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Comparative Research on Typical Measure Methods of the Carbon Sequestration Benefits of Urban Trees Based on the UAV and the 3D Laser: Evidence from Shanghai, China

Xiaoyan Ma [1,2], Qinghua Zou [1,2], Ming Liu [3] and Jun Li [4,*]

[1] College of Architecture and Urban Planning, Tongji University, Shanghai 200092, China; xiaoyan_ma@tongji.edu.cn (X.M.); 2030139@tongji.edu.cn (Q.Z.)
[2] Key Laboratory of Ecology and Energy-Saving Study of Dense Habitat, Ministry of Education, Tongji University, Shanghai 200092, China
[3] College of Architecture, Nanjing TECH University, Nanjing 211816, China; mingliu@njtech.edu.cn
[4] School of Aerospace Engineering and Applied Mechanics, Tongji University, Shanghai 200092, China
* Correspondence: muziyi@tongji.edu.cn

Abstract: The Carbon Sequestration Benefits (CSB) of vegetation and forest have received more and more attention with the increase in CO_2 density in the atmosphere. The evaluation of the CSB of existing vegetation and forest has also become one of the important research topics in urban ecology. In the existing research, the evaluation of CSB methods can be categorized into a two-dimension index and three-dimension index. The two-dimension index mainly focuses on leaf area method and leaf area index method. Additionally, the three-dimension index mostly focuses on the Three-Dimension Green Quantity (3DGQ) method which further includes Approximate Geometry Model (AGM), Point Cloud (PC) method using 3D laser, and Point Cloud Convex Hull Slicing (PCCHS) method, etc. In this paper, we take Shanghai as the study area, and address the top 15 species with each species having 30 trees of the same age from Shanghai to calculate the average annual CSB of the 15 species using the two-dimension index and three-dimension index. Through this, we analyze the difference of the same species in different indexes in the same categories and in different categories. The research results provide a research basis for the in-depth exploration of the three-dimensional spatial pattern of urban green space and ecological benefit evaluation.

Keywords: urban green space; carbon sequestration benefits; unmanned aerial vehicle (UAV); 3D laser

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1. Introduction

Urban green space is closely related to the existence and development of human beings [1], and it has service functions such as moderating some of the urban heat island effects [2], regulating microclimate [3], purifying pollution [4], conserving water sources, maintaining water and soil [5], preventing wind and sand fixation, and protecting biodiversity [6]. At this stage, the concentration of CO_2 in the atmosphere continues to increase, and the global climate change has intensified. The carbon peak and carbon neutral are the common goals of the world. Green plants absorb CO_2 through photosynthesis in leaves, thereby reducing the concentration of CO_2 in the environment. It is known to be a natural carbon sink. In urban construction, especially in areas with high population density, reasonable planning of green space, optimization of green vegetation structure, and improvement of ecological benefits have attracted much attention [7]. Furthermore, in order to improve the planning and design of urban green space, landscape metrics that can qualify and assess the climatic functions of urban green space are needed.

There is an extensive amount of research that has been done on the evaluation of urban green space. According to the calculation factors, they could be classified into two categories: two-dimension index and three-dimension index. The two-dimension index includes the well-known Green Index (GI), i.e., percentage area of green space [8], the canopy cover [9], the leaf area density [10], the Total Leaf Area (TLA) [11], and the Leaf Area Index (LAI) [12], etc. The TLA and LAI was widely researched due to it being very close to the photosynthesis in leaves. Thus, many studies have been done on how to measure these indexes (See Section 1.1 for more details). However, the urban green space is a three-dimensional distribution space. Therefore, inevitably, it has certain limitations when using these two-dimensional indicators to measure the amount of green space in three-dimensional urban green spaces. The most used three-dimension index is the Three-Dimension Green Quantity (3DGQ). There are many studies on how to calculate the 3DGQ (See Section 1.2 for more details).

1.1. Leaf Area Index and Total Leaf Area

The LAI [12,13] is defined as the total leaf area projected onto the unit land area which quantitatively describes the growth and density of leaves at the population level. Its value closely relates to the photosynthetic respiration, water transpiration, and plant productivity of plants [14]. Therefore, LAI is usually used to evaluate the ecological benefit and greening level of green space. Field measurement methods for LAI include *direct* and *indirect* methods.

