit pavement area of concrete and brick can be reduced by approximately 12.6% when residual soil generated after the excavation of pavement is reused for the establishment of mounding to secure the growth soil depth of the tree. Although energy was consumed in the establishment of mounding, it was less than that consumed by the transport of residual soil.

3.2.4. Vegetation Growth

The average cumulative carbon uptake per unit area by tree growth during the life cycle of the study park was $17.23 \pm 1.88\ kg/m^2$. The cumulative carbon uptake of grass was absent or at most $1.01\ kg/m^2$ depending on the park, with an average of $0.57 \pm 0.05\ kg/m^2$. The cumulative carbon uptake by trees was relatively greater with larger sizes, higher densities, and multi-layered structures compared to those of smaller sizes, lower density, and single-layered structures. It was analyzed that the cumulative carbon uptake after 10, 20, and 30 years was increased by 16, 50, and 108 times, respectively, compared to at the time of planting (Table 8).

Table 8. Changes in cumulative carbon uptake per unit area over the life cycle of study parks (kg/m^2).

Life Cycle (Year)			
After Planting	**10**	**20**	**30**
0.16 ± 0.02	2.54 ± 0.28	7.95 ± 0.86	17.23 ± 1.88

Reportedly, the cumulative carbon uptake per unit area for 30 years of ecological planting reflecting the structure of Korea's riparian greenspace is about $28.1\ kg/m^2$ [7]. Comparing this to a previous study, the carbon uptake in this study was 39% lower, which is estimated to be due to differences in the growth rate, size, and density of trees. Strohbach et al. (2012) reported that the cumulative carbon uptake of high-density planted landscapes such as forests was 1.4 times higher than that of low-density planted landscapes [18].

3.2.5. Management

The average carbon emissions per unit area by management over the life cycle of the study park were 1679.4 ± 131.2 g/m^2 (vegetation: 1677.5 g/m^2, paving materials: 1.9 g/m^2) (Table 9). The proportion of carbon emissions by management activity was the highest at 92.0% for mowing, followed by irrigation at 4.3%, fertilization at 3.3%, pest control at 0.3%, and repainting at 0.1%. In other words, the main management activity that caused carbon emissions in the park was mowing, which is implemented about 6.8 ± 0.6 times per year. The amount of grass mowed (dry weight) per unit grass area averaged 39.7 ± 3.3 g/m^2/time and the gasoline consumption when operating the grass mower averaged 2.6 ± 0.7 mL/m^2/time. Considering that the cumulative carbon uptake per unit area of the grass in the study park averaged 0.57 ± 0.05 kg/m^2, the grass emitted 2.7 times the amount of carbon sequestered due to mowing. These results indicate that a planting design that allocates a large grass area is not desirable in terms of carbon reduction. Livesley et al. (2010) and Townsend-Small and Czimczik (2010) reported that grass is not a suitable carbon reduction material in city because it can emit more carbon than what it sequesters due to management [67,68].

Table 9. Carbon emissions per unit area by vegetation management over the life cycle (g/m^2).

Mowing		Irrigation	Fertilization	Pest Control	Total
Mower	**Amount of Mown Grass**				
131.4 ± 11.5	1414.7 ± 123.2	72.8 ± 8.3	54.8 ± 5.2	3.8 ± 0.4	1677.5 ± 131.5

3.2.6. Demolition and Disposal

The carbon emissions per unit area from the removal and disposal of pavements and trees in the study park averaged 0.28 ± 0.03 kg/m^2 (demolition: 0.09 ± 0.01 kg/m^2, disposal: 0.19 ± 0.02 kg/m^2) (Table 10). The main carbon emissions factors were landfill and incineration of waste. In particular, wood incineration reduced the carbon reduction effect in urban parks by returning the carbon that trees had fixed for decades to the atmosphere. Therefore, promoting their role as sources of carbon uptake in urban parks requires maintaining the carbon fixation effect of wood by using felled wood to produce wood chips or wood products. On the other hand, carbon emissions from paving materials removal and landfill tended to increase as the occupancy ratio of concrete increased.

Table 10. Carbon emissions per unit area by demolition and disposal of study parks (kg/m^2).

Paving Material			Tree			Grand Total
Removal	**Landfill**	**Total**	**Logging**	**Incineration**	**Total**	
0.05 ± 0.01	0.06 ± 0.01	0.11 ± 0.02	0.04 ± 0.00	0.13 ± 0.01	0.17 ± 0.02	0.28 ± 0.03

3.2.7. Carbon Budget

The net carbon uptake per unit area averaged 8.51 ± 1.80 kg/m^2, considering the cumulative carbon uptake by trees and grass growth and the carbon emissions from materials production, transport, construction, management, demolition, and disposal during the life cycle of study parks (Table 11). As shown in Figure 6, at the time of construction, the carbon emissions of the study parks were higher than the sequestration, but the cumulative carbon uptake exceeded the emissions at 20 years after construction. However, in some study parks, the carbon uptake exceeded the emissions from 13 years after construction due to the wider tree planting space and higher planting density compared to other parks. On the other hand, although the carbon emissions of urban parks were high at the time of construction, thereafter, they tended to increase slowly compared to the carbon uptake of vegetation. It was discovered that the carbon release and uptake of urban parks increased by 1.2 times and 102.6 times, respectively, compared to the time of construction. This

suggests that even if a large quantity of resources and energy are initially put into urban park, relatively little energy is required after construction.

