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Carbon and $PM_{2.5}$ Reduction and Design Guidelines for Street Trees in Korea

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Received: 16 November 2020; Accepted: 10 December 2020; Published: 12 December 2020

Abstract: An increasing concentration of air pollutants, which negatively affect human health and living environment, present a serious environmental concern around the world. Street trees can help reduce carbon (C) and $PM_{2.5}$ in cities that lack sufficient greenspace. This study quantified C uptake and $PM_{2.5}$ deposition on street trees in the Republic of Korea and suggested sustainable design guidelines to enhance the effects of C and $PM_{2.5}$ reduction. The mean C uptake and the $PM_{2.5}$ deposition on street trees per unit area were 0.6 ± 0.1 t/ha/y and 2.0 ± 0.3 kg/ha/y, respectively. The major determining factors of the levels of C uptake and $PM_{2.5}$ deposition on street trees were the species, density, size, and layering structure of the planted trees. Street trees in the Republic of Korea annually offset C and $PM_{2.5}$ emissions from vehicles by 1.4% and 180%, respectively. Based on these results, design guidelines are suggested that can contribute to sharing the value and the importance of planting street trees for the reduction of C and $PM_{2.5}$ levels in greenspaces.

Keywords: urban tree; planting tree structure; carbon uptake; particulate matter; deposition; design model

1. Introduction

Streets are a major source of carbon dioxide (CO_2) and fine dusts produced during vehicle operation in urban living spaces [1]. Notably, citizens' outdoor activities are concentrated in these spaces; hence, the air quality can affect people detrimentally [2]. Airborne gaseous materials and dust that cause pollution have a negative impact on human health and the living environment [2]. CO_2 is a gas responsible for 50% of climate change [3]. The current generation is already experiencing climate change, such as abnormal temperatures and rainfall changes due to the increase in CO_2 concentration. According to the World Health Organization (WHO) [4], particulate matter is a Class 1 carcinogen; hence, it is very harmful to the human body, causing or contributing to respiratory diseases, pulmonary functional damage, and heart diseases. Notably, the number of days per year with high concentrations of particulate matter in the atmosphere has also been increasing in recent years, increasing concerns over the seriousness of the issue worldwide.

Recently, considering the seriousness of climate change, the international community has made diverse efforts such as specifying nation-specific greenhouse gas emission reduction goals, standardizing air quality monitoring equipment, controlling the emissions of air pollution matter, and reinforcing monitoring efforts in response to the increasing levels of air pollution [5]. The Republic of Korea has also established and implemented a master plan for responding to climate change, as well as comprehensive countermeasures for the control of particulate matter [6,7].

In 2018, the average global CO_2 concentration was 407 ppm, indicating a 45% increase from pre-industrial levels [8]. In the Republic of Korea, the atmospheric CO_2 concentration in 2018 was 415 ppm: 8 ppm higher than the global average [8]. The global concentration of particulate matter escalated by 9% from 1990 to 2015 (from 40 μg/m^3 to 44 μg/m^3) [9]. In the Republic of Korea, the concentration of particulate matter was 25 μg/m^3 in 2017, higher than the annual level of 10 μg/m^3 recommended by the World Meteorological Organization (WMO) [10].

Urban trees (planted in streets, parks, and gardens) directly sequester and accumulate atmospheric CO_2 as part of the growth process through photosynthesis [11]. Urban trees can also adsorb particulate matter concentration through their leaves [12]. Notably, streets represent an important potential space in which a reduction of carbon (C) and $PM_{2.5}$ can be achieved by planting trees in cities that lack sufficient greenspace. Early studies [3,13] related to C uptake in urban greenspaces in the Republic of Korea were conducted in the late 1990s, although relevant information about street trees in individual cities and regions is still limited. Moreover, there is currently little information on $PM_{2.5}$ reduction in street and design guidelines of street trees, not only in the Republic of Korea but also globally.

Some studies exist on the reduction of atmospheric C and $PM_{2.5}$ by street trees, for example [14–19]. Jin et al. [14] measured the seasonal $PM_{2.5}$ concentrations in the streets of a residential area in Shanghai (China) and quantified the amount of $PM_{2.5}$ deposited by street trees. Russo et al. [15] explored the effects of the C offset caused by urban street trees in Bolzano (Italy) by estimating their C storage and uptake and comparing these variables with vehicle emissions. Tang et al. [16] investigated the extent of C reduction by street trees in Beijing (China) by quantifying their C storage and uptake. Zhao et al. [17] investigated three street sections in Nantong City (China), estimating the C uptake and the amount of $PM_{2.5}$ deposition by mobile laser scanning and the i-Tree Eco model. Jo et al. [18] quantified the C storage and uptake per unit area through a field survey of street trees in Seoul (Republic of Korea). Neto and Sarment [19] measured C storage quantity, density, and value using open data and allometric equations for the seven most represented urban tree species, including street trees in Lisbon (Portugal).

As mentioned above, only a few studies have focused on the reduction of C and $PM_{2.5}$ in street trees. The aim of this study is to quantify C uptake and $PM_{2.5}$ deposition on street trees in the Republic of Korea, and to suggest sustainable design guidelines to enhance effects of C and $PM_{2.5}$ reduction. This study can contribute to sharing the value of street trees internationally and the importance of planting as there is a lack of studies on the reduction of C and $PM_{2.5}$ levels by street trees.

2. Materials and Methods

2.1. Selection of Study Cities and Characteristics

The study cities were selected by considering their regional distribution and size to quantify the C uptake and $PM_{2.5}$ of street trees in the Republic of Korea. The cities selected for the study included Seoul (the capital of the Republic of Korea, located in the northwest of country), Daejeon (in the center), Daegu (in the southwest), Chuncheon (in the northeast), and Suncheon (in the south) (Figure 1). Seoul, Daejeon, and Daegu are either capital or metropolitan cities with a high population density, while Chuncheon and Suncheon are small and medium-sized cities with a relatively lower population density.