In the direct methods, the LAI is calculated through the calculation of total leaf area, which includes the grid method, the paper sample weighing method, the leaf area meter method, the punching weighing method, the fresh weight method, etc. Most of these methods have low efficiency and require cumbersome operations to enhance the efficiency. However, the error still cannot be estimated after cumbersome and destructive operations.

In the indirect methods, the measurement is obtained by converting the area of the intermediate objects using the coefficient regression method, image processing method, etc. These methods include the remote sensing image method [15], radiometric method, plant canopy analyzer method [16], lidar scanning method [17–19], hyperspectral measurement method, digital hemisphere photography method [20], etc. Van Gardingen et al. [16] used the hemispherical radiation leaf area meter to measure the LAI of the vegetation canopy and proposed a logarithmic average method to reduce the error. Carlo et al. [20] used Digital Hemispherical Photography (DHP) to measure the LAI of hardwood and used Can-Eye software to quantify the influence of user subjectivity on the estimated value which enhance the overall reliability. Sun Yue [21] established a remote sensing inversion method of LAI based on the least square method and on the low-altitude aerial photography images obtained by UAV and satellite images. This method reduced the relative error of the overall vegetation LAI from 35% to 27%. Additionally, herbs had a greater impact, with the relative error dropping from 56% to 32%. Similarly, the indirect methods also have low accuracy because most of them are easily affected by the surrounding conditions.

To enhance the measurement accuracy, many studies have correlated the LAI with plant characteristics [22], and established regression models to use characteristic parameters, such as canopy height, crown width, age, and planting density, etc. Peper et al. [23] proposed a model for predicting the exponential growth of the TLA based on tree height, crown diameter, crown height, and LAI. Guiterman et al. [24] revised the LAI allometric growth model by introducing the plant density and applying data records of the coniferous forest in central Maine for 17 consecutive years. It is able to evaluate the urban green volume and their ecological benefits combining the urban plant structure. Chen Zixin et al. [25] established a regression model for calculating the total leaf area of different plants according to the correlation between the leaf surface of individual plants and diameter at breast height, crown height, and crown width. They used the model to conduct a series of studies on the ecological function of urban garden plants in Beijing. Song Ziwei et al. [26] established a leaf area model of 25 common road greening tree species in Beijing, and quantitatively evaluated their ecological benefits.

Due to the application of equipment with optical instrument functions such as hyper spectrometer and lidar, and the introduction of new technologies, as well as the establishment of regression models of LAI and plant characteristics, leaf area measurement is becoming more and more efficient and convenient. However, there is still room for improvement in measurement accuracy because the leaf shape of plants is affected by the environment such as growth space and climate, and the growth conditions of the same plant in urban and suburban areas are also very different, as well as the uncertainty caused by the scale of research.

1.2. Three-Dimension Green Quantity

The 3DGQ of a tree refers to the volume of space occupied by the stems and leaves [27], as presented in Figure 1. It is the first three-dimensional index of the urban greening index system [27,28]. Zhou Jianhua proposed the method of "simulating the three-dimensional quantity with the plane quantity" to measure the 3DGQ of trees [27]. Using remote sensing images combined with field research to analyze various data of tree species, he established a crown diameter-crown height regression model [28]. The model reveals the spatial structure of greening and quantitatively studies the relationship between trees and ecological benefits to evaluate the quality of the urban ecological environment [29]. A large number of studies based on this model have emerged subsequently, such as using tree shadows to calculate tree height and crown diameter and using geometric shapes to obtain green volume [27,28]. The more commonly used method is to process the tree crown data hierarchically to obtain several small, truncated cones, and the accumulation of the truncated and conical volumes to obtain the 3DGQ [30]. Considering the irregular shape of the tree, using the cross-sectional area of the canopy as the base area of the layered geometry volume calculation instead of the regular circle improves the volume calculation accuracy [31].