Table 11. Carbon budget per unit area over the life cycle of study parks (kg/m^2).

Study Parks	Carbon Uptake					Carbon Emissions								Net Carbon Uptake
	Tree	Grass	Production			Trans Port [1]	Construction			Management	Demolition and Disposal			
			Tree	Grass	Paving		Planting	Grading	Paving					
1	16.19	-	2.38	-	7.39	1.08	0.39	1.018	0.069	0.18	0.47			3.21
2	31.81	0.11	3.34	0.32	2.81	0.97	0.41	0.034	0.125	0.56	0.94			22.41
3	9.90	0.36	0.51	1.04	3.41	0.73	0.26	0.046	0.109	1.04	0.31			2.81
4	14.85	0.43	1.67	1.26	5.23	0.76	0.49	0.003	0.132	1.31	0.28			4.16
5	12.57	0.67	0.80	1.94	1.04	0.47	0.57	1.325	0.039	1.92	0.25			4.88
6	19.33	0.63	0.95	1.82	2.09	0.41	0.55	0.125	0.063	1.83	0.24			11.87
7	48.78	0.42	2.08	1.23	5.48	0.86	0.66	0.181	0.169	1.49	0.50			36.56
8	26.87	0.33	1.23	0.97	5.57	0.83	0.42	0.072	0.119	1.08	0.38			16.53
9	30.70	0.71	1.34	2.06	1.02	0.40	0.52	0.142	0.045	2.14	0.34			23.40
10	20.61	0.75	0.86	2.17	2.93	0.59	0.66	0.700	0.150	2.14	0.28			10.87
11	19.26	0.73	0.45	2.13	3.02	0.64	0.60	0.601	0.145	2.08	0.23			10.10
12	38.79	0.43	2.08	1.25	3.56	0.72	0.60	0.084	0.163	1.40	0.29			29.07
13	4.90	0.15	0.43	0.44	8.70	1.18	0.18	0.098	0.289	0.45	0.12			−6.83
14	13.42	0.49	0.28	1.42	3.54	0.51	0.41	0.004	0.104	1.40	0.13			6.11
15	18.33	0.84	0.35	2.44	2.91	0.47	0.63	0.007	0.096	2.38	0.18			9.71
16	16.40	0.85	0.37	2.47	3.01	0.48	0.65	0.005	0.098	2.40	0.17			7.60
17	16.98	0.91	0.38	2.65	2.37	0.42	0.66	0.005	0.086	2.56	0.17			8.59
18	15.33	0.82	0.41	2.37	3.32	0.51	0.67	0.004	0.107	2.31	0.18			6.27
19	19.47	0.94	0.31	2.74	2.15	0.38	0.71	0.005	0.072	2.66	0.17			11.21
20	18.59	0.80	0.55	2.33	3.20	0.51	0.63	0.005	0.098	2.29	0.21			9.58
21	17.27	0.78	0.47	2.25	3.58	0.54	0.62	0.005	0.107	2.20	0.20			8.06
22	8.29	0.26	0.90	0.75	1.21	0.47	0.31	0.115	0.072	0.86	0.27			3.58
23	24.55	0.60	1.41	1.74	0.28	0.43	0.69	0.208	0.049	1.80	0.37			18.17
24	12.43	0.24	0.91	0.69	4.88	0.90	0.32	0.015	0.099	0.79	0.26			3.79
25	7.27	0.40	0.86	1.16	2.32	0.56	0.33	0.017	0.048	1.15	0.37			0.86
26	7.20	0.62	0.30	1.79	1.64	0.32	0.43	0.040	0.041	1.72	0.12			1.40
27	13.43	0.49	0.45	1.43	5.05	0.72	0.45	0.262	0.220	1.43	0.28			3.62
28	5.23	0.44	0.51	1.27	5.26	0.71	0.32	0.213	0.054	1.23	0.17			−4.06
29	3.48	1.01	1.29	2.94	0.08	0.33	0.92	0.051	0.003	2.82	0.27			−4.21
30	4.68	1.00	0.33	2.89	2.08	0.34	0.57	0.678	0.076	2.73	0.15			−4.17
Mean	17.23 ± 1.88	0.57 ± 0.05	0.94 ± 0.14	1.67 ± 0.15	3.30 ± 0.36	0.61 ± 0.04	0.52 ± 0.03	0.202 ± 0.060	0.102 ± 0.011	1.68 ± 0.13	0.28 ± 0.03			8.51 ± 1.80