The total area by the study cities is approximately 243,302 ha (Seoul: 60,522 ha, Daejeon: 49,582 ha, Daegu: 79,792 ha, Chuncheon: 33,531 ha, and Suncheon: 19,875 ha). The total area is approximately 14% of the total area in the Republic of Korea [20–24]. The population density was 161 persons/ha in Seoul, 5–20 times higher than in Daejeon (30 persons/ha), Daegu (31 persons/ha), Chuncheon (8 persons/ha), and Suncheon (13 persons/ha). The mean annual temperature during the period of 10 years from 2012–2019 was the highest in Suncheon, located in the south of the peninsula (14.8 °C), whereas the temperature in Chuncheon was the lowest at 11.5 °C. The mean annual wind speed ranged from 1.4–2.5 m/s [20–24].

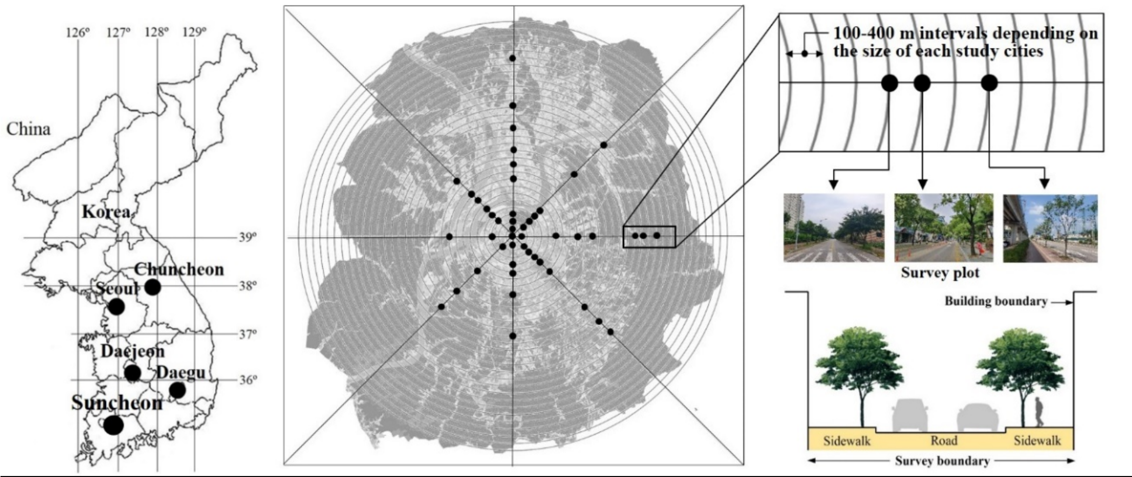

Figure 1. Location of five study cities and systematic sampling design used in this study.

2.2. Sampling of Study Streets

A total of 236 samples were selected by applying a systematic sampling method to a 1:1000-scale aerial photograph [25]. The number of samples collected in the study cities were 50 in Seoul, 47 in Daejeon, 50 in Daegu, 45 in Chuncheon, and 44 in Suncheon. Eight straight lines radiating from the center of each of the study cities were drawn in equidistant directions and looping circles were plotted at 400 m intervals in Seoul and Daejeon, 300 m in Daegu, and 100 m in Chuncheon and Suncheon, depending upon the size of the area occupied by the city. The points at which the circles and lines coincided were subject to sample extraction. One-lane roads or streets without sidewalks were excluded from this study. The samples were determined based on whether they contained a majority of the street tree species in the study city, the cost and time required for a field survey, and the statistical reliability of the research data.

2.3. Survey and Analysis of Tree Planting

The sample points along the streets in the study cities were visited, and a survey plot for each point was established up to 40 m on each side in length from the point (a total of 80 m) and to the building boundaries along both sidewalks in width (Figure 1). The field-surveyed data included the species, stem diameter (at breast height of 1.2 m (dbh) for trees, at 15 cm above ground for shrubs (≤2 cm in dbh)), the height, crown width, vertical structures, and pruning status. Vertical structures were divided into single-layered and multi-layered structures. If only trees or shrubs were planted, they were classified as single-layered structures. If trees and shrubs were planted together, they were classified as multi-layered structures.

Moreover, the potential planting space that can accommodate newly planted trees without interference from utility lines and street facilities were measured. In other words, the space for additional planting of trees with a height of 3 m or more and a crown width of 2 m or more were measured. The surveyed data were used to analyze structural characteristics (e.g., the density and cover per unit area, the dbh distribution, and the importance value of species). These data were hence applied to estimate the C uptake and the $PM_{2.5}$ deposition in each study street.

2.4. Estimation of C Uptake and $PM_{2.5}$ Deposition

The C uptake per tree was estimated using the quantification models developed for the urban trees of each species [11,25–30] (Table 1). The quantification models, which apply the stem diameter as the independent variable, were derived from measurements of the seasonal CO_2 rate of exchange of urban trees or were based on the direct harvesting method. In the absence of a quantification model for a particular species, regression models for the same genus or group were substituted to obtain the average C estimates.

Table 1. Regression model sources of tree and shrub species used to compute C uptake in study streets.