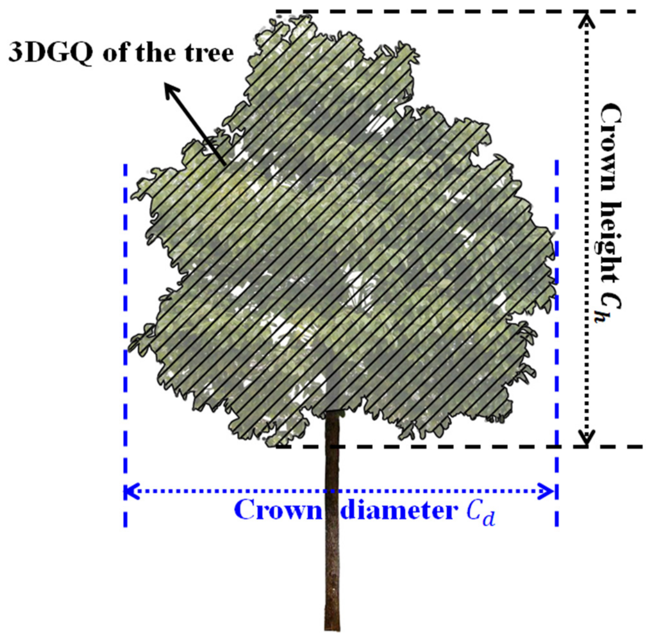

Figure 1. Diagram of the definition of three-dimension green quantity (3DGQ).

These widely used methods are mainly based on the optimization of mathematical models. However, due to the gaps between leaves, the estimated 3DGQ is larger than the actual value. With the application of new technologies and instruments, a large number of studies have been proposed to enhance the evaluation accuracy of 3DGQ of a single tree. For example, the Point Cloud (PC) method obtains the shape of the canopy through a vehicle-mounted laser, and then calculates the volume of the shape [32–34]. Combine the UAV aerial photography and GIS to establish the "crown diameter-crown height" equation to calculate crown height through crown width, then, combined with the matched geometry (named as Approximate Geometry Model, AGM) to calculate the 3DGQ of an individual tree and then the whole study area [1]. Fengxia Li et al. used aerial remote sensing and high-precision laser 3D scanning Point Cloud (PC) to count tree data and form a regular spatial geometry and calculated the 3DGQ according to the effective ratio through the differential method. The error between the 3DGQ of a single tree and the actual measured value is less than 10% [35]. The quantitative estimation accuracy of the 3DGQ in Xi'an city is as high as 88.07% [36]. On the basis of spatial geometric volume estimation, scholars further introduced parameters such as perspective density, and used 3D laser scanning of tree volume and surface area to calculate the percentage of leaf area in three views, that is, perspective density. Rufei Liu et al. [37] used the PC method defect rate of the tree canopy to establish a 3DGQ calculation model. The average deviation of the 3DGQ of 35 street trees are reduced to 4.1%. However, the deviation of canopy volume is irregular, and the canopy defects of different plants are quite different. The Point Cloud Convex Hull Slicing (PCCHS) method [38] is the combination of the AGM and PC method. In PCCHS, the authors use a 3D laser to obtain the point cloud data, then, use the convex hull to obtain the approximate geometry of these data. Finally, they calculate the 3DGQ through calculating the volume of the convex hull of these point data.

In the following, we will take the Shanghai Chenshan Botanical Garden (Shanghai, China) as the study area to compare and analyze the typical two-dimension index and three-dimension index.

2. Materials and Methods

2.1. Study Area

This study was conducted in Shanghai (121°50′ E, 31°40′ N), China. Shanghai is one of the four direct-administered municipalities of the People's Republic of China. It is the most populous city proper in China and in the world. It has a resident population of 24.87 million (the Seventh National Census, November 2020) and covers an area of 634,050 ha. It has 532 gardens (December 2021), and the largest botanical garden has more than 6000 species of plants: the Shanghai Chenshan Botanical Garden. Through the plant data from Shanghai Municipal Park Management Department, we choose the 15 species of tree, as in Table 1.

Table 1. Basic information of 15 species with each having 30 trees.

No.	Species	Growth Type	Matched Geometry	Crown Height (m)	Crown Diameter (m)
N_1	Cinnamomum camphora	Evergreen tree	Ellipsoid	8.83–9.98	4.41–6.75
N_2	Platanus	Deciduous tree	Ellipsoid	9.07–10.45	8.11–10.40
N_3	Magnolia grandiflora	Evergreen tree	Ellipsoid	3.14–3.68	2.33–3.48
N_4	Cedrus deodara	Evergreen tree	Cone	8.31–8.75	4.77–6.62
N_5	Osmanthus fragrans	Evergreen tree	Ellipsoid	3.32–3.54	2.34–5.17
N_6	Ginkgo biloba	Deciduous tree	Ellipsoid	3.55–3.83	4.02–5.54
N_7	Robinia pseudoacacia	Deciduous tree	Ellipsoid	8.45–9.33	6.83–8.33
N_8	PopulusL.	Deciduous tree	Fan-shere	13.94–14.70	5.12–7.35
N_9	Salix babylonica	Deciduous tree	Ellipsoid	6.11–8.15	5.66–7.79
N_{10}	Ulmus pumila	Deciduous tree	Ellipsoid	9.83–11.38	5.27–7.20
N_{11}	Populus × canadensis Moench	Deciduous tree	Ellipsoid	11.67–13.76	3.65–6.12
N_{12}	Ailanthus altissima	Deciduous tree	Hemisphere	7.45–9.18	8.89–11.77
N_{13}	Morus alba	Deciduous shrub	Ellipsoid	5.95–6.97	4.84–7.75
N_{14}	Syringa oblata	Deciduous shrub	Ellipsoid	1.14–2.12	1.15–3.76
N_{15}	Platycladus orientalis	Evergreen tree	Cone	3.87–4.91	0.92–3.35