[1] Carbon emissions of medium distance.
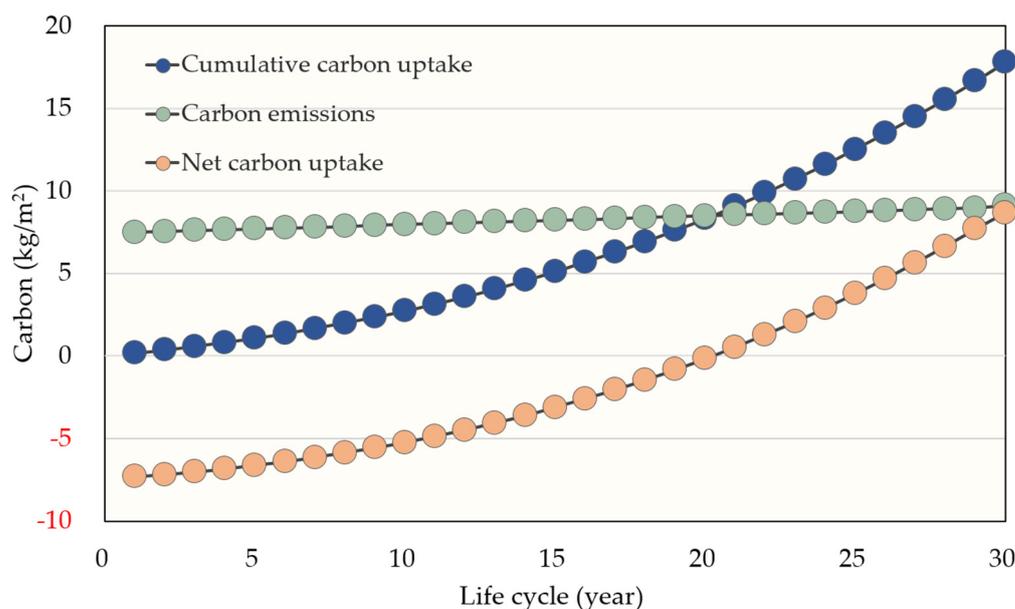
Figure 6. Changes in net carbon uptake per unit area over the life cycle of study parks.

The trees in the study parks played an important role in offsetting 0.4–3.9 times the carbon they had emitted over their life cycle. In other words, it was found that urban parks

play an important role as a source of carbon uptake in delaying and mitigating the effects of climate change in cities where carbon emissions are dominant. No previous studies have partially considered materials production but the carbon uptake by trees tended to be 2.2 times greater than their emissions [20]. On the other hand, some study parks had more carbon emissions than uptake due to the distribution of considerable grass and impervious areas, lower tree density, and single-layered planting. That is, in these parks, grass and impervious space occupied more than 70% of the total park area, or the tree density per unit area was only 24–34% of the average (5.8 trees/100 m^2). Therefore, it is necessary to minimize grass and impervious areas and expand the tree planting space to enhance the role of urban parks as a source of carbon uptake.

Regarding the ratio of carbon emissions at each stage in the life cycle of study parks, the production of paving materials accounted for the highest at 35.5%, followed by management at 18.1%, grass production at 17.9%, tree production at 10.1%, construction at 8.9%, and transport at 6.5%. Transport is the result of calculations based on the medium distance of 200 km. Applying the distance of 400 km doubles the carbon emissions from transport and decreases the net carbon uptake per unit area of the study park to an average of 7.90 ± 1.79 kg/m^2. On the other hand, it was found that the net carbon uptake per unit area of the study park based on the short-distance 20 km was 9.05 ± 1.80 kg/m^2, which is an increase of 1.2 and 1.1 times compared to the long and short distances, respectively.

3.3. Ecological Design and Construction Strategies

The carbon uptake of urban parks differs greatly depending on the land use type, landscape materials, and tree planting structures, even if parks have the same size. As a result of the life cycle assessment of the carbon budget for the study parks, grass and impervious areas, which occupy significant spaces in parks, were found to be the main factors causing carbon emissions in parks. The grass, which occupied 41% of study park areas, emitted 2.7 times more than its carbon uptake every year due to management. In addition, the carbon emissions from grass production was about 4.81 kg/m^2, which was 1.6 times higher than that of producing a tree with a DBH of 10 cm (2.5 kg/tree) [21]. In study parks where about 70% of the total area was grass, the carbon emissions were 1.7–1.9 times higher than the uptake due to their production and management. If the grass area of these parks was reduced by 50% and tree planting space was expanded by that size, the carbon uptake increased by 1.1–1.2 times over the emission. Therefore, it is desirable to minimize the grass area except for inevitable uses and expand the tree planting space.

Excluding planting spaces, the land cover types that dominated the study parks were brick, ocher, and concrete. According to this study, brick and concrete emitted up to 10 times and 15 times more carbon, respectively, than other paving materials during their production, transport, and construction. This suggests that excessive use of these materials reduces the carbon uptake capacity of urban parks. In study parks where 78% of the total area was brick and concrete, the carbon emissions were 2.4 times higher than the uptake. Concrete and brick were mainly used to pave the sidewalks and squares, and the width of the sidewalks was in the range of 2–10 m, whereas the size of the squares was in the range of 5–25% of the total park area. Excessive sidewalks and squares cause the unnecessary use of energy and resources, thereby aggravating carbon emissions. Therefore, to increase the net carbon uptake of urban parks, it is desirable to only secure necessary sidewalks and squares for essential uses.