	Species	Diameter Range [1] (cm)	Reference
Tree	*Abies holophylla*	5–19	Jo et al., 2014
	Acer palmatum	7–27	Jo and Cho, 1998
		5–20	Jo and Ahn, 2012
	Chionanthus retusus	3–11	Jo et al., 2014
	Cornus officinalis	3–15	Jo et al., 2014
	Ginkgo biloba	6–31	Jo and Cho, 1998
		5–25	Jo and Ahn, 2012
	Pinus densiflora	5–29	Jo and Ahn, 2001; Jo et al., 2013
	Pinus koraiensis	5–33	Jo and Ahn, 2001; Jo et al., 2013
	Platanus occidentalis	10–58	Jo and Cho, 1998
	Prunus yedoensis	5–23	Jo and Ahn, 2012
	Taxus cuspidata	2–15	Jo et al., 2014
	Zelkova serrata	6–34	Jo and Cho, 1998
		5–28	Jo and Ahn, 2012
	General hardwoods	3–28	Jo, 2020
	General softwoods	5–31	Jo, 2020
Shrub	*Pinus* spp.	0.6–3.5	Jo, 2002
	Quercus spp.	0.5–4.0	Jo, 2002
	Rhododendron spp.	0.4–3.4	Jo, 2002
	General hardwoods	0.4–4.0	Jo, 2001; 2002
	General softwoods	0.4–4.0	Jo, 2001; 2002

[1] Stem diameter at breast height of 1.2 m for trees and diameter at 15 cm above ground for shrubs.

The $PM_{2.5}$ deposition per tree was computed by applying a dry deposition model [26,31], which was based on the deposition velocity, total leaf area, and resuspension ratio in consideration of the wind speed. The $PM_{2.5}$ concentration was obtained from data measured over the last three years of observations (2014–2017) in the study cities [32]. The $PM_{2.5}$ model applied in this study is as follows:

$$Y = (VPM_{2.5} \times LA \times C \times 3600) - R.$$

Y: $PM_{2.5}$ Amount of Deposition (g/m^2/h), $VPM_{2.5}$: Deposition Velocity (m/s), LA: Total Leaf Area (m^2), C: Atmospheric Concentration (g/m^3), R: Amount of Resuspension (g/m^2/h).

Based on the estimations per tree, the mean C uptake and the $PM_{2.5}$ deposition per unit of street area were calculated per unit of crown cover. Subsequently, the average C uptake and $PM_{2.5}$ deposits per unit of street area in the study cities were applied to the total area of the street trees in the Republic of Korea to estimate the total C and $PM_{2.5}$ reduction of all the street trees.

2.5. Estimation of Emission Offset and Economic Value

Based on the annual estimates of the C and $PM_{2.5}$ emissions from vehicles in the study cities [33,34], the C and $PM_{2.5}$ reduction in the streets were calculated with respect to the C emission. Additionally, the economic value of the C uptake by street trees was estimated by taking into account the cost of C capture and storage applicable to each country's reduction [35]: an average of \$116/t was considered. The economic value of $PM_{2.5}$ deposition was calculated by applying the treatment cost proposed by Murray et al. [36]. All of these values were calculated by considering an Organisation for Economic Co-operation and Development (OECD) annual inflation rate of \$9074/t [37] for the period 1994–2017.

3. Results and Discussion

3.1. Characteristics of Study Street

The total street area in the Republic of Korea was 179,904 ha [38] and the area in which the trees were planted covered 71,962 ha. The total street area in the study cities ranged from 1328–8729 ha (Table 2) and, of the total street area, only 25–45% was planted with street trees. According to this study, the road width excluding sidewalk in the study cities ranged from 6–36 m, with an average width being 14.2 ± 0.4 m. The sidewalk width ranged from 1–9 m, with an average width being 3.6 ± 0.1 m. The intervals at which street trees were planted ranged from 4–11 m, with an average interval being 7.3 ± 0.1 m. The standard interval for planting street trees in the Republic of Korea is 6–8 m [39] and is adjustable according to the surrounding street conditions, growth conditions of tree species, etc. Most of the street trees in the study cities were planted in 1 row and only 4% of them were planted in 2 rows.

Table 2. Characteristics of study streets.

City	Total Street Area (ha)	Number of Street Trees (Tree)	Width (m)		Street Tree Planting Intervals (m)
			Road [1]	Sidewalk	
Seoul	8729	307,351	14.9 ± 1.2	3.9 ± 0.2	6.4 ± 0.2
Daejeon	5818	140,793	13.6 ± 0.9	3.7 ± 0.2	7.5 ± 0.2
Daegu	3440	225,980	16.4 ± 0.9	4.1 ± 0.2	7.4 ± 0.1
Chuncheon	1381	25,929	12.2 ± 0.6	3.4 ± 0.1	8.1 ± 0.3
Suncheon	1328	63,460	13.4 ± 0.7	3.3 ± 0.1	7.0 ± 0.2

[1] Road width excluding sidewalk.

3.2. Distribution of Street Trees

The density of the planted street trees ranged from 0.1 to 6.0 trees/100 m^2 in this study, with an average density being 1.0 ± 0.1 trees/100 m^2 (Table 3). Daejeon had the highest tree density (1.4 trees/100 m^2), followed by Seoul and Daegu (both with 1.0 trees/100 m^2), Chuncheon (0.9 trees/100 m^2), and Suncheon (0.8 trees/100 m^2). Compared with similar studies related to density of street trees, the planting density of street trees in this study was 50% lower than the density of 2.2 trees/100 m^2 (street planting interval of 3–5 m) in the street trees of Beijing [16].

Table 3. Street tree planting structures in study cities.

City	Density (Tree/100 m^2)	Cover [1] (%)	Mean dbh (cm)	Vertical Structure (%)		Species Composition (%)		
				Single-Layer	Multi-Layer	Deci-Duous	Ever-Green	Mix
Seoul	1.0 ± 0.1	12.1 ± 1.0	21.7	73.3	26.7	58.7	4.3	37.0
Daejeon	1.4 ± 0.1	15.6 ± 1.3	20.1	75.0	25.0	76.1	0.0	23.9
Daegu	1.0 ± 0.1	14.9 ± 1.2	21.5	75.9	24.1	78.4	0.0	21.6
Chuncheon	0.9 ± 0.1	8.4 ± 0.9	20.7	88.6	11.4	90.9	0.0	9.1
Suncheon	0.8 ± 0.1	11.7 ± 1.8	21.1	64.4	35.6	42.9	23.8	33.3
Mean	1.0 ± 0.1	12.5 ± 1.4	21.0 ± 0.2	75.4	24.6	69.9	5.2	24.9

[1] Cover includes shrubs.