2.2. Data Collection and Processing

In this work, we focus on the comparison of different estimation methods on the same tree at the same time. The procedure for the evaluation of 3DGQ and C_{ApT} as in Figure 2. The data collection was conducted from 10 July to 20 August 2021, during the lush vegetation period in summer in Shanghai Chenshan Botanical Garden. The data collection is divided into two groups for simultaneous collection, one group is responsible for UAV aerial photography, and the other group is responsible for 3D laser point cloud scanning.

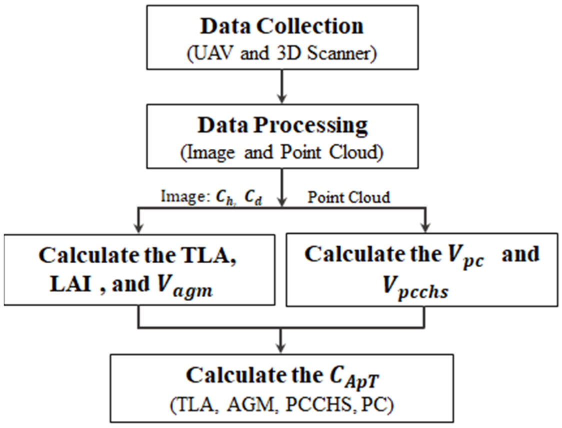

Figure 2. The procedure for the evaluation of 3DGQ and C_{ApT}.

2.2.1. UAV Image Data Collection and Processing

We used an aerial photography system to collect low-altitude high-resolution images of 15 tree species, each with 30 trees of the same age. The system is integrated by a quadrotor UAV (DJI, Inspire 2), an aerial camera, an airborne positioning system, an aerial planning and design software and flight management system. The UAV was equipment with X7 gimbal camera which supports 10 burst photos in JPEG + DNG, and DNG unlimited burst photos of 20 frames per second with each photo has 24 million pixels.

For each species, we chose one tree and use the UAV takes 30 photos of its top, left, and right views, with 10 burst photos of each view. Finally, we took a total of 13,500 images.

In image processing, we used OpenCV (in C language), CvMat data structure, to process these images to obtain the average crown height and average crown diameter of each tree (as presented in Table 1). Substitute the data in Table 1 into the model in Section 2.3.2, and then the 3DGQ of the crown can be calculated.

2.2.2. 3D Laser Point Cloud Collection and Processing

The point cloud data collection platform adopts the FARO Photon120 three-dimensional ground laser scanner, and the scanning range are set as 360° in the horizontal direction, 320° in the vertical direction, and the resolution is 1/4 (10,000/360°). For each tree, we set up 3 scan points, which form an approximately equilateral triangle. A total of 450 trees was scanned.

In data processing, we firstly used 3D laser scanning for point cloud denoising and coordinate matching in the FARO SCENE software which comes with the 3D laser. Then, we used MATLAB, VC++, combined with the mathematical model in "Section 2.3.2" to process these data and obtain the 3DGQ.