In urban parks, the carbon uptake by trees may be different depending on the species, planting density, size, and vertical structure of the trees planted, even if the planting area is similar. In fact, one study park where tree planting space accounted for 18% of the total park area had 5.9 times higher carbon uptake per unit area than a park with planting space for 49%. In this park, *Zelkova serrata* and *Pinus koraiensis* with good growth rates were dominant, and density of the planted trees was 17.2 trees/100 m^2, which is three times higher than the average of study parks (5.8 trees/100 m^2). As such, to increase tree biomass and carbon uptake per unit area, it would be desirable to plant tree species with

good growth rates in multi-layered and cluster structures in which herbs, shrubs, and trees overlap.

The major carbon emission factors of construction were irrigation of vegetation and changes in the natural topography, such as fill and cut. In fact, carbon emissions due to irrigation and natural topography changes accounted for 60% and 75%, respectively, in the planting and grading construction of study parks. It is necessary to devise methods that utilize rainwater in addition to the water from the sewage treatment plant for irrigation in order to reduce the resulting emissions. The carbon emissions per unit earthwork volume due to natural topography changes are estimated to be about 1.0 kg/m^3. If there is no need to bring soil out and or put it in because the fill and cut amounts are equal, the carbon emissions can be reduced. In the case of study parks where the cut amount was 4.5 times greater than the fill amount, we found that the carbon emissions could be reduced by approximately 90% if the soil remaining after the cut was used for the fill. In addition, in order for carbon emissions to be minimized during construction, it is advantageous to use the residual soil after paving for mounding or to retain existing trees. If it is fully used for mounding, concrete and brick can reduce the carbon emissions per unit pavement area according to the construction by 12.6%. Since the carbon emitted from the removal and incineration of trees with a DBH of 30 cm is about 4.7 kg/tree, this emission can be reduced by preserving existing trees as much as possible, except in unavoidable cases.

Meanwhile, according to the results of this study, in addition to the above design and construction strategies, urban parks can enhance their carbon reduction effects by using local materials, applying eco-friendly agricultural materials, and recycling waste resources. Purchasing local materials that can be acquired within a short distance (20 km) of the park can reduce carbon emissions of transportation by 1/20 compared to long-distance (400 km) acquisition. The carbon emissions from compost production are 25% of those of chemical fertilizers [60]. Therefore, in the case of fertilization, instead of chemical fertilizers that emit carbon during the manufacturing process, organic matter should be supplied by laying compost or wood chips.

After 30 years of construction, carbon emissions from cutting, loading, transporting, and incinerating trees with a DBH of 40 cm were about 12.1 kg/tree. In addition, wood incineration returns the carbon that trees have fixed for decades to the atmosphere, eventually reducing the carbon uptake of urban parks. Therefore, enhancing the role of carbon uptake sources in urban parks requires maintaining the carbon fixation effect of wood by applying benches, paving materials, and wood chips, which are recycled from removed wood, from the design stage. According to a previous study, recycled products can reduce energy consumption by one-fifth compared to existing products [69].