The cover of the planted street trees and shrubs ranged from 0.5 to 39.0% in this study, with an average being 12.5 ± 1.4%. Daejeon had the highest tree cover (15.6 ± 1.2%), followed by Daegu (14.9 ± 1.0%), Seoul (12.1 ± 0.9%), Suncheon (11.7 ± 1.2%), and Chuncheon (8.4 ± 1.3%). The tree cover of streets in Davis (United States) and in Canada were reported to range from 14 to 22% [40,41]. Compared with similar studies related to cover of street trees, the tree cover in this study was 15.7–46.4% lower.

The dbh of the street trees averaged 21.0 ± 0.2 cm across all the streets in this study. Trees with a dbh of <20 cm accounted for 46.7% of all the planted trees, which was the highest percentage of trees, followed by 20–30 cm (32.1%) and >30 cm (21.2%) (Figure 2). The dbh of street trees in Italy and China were reported to range from 23.1 to 34.9 cm [15,16]. Compared to these studies, the dbh of trees obtained in this study were similar or up to 36.1% lower.

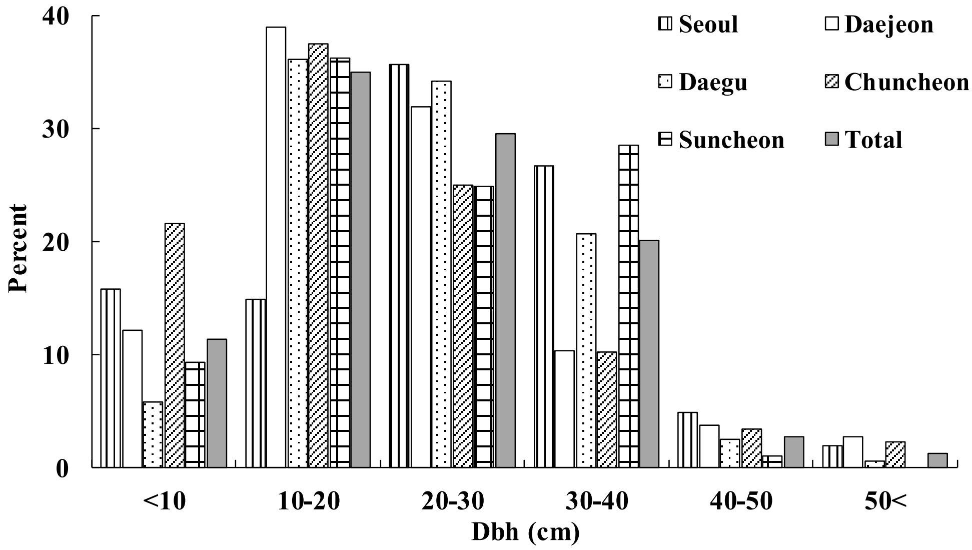

Figure 2. Dbh distribution of street trees in study cities.

A total of 52 tree species were found in the study streets, indicating a diverse composition of species. The top 10 species (based on the importance values) were *Ginkgo biloba* (27.3%), *Platanus occidentalis* (15.4%), *Nandina domestica* (6.9%), *Chionanthus retusa* (5.9%), *Rhododendron* spp. (5.2%), *Zelkova serrata* (5.1%), *Prunus yedoensis* (4.6%), *Buxus microphylla* var. *koreana* (3.8%), *Pinus densiflora* (2.2%), and *Metasequoia glyptostroboides* (1.9%). These are major urban landscape tree species of relatively high importance in most cities of the Republic of Korea [42–44].

Concerning the vertical structure of planted trees in the streets of the study cities, single-layered structures (i.e., the planting of only trees or shrubs) accounted for 70.6%, whereas multi-layered structures (i.e., the planting of trees and shrubs) accounted for 29.4%. The single-layered planting might be unfavorable to a reduction of C and $PM_{2.5}$ per unit area [45,46]. Concerning the ratio of planting deciduous and evergreen trees on the streets in the study cities, only deciduous trees were planted in 69.9% of the total streets, a mix of deciduous and evergreen trees were planted in 24.9%, and only evergreen trees were planted in 5.2%.

3.3. C Uptake and $PM_{2.5}$ Deposition

The C uptake by planted street trees per unit area in the study cities ranged from 0.1 to 3.9 t/ha/y, with an average uptake being 0.64 ± 0.08 t/ha/y (Table 4). Daejeon, with the relatively highest rates of tree density and cover, had the highest C uptake at 0.72 ± 0.07 t/ha/y, followed by Seoul at 0.70 ± 0.08 t/ha/y, Suncheon at 0.67 ± 0.09 t/ha/y, and Daegu at 0.66 ± 0.09 t/ha/y. On the other hand, Chuncheon, which had a lower tree cover ratio than the other cities, had a C uptake of 0.46 ± 0.06 t/ha/y (the lowest). C uptake by street trees in this study was about 51% lower than the C uptake of 1.3 t/ha/y in street trees of Beijing, China [16]. This result might be attributable to differences in the size and density of the planted trees. The C uptake by planted street trees per unit of tree cover ranged from 0.11 to 2.51 kg/m^2/y depending on the study cities, with an average uptake being 0.53 ± 0.04 kg/m^2/y. Meanwhile, the C uptake by Italy's street trees was reported to 0.24 kg/m^2/y [15]. The average C uptake per unit tree cover of the trees in this study was larger than that in [16] studies.

Table 4. C uptake and $PM_{2.5}$ deposition by street trees and shrubs planted in study cities.