2.3. Evaluation of LAI, TLA and 3DGQ

2.3.1. Mathematical Model of LAI and TLA

In this paper, we adopt the regression model, proposed by McPherson et al. [39], to calculate the *TLA*:

$$S_{TLA} = \exp(0.6031 + 0.2375C_h + 0.6906C_d - 0.0123S_1) + 0.1824 \quad (1)$$

where S_{TLA} is the total leaf area, m^2; C_h is the crown height, m; C_d is the crown diameter, m, and

$$S_1 = \pi C_d(C_h + C_d)/2 \quad (2)$$

The area of land covered by trees is the projected area of the tree canopy, S_{PA},

$$S_{PA} = \pi C_d^2/4 \tag{3}$$

Then, the leaf area index per plant is given as

$$I_{LA} = S_{TLA}/S_{PA} \tag{4}$$

2.3.2. Mathematical Model of 3DGQ

For the calculation of 3DGQ, this paper adopts the Approximate Geometry Model (AGM), the Point Cloud Convex Hull Slicing (PCCHS) method, and the Point Cloud (PC) method. The 3DGQ of PC is directly calculated through the VC++ and MATLAB when processing the point cloud data without a mathematical model. The mathematical model of AGM and PCCHS is detailed as follows:

- 3DGQ of AGM

In this paper, the matched geometry of the species and the corresponding volume formula are presented in Tables 1 and 2, respectively.

Table 2. The 3DGQ of approximate geometry model (AGM).

No.	Geometry	3DGQ-V_{agm}
1	Ellipsoid	$\pi C_d^2 C_h/6$
2	Cone	$\pi C_d^2 C_h/12$
3	Fan-shere	$\pi\left(2C_h^3 - C_h^2 \cdot \sqrt{4C_h^2 - C_d^2}\right)/3$
4	Cylinder	$\pi C_d^2 C_h/4$
5	Hemisphere	$\pi C_d^2 C_h/6$

C_h is the crown height; C_d is the crown diameter.

- 3DGQ of PCCHS

The convex hull is a widely used concept from applied mathematics. In a real vector space V, for a given set X, the intersection S of all convex sets containing X is called the convex hull of X. Using a convex hull to calculate, the 3DGQ is given as follows:

The convex hull of the canopy point cloud is divided at equal intervals from the bottom to the top, and the convex hull is constructed with the plane point cloud data set contained in each slice, and then the area of each slice is calculated according to the discretized Green formula [40],

$$S = \frac{1}{2}\sum_{i=1}^{n}[x_i(y_{i+1} - y_i) - y_i(x_{i+1} - x_i)] \tag{5}$$

where, n is the number of convex hull vertices, x_i is the x-coordinate of the i-th vertex, x_{i+1} is the x-coordinate of the (i + 1)-th vertex, y_i is the x-coordinate of the i-th vertex, y_{i+1} is the x-coordinate of the (i + 1)-th vertex.

The space between each two slices is approximately regarded as a table body, and the 3DGQ is calculated by using the table body accumulation and calculation formula,

$$V_{pcchs} = \frac{1}{3}\sum_{i=1}^{n-1}\left(S_i + \sqrt{S_i S_{i+1}} + S_{i+1}\right)h_i \tag{6}$$

where S_i is the slice area of the i-th layer (m^2), S_{i+1} is the slice area of the (i + 1)-th layer (m^2), h_i is the interval between adjacent slices (m), and V_{pcchs} is the 3DGQ (m^3), and n is the number of slice layers.

2.4. Evaluation of Carbon Sequestration Benefits

In the existing research, the authors mostly use the assimilation method to measure the plant Carbon Sequestration Benefits (CSB). Through photosynthesis to measure the instantaneous CO_2 concentration and water in and out of plant leaves and multiply the plant TLA by the net photosynthesis per unit time of the plant (photosynthetic accumulation minus respiration accumulation) to obtain the plant CSB [41].

In this paper, the daily CSB per unit leaf area of trees, $W_{d(CO_2)}$ $\left(g{\cdot}m^{-2}{\cdot}d^{-1}\right)$, in the literature was used (see Table 3 for details). When calculating the annual carbon sequestration of plants, it is necessary to subtract the number of rainy days in the green period of the year [42]. Statistical analysis of the monthly average rainfall days in Shanghai from 1961 to 2015 [43] shows that the annual rainfall days are 145.72 days, the number of days without rainfall is 220.28 days, and the number of days without rainfall outside winter is 159.29 days. The number of rainy days is 220.28 days. When calculating the annual carbon sequestration of deciduous vegetation, it is calculated as 159.29 days without rain in winter.

Table 3. Comparisons of 3DGQ and annual CSB per year per tree of 15 tree species.