The above ecological design and construction strategies were applied to study parks, and the carbon budgets before and after their application were analyzed for comparison. Figure 7 illustrates the ecological design and construction strategies applied to study parks and the before and after application. When these strategies were applied, study parks could increase their net carbon uptake by 9.2 times compared to the existing parks. In other words, the net carbon uptake over the life cycle of the existing study parks was about $8.51 \pm 1.80 \text{ kg/m}^2$, whereas that after applying the ecological design and construction strategies was $78.1 \pm 10.0 \text{ kg/m}^2$. Even in the same park, the carbon reduction effect is very different depending on the constituent material, design, and construction. If the role of urban parks as carbon uptake sources is strengthened through the application and exploration of such ecological design and construction strategies in cities dominated by artificial landscapes, various ecosystem services and citizen's well-being will also be improved.
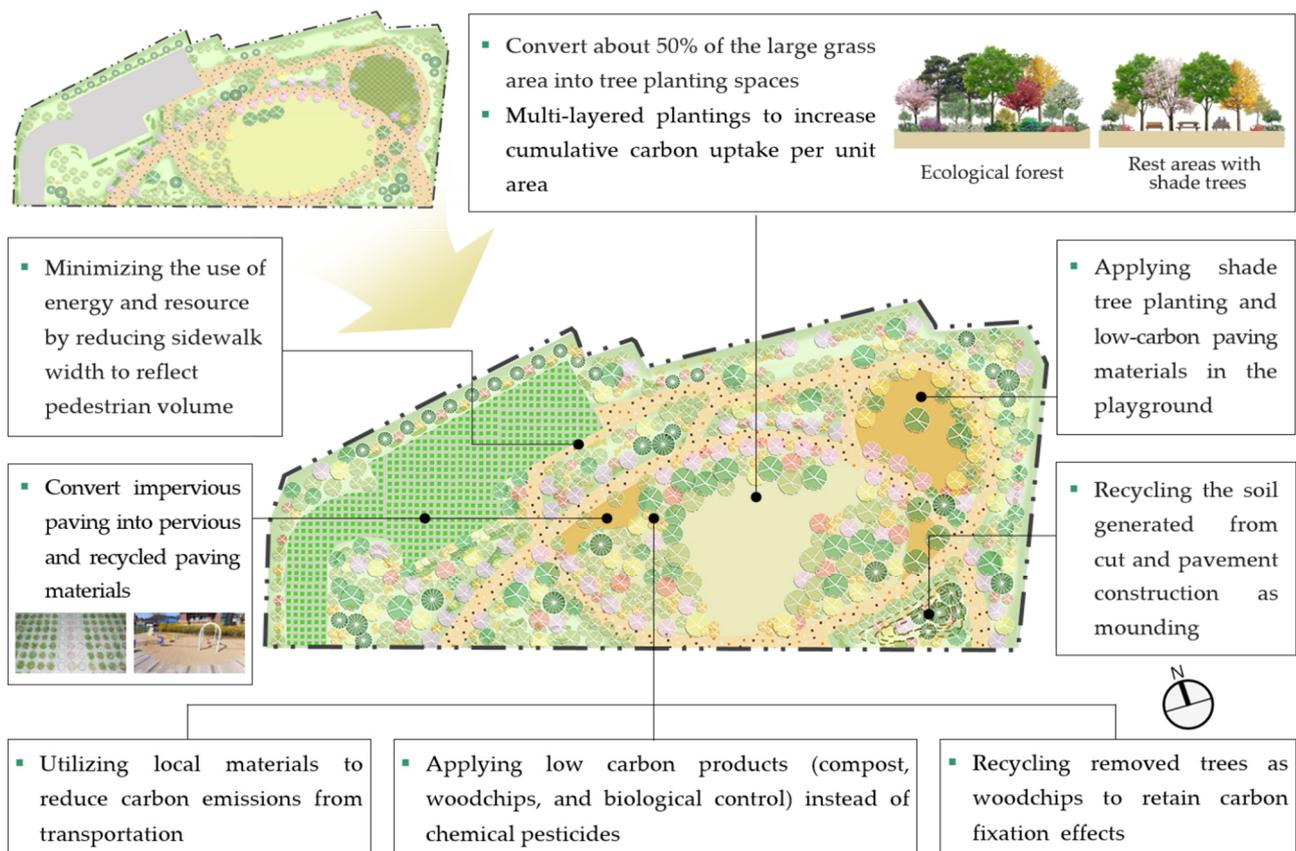
Figure 7. Ecological design and construction strategies to enhance carbon reduction effects of study parks.

4. Conclusions

Urban parks with the potential to secure significant carbon uptake sources in cities where energy consumption is dominant provide a variety of services such as urban heat island mitigation, air purification, wildlife inhabitation, and rainfall interception. The life cycle assessment of the carbon budget of urban parks is very important for clarifying the carbon reduction effect and exploring strategies to maximize its effect. Therefore, this study estimated the carbon budget of urban parks over their life cycle according to land cover type and explored ecological design and construction strategies to maximize carbon reduction.

The average cumulative carbon uptake per unit area by tree and grass growth during the life cycle of the study park was 17.8 kg/m². The total carbon emissions per unit area due to materials production, transport, construction, management, demolition, and disposal was 9.3 kg/m², and major carbon emissions factors were paving materials production, management, and grass production. The net carbon uptake per unit area of the study park in consideration of this averaged 8.5 kg/m², and vegetation offset 0.4 to 3.9 times the carbon emitted over life cycles. In other words, urban parks play an important role as a source of carbon uptake to mitigate the effects of climate change in cities where carbon emissions are dominant. Exceptionally, some study parks had more carbon emissions than uptake due to large grass and impervious area, lower tree density, and single-layered planting.

Reflecting the above study results, ecological design and construction strategies were explored to enhance the carbon reduction effect of urban parks. The strategies proposed in this study include the following: (1) expansion of tree planting spaces through reduction of grass areas; (2) minimization of impervious areas with high carbon emissions; (3) planting of tree species with good growth rates; (4) multi-layered planting with higher carbon reduction per unit area; (5) minimization of changes to existing topography; (6) balance

between cut and fill amounts; (7) utilization of residual soil; (8) preservation of existing trees; (9) use of local materials; (10) application of eco-friendly products instead of chemical fertilizers and pesticides; (11) recycling of waste resources. Applying these strategies to study parks increased the net carbon uptake over the life cycle to about 9.2 times that of before.