City	Per Street Area (ha)		Per Tree Cover (m^2)	
	C Uptake (t/y)	$PM_{2.5}$ Deposition (kg/y)	C Uptake (kg/y)	$PM_{2.5}$ Deposition (g/y)
Seoul	0.70 ± 0.08	2.42 ± 0.38	0.55 ± 0.04	1.95 ± 0.27
Daejeon	0.72 ± 0.07	1.36 ± 0.16	0.47 ± 0.04	0.94 ± 0.09
Daegu	0.66 ± 0.09	2.45 ± 0.38	0.47 ± 0.04	1.71 ± 0.21
Chuncheon	0.46 ± 0.06	0.80 ± 0.11	0.54 ± 0.02	0.92 ± 0.06
Suncheon	0.67 ± 0.09	3.03 ± 0.56	0.62 ± 0.04	3.03 ± 0.51
Mean	0.64 ± 0.08	2.01 ± 0.32	0.53 ± 0.04	1.71 ± 0.23

The $PM_{2.5}$ deposition on planted street trees per unit area in this study cities ranged from 0.1 to 16.5 kg/ha/y, with an average deposition being 2.01 ± 0.32 kg/ha/y. Suncheon, which presented a relatively high ratio of multi-layered structures and evergreen trees, presented the highest $PM_{2.5}$ deposition on planted street trees per unit area (3.03 ± 0.56 kg/ha/y), followed by Daegu (2.45 ± 0.38 kg/ha/y), Seoul (2.42 ± 0.38 kg/ha/y), Daejeon (1.36 ± 0.16 kg/ha/y), and Chuncheon (0.80 ± 0.11 kg/ha/y).

The $PM_{2.5}$ deposition per unit of tree cover of this study cities ranged from 0.40 to 13.77 g/m^2/y, with an average deposition being 1.71 ± 0.23 g/m^2/y. Suncheon was characterized by the largest $PM_{2.5}$ deposition (3.03 ± 0.51 g/m^2/y), followed by Seoul (3.32 ± 0.31 g/m^2/y), Daegu (1.71 ± 0.21 g/m^2/y), Daejeon (0.94 ± 0.09 g/m^2/y), and Chuncheon (0.92 ± 0.06 g/m^2/y). There are no indications about the global levels of $PM_{2.5}$ deposition on planted street trees per unit area and per unit of tree cover. The amount of $PM_{2.5}$ deposition per unit of urban tree cover in the United States was reported to be 0.25 g/m^2/y [31]. Compared with that value, the average amount of $PM_{2.5}$ deposition calculated in our study is remarkably higher. These results might be attributable to differences in the atmospheric concentration levels, wind velocity, etc.

The amount of $PM_{2.5}$ deposition differed between deciduous and evergreen trees. In Seoul, for example, 56 g/y of $PM_{2.5}$ per week were deposited on average on deciduous trees (dbh = 22 cm), while 7 times more $PM_{2.5}$ (399 g/y) was deposited on evergreen trees. The $PM_{2.5}$ deposition was estimated by considering the seasonal average wind velocity in each city: the $PM_{2.5}$ deposition varied depending on the wind velocity and concentration levels of each city. The levels of C uptake by and $PM_{2.5}$ deposition on street trees registered in this study can be used to quantify the reduction effect of several variables (e.g., street area and tree cover).

3.4. Emission Offset and Economic Value

Based on the results above, the street trees in the Republic of Korea C uptake a total of 46,055 t/y and $PM_{2.5}$ deposit a total of 145 t/y (Table 5). The total C and $PM_{2.5}$ emissions from vehicle use were 3,263,960 t/y of C and 80 t/y of $PM_{2.5}$. The street trees in the Republic of Korea offset approximately 1.4% of the C emission from vehicle use. That is, the annual C emission per vehicle is 0.5 t/y [33], and the street trees in the Republic of Korea played a significant role in offsetting the C emissions from approximately 92,110 vehicles. $PM_{2.5}$ deposition of the street trees related to vehicle use was found to be about 181% larger than the amount that was emitted.

If economic value were applied to the total C uptake and $PM_{2.5}$ deposition of street trees in the Republic of Korea, their annual reduction effects would be calculated to be $5,996,423/y for C and $1,467,086/y for $PM_{2.5}$. The sum of these annual values is $7,463,509/y: 14% of the annual planting budget for street trees in the Republic of Korea [43]. In the Republic of Korea, only 40% of the total street area is lined with trees. Although additional street trees are being planted every year (1932 ha/y) [43], they cover only 1% of total street area in the Republic of Korea. In order to improve the effects of C and $PM_{2.5}$ reduction, active tree planting is required in sections without street trees, as well as in potential planting spaces.

Table 5. Total C uptake and $PM_{2.5}$ deposition by street trees and economic value in the Republic of Korea.

City	Total C Uptake (t/y)	C Offset (%)	Total $PM_{2.5}$ Deposition (t/y)	$PM_{2.5}$ Offset (%)	Value ($/y)
Seoul	2444	0.5	8.4	80.0	360,190
Daejeon	1676	1.5	3.2	145.2	223,087
Daegu	908	0.5	3.4	86.9	135,937
Chuncheon	254	1.2	0.4	118.2	33,486
Suncheon	356	1.6	1.6	449.6	55,890
Korea	46,055	1.4	144.6	180.8	7,463,509

3.5. Design Guidelines

The planting structure of street trees included in the study cities was analyzed, and problems related to C and $PM_{2.5}$ reduction were found to be mainly due to the following reasons: a single-layered structure, low density, limited growing space, insufficient composition of tree species, and poor management such as excessive pruning (Figure 3).

(**a**) (**b**) (**c**) (**d**)

Figure 3. Major problems of street trees in the study cities. (**a**) Single-layered structure; (**b**) Low density; (**c**) Limited growing space; (**d**) Excessive pruning.