No.	$W_{d(CO_2)}$ $(g{\cdot}m^{-2}{\cdot}d^{-1})$	S_{TLA} (m^2)	3DGQ (m^3)			C_{ApT} (kg)			
			V_{agm}	V_{pcchs}	V_{pc}	TLA	*AGM*	*PCCHS*	*PC*
N_1	13.17 [44]	143.74	136.53	80.33	15.36	417.01	662.17	389.60	74.50
N_2	8.37 [44]	364.92	429.23	301.11	96.08	486.53	1124.58	788.91	251.73
N_3	4.12 [44]	17.77	11.37	6.22	2.56	16.13	55.14	30.17	12.42
N_4	1.80 [45]	122.52	58.22	47.18	30.01	48.58	282.37	228.82	145.55
N_5	6.54 [44]	35.08	27.19	18.14	4.47	50.54	131.87	87.98	21.68
N_6	8.61 [44]	53.13	42.64	21.17	10.12	72.86	111.72	55.47	26.51
N_7	4.18 [46]	251.41	264.19	21.69	10.43	167.40	692.18	56.83	27.33
N_8	13.90 [47]	334.44	141.59	8.70	7.71	740.49	370.97	22.79	20.20
N_9	2.91 [48]	183.03	180.36	49.36	12.21	84.84	472.54	129.32	31.99
N_{10}	21.52 [48]	228.17	229.13	12.04	3.95	782.15	600.32	31.54	10.35
N_{11}	12.06 [49]	175.97	128.73	10.75	5.89	338.05	337.27	28.17	15.43
N_{12}	13.10 [50]	414.72	250.41	222.84	128.24	865.40	656.07	583.84	335.99
N_{13}	10.69 [51]	150.91	145.34	68.05	20.16	256.97	380.79	178.29	52.82
N_{14}	12.37 [46]	13.49	5.46	3.31	1.26	26.58	14.305	8.67	3.30
N_{15}	11.92 [50]	15.51	3.98	2.25	0.75	40.72	19.30	10.91	3.64

For each species, each calculated value in S_{TLA}, 3DGQ, and C_{ApT} in this table was given by the mean of 30 trees.

2.4.1. Annual CSB per Tree in TLA Method

We adopt different methods when calculating the annual CSB, C_{ApT} (kg), of evergreen tree and deciduous tree:

$$C_{ApT} \text{ of evergreen tree (kg)} = W_{d(CO_2)} \cdot S_{TLA}\ 220.27/1000 \tag{7}$$

$$C_{ApT} \text{ of deciduous tree (kg)} = W_{d(CO_2)}\ S_{TLA}\ 159.29/1000 \tag{8}$$

2.4.2. Annual CSB per Tree in 3DGQ Method

In this paper, the calculation of annual CSB of an individual tree uses the 3DGQ which is given by Jianhua Zhou et al. [29]:

$$C_{ApT} \text{ of evergreen tree (kg)} = 4.85\ V_{3DGQ} \tag{9}$$

$$C_{ApT} \text{ of deciduous tree (kg)} = 2.62\ V_{3DGQ} \tag{10}$$

where V_{3DGQ} could be V_{agm}, V_{pcchs}, and V_{pc} when using AGM, PCCHS, and PC methods, respectively.

2.4.3. The CSB in LAI Method

The LAI method is usually used to evaluate the daily CSB per unit land area. This is important when evaluating the CSB of a widely forest. In this paper, we take the single tree as an example; thus, the calculation would be the daily CSB of single tree per unit land area, Q_{CO_2} ($\text{g}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$). Additionally, it is given by

$$Q_{CO_2} = I_{LA} \cdot W_{d(CO_2)} \tag{11}$$

Then, the CSB of the tree per year (kg) is given by

$$\begin{aligned} C_{ApT} \text{ of evergreen tree (kg)} &= Q_{CO_2} \cdot S_{PA} \cdot 220.27/1000 \\ &= W_{d(CO_2)} \cdot S_{TLA} \cdot 220.27/1000 \end{aligned} \tag{12}$$

$$\begin{aligned} C_{ApT} \text{ of deciduous tree (kg)} &= Q_{CO_2} \cdot S_{PA}\ 159.29/1000 \\ &= W_{d(CO_2)} \cdot S_{TLA} \cdot 159.29/1000 \end{aligned} \tag{13}$$

Equations (12) and (13) are the same as Equations (7) and (8). This is because the LAI is given by Equation (4). Thus, in the following, we will only present the CSB in TLA case because the TLA and LAI has the same calculations.