This study has limitations in that it did not consider carbon emissions of shrubs, facilities, and buildings over the life cycle of urban parks. Nevertheless, in light of previous studies that focused solely on trees' carbon uptake, this study is meaningful in that it is the first to quantify the carbon budget over the life cycle of an urban park by considering land cover types. The carbon budget indicators, ecological designs, and construction strategies proposed in this study are expected to be useful information for the implementation of carbon-neutral policies and greenspace establishment projects, which have become major issues in recent years. In addition, low-carbon urban parks based on these study results can contribute to realizing the well-being of citizens by providing a comfortable living environment and landscape. In the future, it will be necessary to clarify the carbon budget according to the lifetime of an urban park by considering the scope of the life cycle not reflected in this study.

References

1. UN (United Nations). *Paris Agreement*; UN: New York, NY, USA, 2015.
2. IPCC (Intergovernmental Panel on Climate Change). *IPCC Special Report on Global Warming of 1.5 °C*; IPCC: Geneva, Switzerland, 2018.
3. EU (European Union). *The Action Plan of European Green Deal*; EU: Brussels, Belgium, 2019.
4. MEAE (Ministry of Economic Affairs and Employment). *Finland's Long-Term Low Greenhouse Gas Emission Development Strategy*; MEAE: Helsinki, Finland, 2020.
5. Cheongwadae. *Long-Term Low Carbon Greenhouse Gas Emission Development Strategies*; Cheongwadae: Seoul, Korea, 2020.
6. Jo, H.K. Carbon uptake and emissions in urban landscape, and the role of urban greenspace for several cities in Kangwon Province. *J. Korean Inst. Landsc. Archit.* **1999**, *27*, 39–53.
7. Jo, H.K.; Park, H.M. Effects and improvement of carbon reduction by greenspace establishment in riparian zones. *J. Korean Inst. Landsc. Archit.* **2015**, *43*, 16–24. [CrossRef]
8. Jo, H.K.; Kim, J.Y.; Park, H.M. Carbon reduction and planning strategies for urban parks in Seoul. *Urban For. Urban Green.* **2019**, *41*, 48–54. [CrossRef]
9. UNFCCC (United Nations Framework Convention on Climate Change). *Report of the Conference of the Parties Serving as the Meeting of the Parties to the Kyoto Protocol*; UNFCCC: Montreal, QC, Canada, 2006.
10. KFRI (Korea Forest Research Institute). *A Role of Urban Forests as a Carbon Uptake Source*; KFRI: Seoul, Korea, 2012; p. 20.
11. McPherson, E.G. Atmospheric carbon dioxide reduction by Sacramento's urban forest. *J. Arboric.* **1998**, *24*, 215–223.
12. Nowak, D.J.; Crane, D.E. Carbon storage and sequestration by urban trees in the USA. *Environ. Pollut.* **2002**, *116*, 381–389. [CrossRef]
13. Nowak, D.J.; Greenfield, E.J.; Hoehn, R.E.; Lapoint, E. Carbon storage and sequestration by trees in urban and community areas of the United States. *Environ. Pollut.* **2013**, *178*, 229–236. [CrossRef]