Within the limited space available for street tree planting, it is desirable to form multi-layered structures of high-density where possible to improve the reduction of C and $PM_{2.5}$ (Figure 4). According to previous studies [45,46], it is reported that multi-layered structures are more advantageous in terms of C uptake capacity than single-layered structures. In this study also, the C uptake capacity of multi-layered structures was 1.1–1.2 times higher than single-layered structures. Thus, planting small trees at low density should be avoided and planting in multi-layered structures preferred instead. According to this study, the C uptake of deciduous trees is higher than that of evergreen trees, whereas the $PM_{2.5}$ deposition is higher for evergreen than for deciduous trees. To increase effects of C and $PM_{2.5}$ reduction, mixed planting of deciduous and evergreen trees is advisable. However, in the streets examined in this study, only deciduous trees were planted in approximately 70% of the section. In addition, it is recommended that larger trees be planted, rather than small trees, as well as tree species with good growth rates such as *Zelkova serrata*, *Prunus yedoensis*, *Pinus koraiensis*, and *Pinus densiflora* [45].

Moreover, tree planting space for tree growth should be expanded. As a result of this study, many streets were found with insufficient tree planting or with wide planting intervals that require supplementary tree planting. The potential planting space in the study cities was at a total of 12,418 ha. If these were actively planted with trees and shrubs, approximately 8457 t/y of C could be absorbed while additionally depositing 3 t/y of $PM_{2.5}$. If the growth of a tree is poor, its C uptake and $PM_{2.5}$ deposition also becomes unfavorable; thus, it is necessary to provide good soil for growth and appropriate post-planting care [44]. Regardless of the tree size, the streets included in this study mostly had one tree in a 1–1.2 m^2 tree planting space. Because the roots of street trees spread widely (as opposed to deep into the ground), securing sufficient width (rather than depth) is more important for tree growth [44]. Therefore, normal growth can be promoted by forming elongated planting areas in the form of a belt.

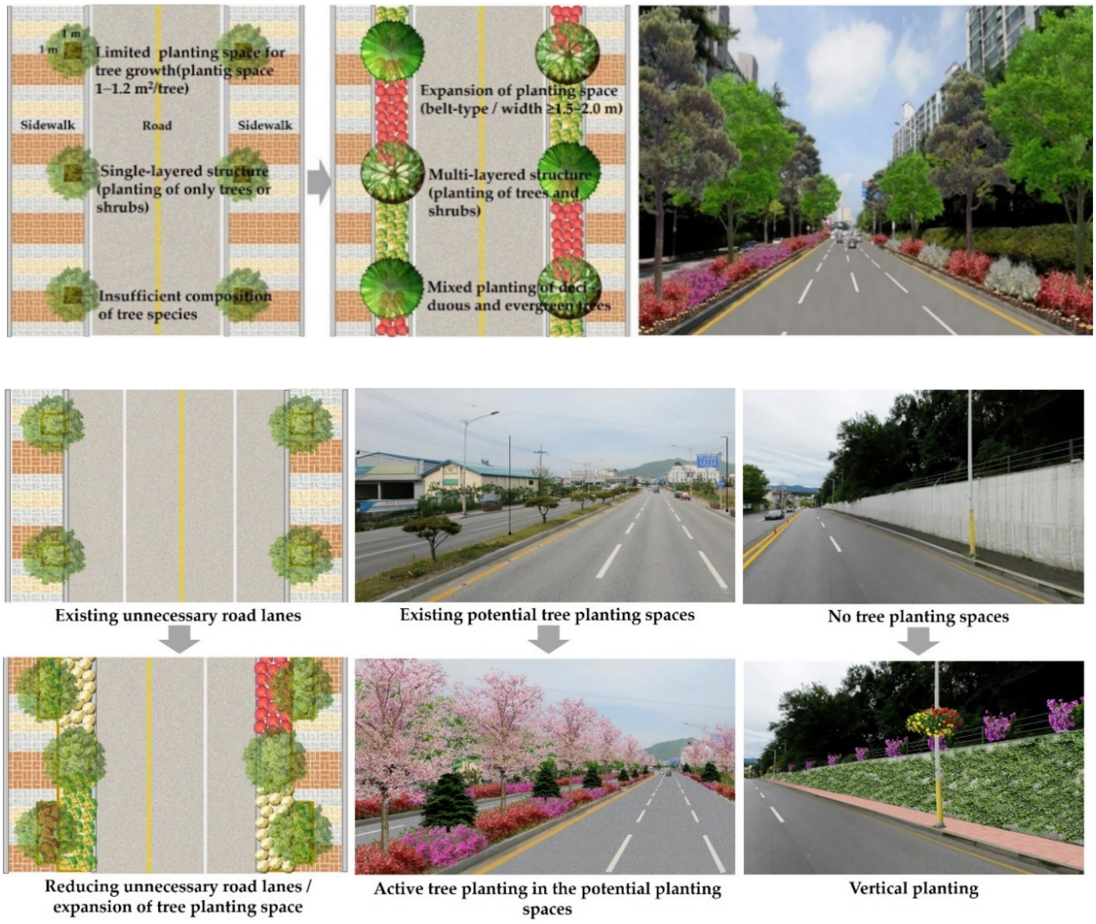

Figure 4. Major design guidelines to enhance effects of C and $PM_{2.5}$ reduction.

Furthermore, by road diet, unnecessary road lanes could be reduced while expanding tree planting to create additional tree areas. Where it is not possible to plant street trees, it will be necessary to increase the tree biomass per unit area by employing artificial ground greening (such as on walls and rooftops). Tree pruning was conducted for reasons such as overhead utility line protection and to prevent the visual disturbance of commercial signs in the study cities. Severe tree pruning to protect utility lines was found at approximately 76% of all the study city streets. Excessive tree pruning may further reduce the already insufficient urban plant leaf area and undermine normal growth and functioning [3]. To ensure the normal growth and proper functioning of street trees, it is desirable to avoid excessive pruning and involve specialists in the process. In addition, existing overhanging utility lines could be placed underground to provide further space for tree growth and to minimize disruption of the streetscape. These design guidelines could help improve C and $PM_{2.5}$ reduction, microclimate amelioration, rainfall interception, and more.