3. Results and Discussions

3.1. Comparisons of Different 3DGQ Calculation Methods

The comparisons of 3DGQ between different calculation methods are presented in Table 3 and Figure 3. It is clearly shown that the calculation result of AGM is larger than that of the other two methods. For those trees whose crowns are irregular, the calculation result of the AGM method (V_{agm}) is significantly higher than that of the PCCHS method (V_{pcchs}) and the PC method (V_{pc}). For example, for robinia pseudoacacia, populusL., salix babylonica, and populus × canadensis moench, the V_{agm} is as high as 1097–1803% than V_{pcchs}. For platanus and cedrus deodara whose shapes are more regular than the aforementioned four tree species, their V_{agm} is 23.40% and 42.55% higher than V_{pcchs}, respectively. For those species' trees with large gaps between branches and leaves, such as salix babylonica, cinnamomum camphora, the V_{pcchs} is 305.82% and 422.98% higher than V_{pc}, respectively. For those trees with small gaps between branches and leaves, such as populusL. and cedrus deodara, the V_{pcchs} is 12.84% and 57.21% higher than V_{pc}, respectively.

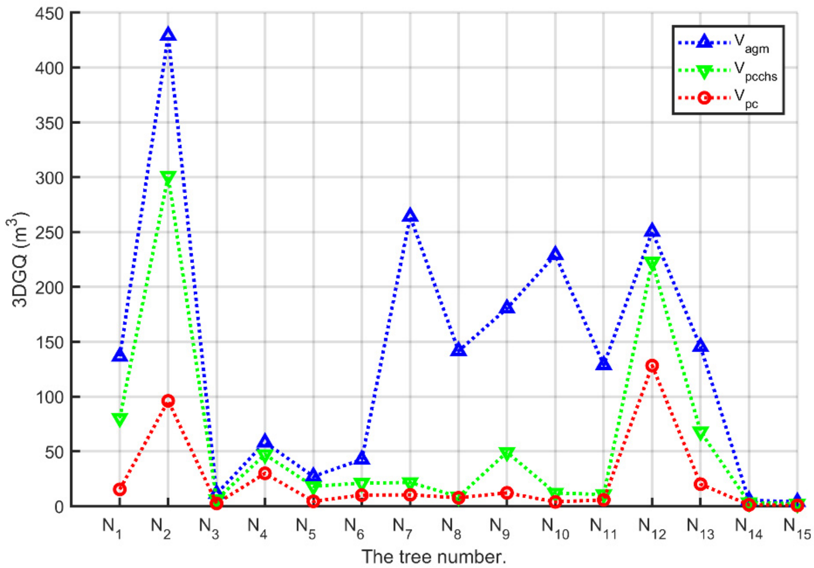

Figure 3. Comparisons of 3DGQ calculation methods, AGM, PCCHS, and PC methods.

Compared with the AGM method, the PCCHS method and the PC method significantly improve the calculation accuracy of the 3DGQ. For tree species with regular shapes and small gaps between branches and leaves, the 3DGQ of the AGM method is within a reasonable range. Due to its advantages of simple calculation and easy data acquisition, it is still a commonly used method at present. For plants with large gaps between them, the 3DGQ of the AGM method is quite different from the actual value, thus, it is not applicable to use this method when there requires a higher accuracy. The PCCHS method and PC method present higher accuracy than AGM method. However, it is usually used in single tree or small-scale field because it takes long time to scan thousands of trees and not applicable to the large-scale field.

3.2. Comparisons of Annual Carbon Sequestration Benefits

In this paper, we calculate the annual carbon sequestration benefits through the 3DGQ and the TLA, as presented in Table 3 and Figure 4. The calculation of these methods is quite different for the same species and the same trees. The TLA method and the AGM method are close to each other, and the deviation ranges from −82.80% to 110.98%. They both have large difference from the PCCHS method and the PC method with the deviation ranges from −82.05% to 3149.19%, and from −66.62% to 7547.00%, respectively. The results show that the overall calculation results of CSB are high. This is because, in the literature, carbon sequestration benefits of trees are rough summarized into two categories: evergreen trees and deciduous trees. It ignores the differences between different species in the same evergreen trees or in the same deciduous trees. There is still a lot of room for improvement in the annual evaluation of CSB through 3DGQ. At present, using 3DGQ to evaluate the ecological benefits is an indirect method, the quantitative relationship between the 3DGQ, the LA, and the LAI needs further optimization.