14. Liu, C.; Li, X. Carbon storage and sequestration by urban forests in Shenyang, China. *Urban For. Urban Green.* **2012**, *11*, 121–128. [CrossRef]
15. Pasher, J.; McGovern, M.; Khoury, M.; Duffe, J. Assessing carbon storage and sequestration by Canada's urban forests using high resolution earth observation data. *Urban For. Urban Green.* **2014**, *13*, 484–494. [CrossRef]
16. Gratani, L.; Varone, L.; Bonito, A. Carbon sequestration of four urban parks in Rome. *Urban For. Urban Green.* **2016**, *19*, 184–193. [CrossRef]
17. Jo, H.K.; Park, H.M. Carbon offset service and design guideline of tree planting for multifamily residential sites in Korea. *Sustainability* **2019**, *11*, 3543. [CrossRef]
18. Strohbach, M.W.; Arnold, E.; Hasse, D. The carbon footprint of urban greenspace-a life cycle approach. *Landsc. Urban Plan.* **2012**, *104*, 220–229. [CrossRef]
19. Kendall, A.; McPherson, E.G. A life cycle greenhouse gas inventory of a tree production system. *Int. J. Life Cycle Assess.* **2012**, *17*, 444–452. [CrossRef]
20. McPherson, E.G.; Kendall, A. A life cycle carbon dioxide inventory of the Million Tree Los Angeles program. *Int. J. Life Cycle Assess.* **2014**, *19*, 1653–1665. [CrossRef]
21. Park, H.M.; Jo, H.K.; Kim, J.Y. Carbon footprint of landscape tree production in Korea. *Sustainability* **2021**, *13*, 5915. [CrossRef]
22. Sharma, A.; Saxena, A.; Sethi, M.; Shree, V.; Goel, V. Life cycle assessment of buildings: A review. *Renew. Sustain. Energy Rev.* **2011**, *15*, 871–875. [CrossRef]
23. Aktas, C.B.; Bilec, M.M. Impact of lifetime on US residential building LCA results. *Int. J. Life Cycle Assess.* **2012**, *17*, 337–349. [CrossRef]
24. Onat, N.C.; Kucukvar, M.; Tatari, O. Scope-based carbon footprint analysis of U.S. residential and commercial buildings: An input-output hybrid life cycle assessment approach. *Build. Environ.* **2014**, *72*, 53–62. [CrossRef]
25. Zhang, J.; Cheng, J.C.P.; Lo, I.M.C. Life cycle carbon footprint measurement of Portland cement and ready mix concrete for a city with local scarcity of resources like Hong Kong. *Int. J. Life Cycle Assess.* **2014**, *19*, 745–757. [CrossRef]
26. Tonini, D.; Schrijvers, D.; Nessi, S.; Gutierrez, P.G.; Giuntoli, J. Carbon footprint of plastic from biomass and recycled feedstock: Methodological insights. *Int. J. Life Cycle Assess.* **2021**, *26*, 221–237. [CrossRef]
27. Trovato, M.R.; Nocera, F.; Giuffrida, S. Life-cycle assessment and monetary measurements for the carbon footprint reduction of public buildings. *Sustainability* **2020**, *12*, 3460. [CrossRef]
28. Sambito, M.; Freni, G. LCA methodology for the quantification of the carbon footprint of the integrated urban water system. *Water* **2017**, *9*, 395–406. [CrossRef]
29. Diacono, M.; Persiani, A.; Testani, E.; Montemurro, F.; Ciaccia, C. Recycling agricultural wastes and by-products in organic farming: Biofertilizer production, yield performance and carbon footprint analysis. *Sustainability* **2019**, *11*, 3824–3840. [CrossRef]
30. Korean Law Information Center. Available online: https://www.law.go.kr/LSW/lsInfoP.do?efYd=20210402&lsiSeq=232035 (accessed on 5 June 2021).
31. Balder, H.; Ehlebracht, K.; Mahler, E. *Street Trees: Planning, Planting, Cultivating*; Patzer Verlagr: Berlin, Germany, 1997.
32. Korea Landscaping Tree Association. Available online: https://klta.or.kr:6016 (accessed on 5 January 2021).
33. KFRI (Korea Forest Research Institute). *Grass Cultivation and Management Technology*; KFRI: Seoul, Korea, 2015.
34. Jo, H.K. Energy consumption and carbon release from management in urban vegetation. *Korean J. Environ. Ecol.* **1999**, *13*, 101–108.
35. KICT (Korea Institute of Construction Technology). *The Environmental Load Unit Composition and Program Development for LCA of Building*; KICT: Goyang, Korea, 2004.
36. KEITI (Korea Environmental Industry and Technology Institute). *The User Guide of Environmental Product Declaration*; KEITI: Seoul, Korea, 2018.
37. Kim, J.D. Estimation and Reduction Strategies of Carbon Emissions from Manufacture of Wood Landscape Facilities. Master's Thesis, Kangwon National University, Chuncheon, Korea, February 2015.
38. MOLIT (Ministry of Land, Infrastructure and Transport). *2012 Construction Standard Production Unit*; MOLIT: Sejong, Korea, 2012.
39. MOLIT (Ministry of Land, Infrastructure and Transport). *2020 Construction Standard Production Unit*; MOLIT: Sejong, Korea, 2020.
40. CAK (Construction Association of Korea). *Operational Cost of Construction Equipment*; CAK: Seoul, Korea, 2020.
41. KSLA (Korean Society of Landscape Architecture). *Estimation Standard of Landscape Architecture*; KSLA: Seoul, Korea, 2016.
42. LH (Land and Housing Institute). *A Preliminary Study on the Planting Condition Improvement by Climate Changes*; LH: Daejeon, Korea, 2017.
43. Jo, H.K. Landscape Carbon Budgets and Planning Guidelines for Greenspaces in Urban Residential Lands. Ph.D. Thesis, University of Arizona, Tucson, AZ, USA, 1993.
44. Jo, H.K.; Park, H.M. Changes in growth rate and carbon sequestration by age of landscape trees. *J. Korean Inst. Landsc. Archit.* **2017**, *45*, 97–104.
45. MOLIT (Ministry of Land, Infrastructure and Transport). *The Guidelines for Sidewalk Installation and Management*; MOLIT: Sejong, Korea, 2018.
46. Jo, H.K.; McPherson, E.G. Carbon storage and flux in urban residential greenspace. *J. Environ. Manag.* **1995**, *45*, 109–133. [CrossRef]
47. Jo, H.K.; Kim, J.Y.; Park, H.M. Carbon reduction effects of urban landscape trees and development of quantitative models: For five native species. *J. Korean Inst. Landsc. Archit.* **2014**, *42*, 13–21. [CrossRef]