4. Conclusions

Street trees can help reduce C and $PM_{2.5}$ in cities that lack sufficient greenspace as well as play a key role in enhancing diverse values. This study concerned the quantification of C and $PM_{2.5}$ reduction conducted thus far; planting design for enhancing the diversity of street trees has not yet been reported. This study quantified C uptake and $PM_{2.5}$ deposition on street trees in the Republic of Korea and suggested sustainable design guidelines to enhance effects of C and $PM_{2.5}$ reduction.

The density and cover of street trees in the study cities averaged approximately 1.0 trees/100 m^2 and 12.5%, respectively. C uptake and $PM_{2.5}$ deposition per unit area were 0.6 t/ha/y and 2.0 kg/ha/y, respectively. This result might be attributable to differences in the size and density, species, and layer structure of the planted trees. The planted trees across all streets in the Republic of Korea played a significant role in offsetting approximately 1.4% of C emissions from vehicle use and deposited 181% of the $PM_{2.5}$ emissions. The economic value of C and $PM_{2.5}$ reduction amounted to $7,463,509/y, which is approximately 14% of the annual planting budget for street trees in the Republic of Korea.

The street trees in the study cities were limited in optimizing C and $PM_{2.5}$ reduction because of a single-layered structure, low density, limited growing space, insufficient composition of tree species, and poor management such as excessive pruning. To enhance effects of C and $PM_{2.5}$ reduction in the street trees, this study proposed design guidelines including multi-layered structures of high-density, the mixed planting of deciduous and evergreen trees with a good growth rate, active tree planting in the potential planting spaces, the securing of ground and space for plant growth (belt-type planting space), road diet, artificial ground greening, and avoiding excessive tree pruning.

Most cities in the Republic of Korea only record the species and number of planted street trees, and data on important variables for assessing the diversified values of street trees such as planted tree density or size are not available. In the future, it is necessary to advance the open data system so that big data on relevant items that are lacking can be easily used by experts and the general public. This study contributes to expanding this fundamental information, which supplements the information gathered during our on-site investigation. The indicator of the amount of C uptake and $PM_{2.5}$ deposition is useful in quantifying the role of street trees in offsetting C and $PM_{2.5}$. Any subsequent study would need to establish a C uptake and $PM_{2.5}$ deposition indicator according to the type of greenspace (such as parks and gardens), then compare it with the case of street trees, and establish design guidelines for each type of greenspace for improved effects of C and $PM_{2.5}$ reduction.

Author Contributions: All authors significantly contributed to this paper. Conceptualization, H.-K.J.; methodology, H.-K.J., J.-Y.K., and H.-M.P.; investigation, H.-K.J., J.-Y.K., and H.-M.P.; analysis, J.-Y.K.; writing—original draft preparation, H.-K.J. and J.-Y.K.; writing—review and editing, H.-K.J. and J.-Y.K.; visualization, H.-M.P.; supervision, H.-K.J. All authors have read and agreed to the published version of the manuscript.

Funding: This study was carried out with the support of the "R&D Program for Forest Science Technology (Project No. 2017043B10-1919-BB01; 2019151A00-2023-0301)" provided by the Korea Forest Service (Korea Forestry Promotion Institute).

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

References

1. National Institute of Environmental Research (NIER). *National Air Pollutants Emission*; NIER: Incheon, Korea, 2018.
2. Manisalidis, I.; Stavropoulou, E.; Stavropoulou, A.; Bezirtzoglou, E. Environmental and health impacts of air pollution: A review. *Front. Public Health* **2020**, *8*, 14. [CrossRef] [PubMed]
3. 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.
4. World Health Organization (WHO). Available online: https://www.euro.who.int/en/health-topics/environment-and-health/urban-health/news/news/2013/10/outdoor-air-pollution-a-leading-environmental-cause-of-cancer-deaths (accessed on 3 June 2020).
5. Korea Institute for International Economic Policy (KIEP). *International Responses to Transboundary Air Pollution and their Implications*; KIEP: Sejong, Korea, 2017.
6. Ministry of Culture, Sports and Tourism. Republic of Korea. Available online: https://www.korea.kr/special/policyCurationView.do?newsId=148864591 (accessed on 20 July 2020).
7. Cheongwadae. *Plan to Counteract Climate Change I*; Cheongwadae: Seoul, Korea, 2016.
8. Korea Meteorological Administration (KMA). Report of Global Atmosphere Watch 2018. Available online: http://www.climate.go.kr/home/bbs/view.php?code=24&bname=report&vcode=6281&cpage=1&vNum=73&skind=&sword=&category1=&category2= (accessed on 3 June 2020).
9. Health Effects Institute (HEI). State of Global Air 2017. Available online: https://www.stateofglobalair.org/sites/default/files/soga_2017_report.pdf (accessed on 3 June 2020).
10. World Meteorological Organization (WMO). Greenhouse Gas Bulletin No 14. Available online: https://public.wmo.int/en/resources/library/wmo-greenhouse-gas-bulletin-no-14 (accessed on 20 July 2020).