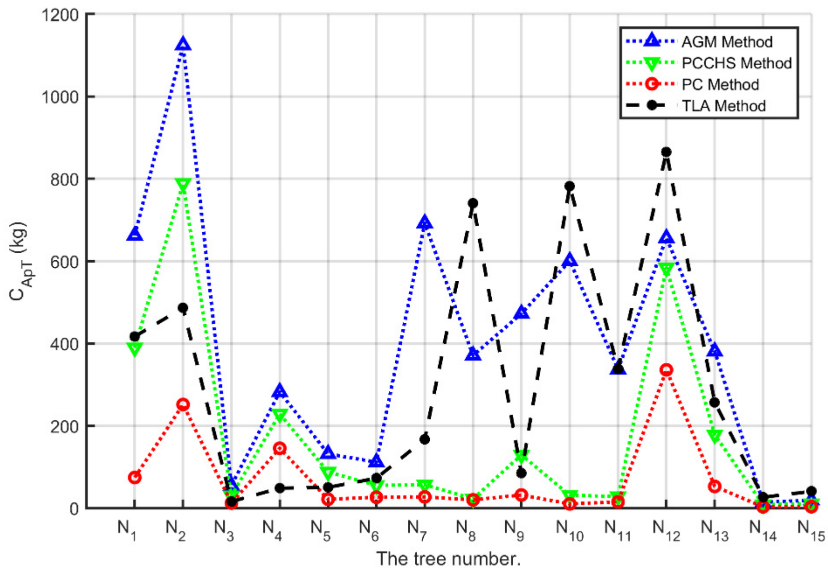

Figure 4. Comparisons of annual carbon sequestration benefits in different methods, AGM method, PCCHS method, PC method, and LA method.

3.3. Discussions

The calculated values in Table 3, V_{agm}, V_{pcchs}, V_{pc}, and C_{ApT} (TLA, AGM, PCCHS, PC) are all estimated values, the actual value of the 3DGQ of the crown and the annual CSB of the tree are unknown. From the analysis in Section 3.2, it can be seen that the estimated value is the upper bound of the actual value. This paper compares the estimation between different calculation methods by finding the lowest upper bound value of the theoretical model. The cause of the error between the estimated value and the actual value are diverse, such as measurement tools, measurement methods, data processing methods, and models, model parameters and so on. The estimation methods mentioned in this paper are precisely by continuously improving these multivariate parameters, thereby improving the evaluation accuracy of the 3DGQ and the annual CSB.

Indeed, all of these three methods have room for improvement. For example, the estimation accuracy of the AGM method can be further enhanced through eliminating part of the stem-leaf gap. Additionally, the estimation accuracy of PCCHS method and the PC method can be further enhanced through using the UAV employed the scanner to scan the top of the crown.

4. Conclusions

The proposal of 3DGQ and the research on its calculation method represent a new direction of quantitative research on urban space. The 3DGQ not only helps to estimate the environmental benefits of greening, but also helps to analyze the rationality of urban green space layout through the estimation of this benefit and provides an important technical basis for garden planning and even the planning of the whole city. There have been many progresses in the field of accurate measurement of the 3DGQ of an individual tree and the evaluation of the 3DGQ of a given scale in a city. With the introduction of new technologies such as UAV oblique photography technology, vehicle mobile measurement technology, image processing, and intelligent identification technology, the acquisition of morphological characteristic data such as 3DGQ is getting faster, more accurate, and more efficient.

However, studies on the correlation between urban 3DGQ and ecosystem services such as urban green space carbon sequestration are still rare. The existing evaluation of carbon sequestration based on 3DGQ has large errors and many limitations. This may be due to the fact that urban remote sensing satellite data is easier to obtain, and the technology of inversion of leaf area index from satellite images is relatively mature, and domestic and foreign research are more inclined to the research on the correlation between leaf area index and urban carbon sequestration. However, the LAI method cannot reflect the plant configuration and community characteristics of urban green space, and it is prone to large deviations in the study of ecological and environmental benefits such as carbon sequestration in urban green space. Therefore, it is necessary to further study the relationship between the 3DGQ and the TLA and LAI and establish an evaluation system for ecosystem services such as carbon sequestration based on the 3DGQ to improve the evaluation accuracy of urban ecosystem services.

The carbon sequestration ability of plants is affected by their own physiological characteristics and natural environment conditions, and there are significant differences in the carbon sequestration ability of different types of plants in different spaces. Studying the ecosystem service functions such as carbon sequestration brought about by the spatial configuration of different types of plants can provide a scientific basis for the planning and design of urban green space.

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