48. Jo, H.K.; Cho, D.H. Annual CO_2 uptake by urban popular landscape tree species. *J. Korean Inst. Landsc. Archit.* **1998**, *26*, 38–53.
49. Jo, H.K.; Ahn, T.W. Carbon storage and uptake by deciduous tree species for urban landscape. *J. Korean Inst. Landsc. Archit.* **2012**, *40*, 160–168. [CrossRef]
50. Jo, H.K.; Kil, S.H.; Park, H.M.; Kim, J.Y. Carbon reduction by and quantitative models for landscape tree species in southern region-for *Camellia japonica*, *Lagerstroemia indica*, and *Quercus myrsinaefolia*. *J. Korean Inst. Landsc. Archit.* **2019**, *47*, 31–38. [CrossRef]
51. Jo, H.K.; Kim, J.Y.; Park, H.M. Carbon reduction services of evergreen broadleaved landscape trees for *Ilex rotunda* and *Machilus thunbergii* in Southern Korea. *J. For. Environ. Sci.* **2019**, *35*, 240–247.
52. Jo, H.K.; Ahn, T.W. Annual CO_2 uptake and atmospheric purification by urban coniferous trees: For *Pinus densiflora* and *Pinus koraiensis*. *Korean J. Environ. Ecol.* **2001**, *15*, 118–124.
53. Jo, H.K.; Kim, J.Y.; Park, H.M. Carbon storage and uptake by evergreen trees for urban landscape for *Pinus densiflora* and *Pinus koraiensis*. *Korean J. Environ. Ecol.* **2013**, *27*, 571–578. [CrossRef]
54. Jo, H.K. *Development of Model and Technology for Establishment, Management and Evaluation of Urban Forests in Living Zone to Improve Carbon Sequestration Sources and Multi-Dimensional Benefits against New Climate Change Regime*; Korea Forest Service: Daejeon, Korea, 2020.
55. Jo, H.K. Indicator for CO_2 Uptake and Atmospheric Purification Evaluation of Vegetation. In *Development of Eco-Indicators for Sustainable Development*; Ministry of Environment: Seoul, Korea, 2001.
56. Jo, H.K. Impacts of urban greenspace on offsetting carbon emissions for middle Korea. *J. Environ. Manag.* **2002**, *64*, 115–126. [CrossRef] [PubMed]
57. ME (Ministry of Environment). *2020 National Greenhouse Gas Inventory Report of Korea*; ME: Sejong, Korea, 2020.
58. KEP (Korea Environment Corporation). *Guidelines for Local Government Greenhouse Gas Inventories*; KEP: Incheon, Korea, 2016.
59. NAS (National Institute of Agricultural Sciences). *Assessment of Carbon Basic Unit and DB Development with Agro-Material*; NAS: Wanju, Korea, 2017.
60. NAS (National Institute of Agricultural Sciences). *Carbon Emission Coefficient for Agro-Materials (Draft)*; NAS: Wanju, Korea, 2020.
61. Lee, J.S.; Kim, K.Y.; Jeong, H.C.; Choi, E.J.; Lee, S.Y.; Heo, J.H.; Jeong, S.C. Estimation of carbon emission coefficients for fertilizer in Korea. In Proceedings of the 2018 KSCC International Conference, Jeju, Korea, 18 June 2018; KSCC: Seoul, Korea, 2018; p. 90.
62. Pitt, G.D. Conservation of embodied energy through landscape design. In *Energy-Conserving Site Design*, 1st ed.; McPherson, E.G., Ed.; ASLA: Washington, DC, USA, 2015; pp. 215–229.
63. Lal, R. Carbon emission from farm operations. *Environ. Int.* **2004**, *30*, 981–990. [CrossRef]
64. Lee, K.H.; Yang, J.H. A Study on the functional unit estimation of energy consumption and carbon dioxide emission in the construction materials. *J. Archit. Inst. Korea Plan. Des.* **2009**, *25*, 43–50.
65. Nowak, D.J.; Endreny, T.A.; Hoehn, R.E.; Yang, Y.; Bodine, A.R.; Zhou, T.; Greenfield, E.J.; Henry, R.; Ellis, A. *Assessing Urban Forest Effects and Values: Toronto's Urban Forest*; USDA Forest Service, Northern Research Station Research Station: Newtown Square, PA, USA, 2012.
66. Jo, H.K. *Development of Planning Program for Urban Greenspace*; Korea Forest Service: Daejeon, Korea, 2009.
67. Livesley, S.; Dougherty, B.; Smith, A.; Navaud, D.; Wylie, L.; Arndt, S. Soil atmosphere exchange of carbon dioxide, methane and nitrous oxide in urban garden systems: Impact of irrigation, fertilizer and mulch. *Urban Ecosyst.* **2010**, *13*, 273–293. [CrossRef]
68. Townsend-Small, A.; Czimczik, C.I. Carbon sequestration and greenhouse gas emissions in urban turf. *Geophys. Res. Lett.* **2010**, *37*, L02707. [CrossRef]
69. Thompson, J.W.; Sorvig, K. *Sustainable Landscape Construction: A Guide to Green Building Outdoors*, 3rd ed.; Island Press: Washington, DC, USA, 2018.
70. Park, H.M. Ecological Design and Construction Strategies through Life Cycle Assessment of Carbon Budget by Land Cover Types in Urban Parks. Ph.D. Dissertation, Kangwon National University, Chuncheon, Korea, February 2021.