11. Jo, H.K. Impacts of urban greenspace on offsetting carbon emissions for middle Korea. *J. Environ. Manag.* **2002**, *64*, 115–126. [CrossRef] [PubMed]
12. Nowak, D.J.; Hirabayashi, S.; Bodian, A.; Greenfield, E. Tree and forest effects on air quality and human health in the United States. *Environ. Pollut.* **2014**, *193*, 119–129. [CrossRef] [PubMed]
13. 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**, *73*, 39–53.
14. Jin, S.; Guo, J.; Wheeler, S.; Kan, L.; Che, S.; Evaluation of impacts of trees on $PM_{2.5}$ dispersion in urban streets. *Atmos. Environ.* **2014**, *99*, 277–287. [CrossRef]
15. Russo, A.; Escobedo, F.; Timilsina, J.N.; Zerbe, S. Transportation carbon dioxide emission offsets by public urban trees: A case study in Bolzano, Italy. *Urban For. Urban Green.* **2015**, *14*, 398–403. [CrossRef]
16. Tang, Y.; Chen, A.; Zhao, S. Carbon storage and sequestration of urban street trees in Beijing, China. *Front. Ecol. Evol.* **2016**, *4*, 1–8.
17. Zhao, Y.; Hu, Q.; LI, H.; Wang, S.; Ai, M. Evaluating carbon sequestration and $PM_{2.5}$ removal of urban street trees using mobile laser scanning data. *Remote Sens.* **2018**, *10*, 1759. [CrossRef]
18. Jo, H.K.; Kim, J.Y.; Park, H.M. Carbon storage and uptake by street trees in Seoul. *J. For. Environ. Sci.* **2018**, *34*, 162–164.
19. Neto, M.C.; Sarment, P. Carbon storage quantity, density, and value using open data and allometric equations. *Information* **2019**, *10*, 133. [CrossRef]
20. Seoul. Statistical Yearbook. Available online: https://data.seoul.go.kr/together/statbook/statbookList.do (accessed on 20 July 2020).
21. Daejeon. Statistical Yearbook. Available online: https://www.daejeon.go.kr/sta/StaStatisticsPubList.do?category=149&menuSeq=185 (accessed on 20 July 2020).
22. Daegu. Statistical Yearbook. Available online: http://stat.daegu.go.kr/statsPublication/statsYearbook.do (accessed on 20 July 2020).
23. Chuncheon. Statistical Yearbook. Available online: http://www.chuncheon.go.kr/chstat/board/list.chuncheon;jsessionid=A3C625CA73568CC6E496D757A3DBE794.worker1?boardId=BBS_0000517&menuCd=DOM_000011104002000000&contentsSid=10727&cpath=%2Fchstat (accessed on 20 July 2020).
24. Suncheon. Statistical Yearbook. Available online: https://www.suncheon.go.kr/kr/info/0004/0003/0003/0002/ (accessed on 20 July 2020).
25. 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.
26. Jo, H.K. *Indicator for CO_2 Uptake and Atmospheric Purification Evaluation of Vegetation*; Ministry of Environment: Seoul, Korea, 2001.
27. 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.
28. 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]
29. 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]
30. 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]
31. Nowak, D.J.; Hirabayashi, S.; Bodine, A.; Hoehn, R. Modeled $PM_{2.5}$ removal by trees in ten U.S. cities and associated health effects. *Environ. Pollut.* **2013**, *178*, 395–402. [CrossRef] [PubMed]
32. Korea Environment Corporation (KECO). Available online: http://www.airkorea.or.kr/web/sidoQualityCompare?itemCode=10008&pMENU_NO=102 (accessed on 20 July 2020).
33. Korean Energy Agency (KEA). Available online: http://bpms.kemco.or.kr/transport_2012/car/car_choice.aspx (accessed on 20 July 2020).
34. National Center for Fine Dust Information. Available online: http://airemiss.nier.go.kr/module/statistics/materialStatistics.do?siteId=airemiss&id=airemiss_030200000000 (accessed on 20 July 2020).
35. Global Carbon Capture and Storage Institute (GCCSI). *Global Costs of Carbon Capture and Storage*; GCCSI: Melbourne, Australia, 2017.

36. Murray, F.J.; Marsh, L.; Bradford, P.A. *New York State Energy Plan*; New York State Energy Office: New York, NY, USA, 1994.
37. Organization for Economic Cooperation and Development (OECD). *The Economics of Climate Change Mitigation Policies and Options for Global Action beyond 2012*; OECD: Paris, France, 2009; p. 11.
38. Korean Statistical Information Service, KOSIS. Available online: http://kosis.kr/statisticsList/statisticsListIndex.do?menuId=M_01_01&vwcd=MT_ZTITLE&parmTabId=M_01_01#SelectStatsBoxDiv (accessed on 20 July 2020).
39. Korea Ministry of Government Legislation. Available online: https://www.law.go.kr/lsSc.do?section=&menuId=1&subMenuId=15&tabMenuId=81&eventGubun=060101&query=%EC%82%B0%EB%A6%BC%EC%A1%B0%EC%84%B1#undefined (accessed on 20 July 2020).
40. Maco, E.; McPherson, E.G. Assessing canopy cover over streets and sidewalks in street tree populations. *J. Arboric.* **2002**, *28*, 270–276.
41. City of Sydney. Available online: https://www.cityofsydney.nsw.gov.au/strategies-action-plans/urban-forest-strategy (accessed on 13 August 2020).
42. Korea Forest Service. Available online: https://huyang.forest.go.kr/kfsweb/cop/bbs/selectBoardList.do?bbsId=BBSMSTR_1069&mn=NKFS_06_09_01 (accessed on 14 August 2020).
43. Korea Forest Service. Available online: https://www.forest.go.kr/kfsweb/cop/bbs/selectBoardArticle.do?nttId=3147054&bbsId=BBSMSTR_1036&pageUnit=10&pageIndex=1&searchtitle=title&searchcont=&searchkey=&searchwriter=&searchWrd=&ctgryLrcls=&ctgryMdcls=&ctgrySmcls=&ntcStartDt=&ntcEndDt=&mn=NKFS_01_01&orgId= (accessed on 14 August 2020).
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. 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]
46. Jo, H.K.; Park, H.M.; Kim, J.Y. Carbon offset service and design guideline of tree planting for multifamily residential sites in Korea. *Sustainability* **2019**, *11*, 3543. [CrossRef]