THREE-DIMENSIONAL GREEN BIOMASS ESTIMATION OF PARK VEGETATION AND ITS ECOLOGICAL BENEFIT VALUE ASSESSMENT IN NANPING CITY, CHINA

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Abstract. Three-dimensional green biomass can indicate the benefits of urban ecosystems. Sixty representative plant communities (20 m × 20 m) in seven parks were selected as sample plots in Nanping City, China. The structural characteristics, three-dimensional green biomass per square meter (PGB), and ecological benefit value of the plant communities in each plot were measured. The results showed that the PGB of Jiufengshan Park was the highest, reaching 5.60 $m^3 \cdot m^{-2}$. The Random forest model revealed that the coverage, diameter at breast height (DBH), and tree number had a highly significant effect on PGB ($P < 0.01$), and tree crown width had a significant effect on the PGB ($P < 0.05$). Therefore, the PGB of parks can be improved by improving the coverage, DBH, tree number, and tree crown width, which would help to increase the ecological benefit value and well-being of human beings.
Keywords: *green volume, ecological benefit, urban forest, random forest, plant communities*

Introduction

In recent years, ecological problems such as atmospheric pollution and the greenhouse effect brought by urban industrial development have become more and more serious, causing great harm to the environment and human health. Urban green space has an important role in dust removal, humidification, and cooling, it is responsible for promoting humans and nature to live in harmony by regulating the physical and mental health of urban residents and landscaping the city's image (Carrus et al., 2015; Li et al., 2022; Wang et al., 2024). Two-dimensional indicators (percentage of greenery coverage and greening rate) measure the amount of greenness of urban vegetation in China. Three-dimensional greenness is the sum of the biomass of trees, shrubs, and grass layers of plant communities, which can accurately measure the relationship between plant green volume and environmental benefits, and plays an important role in urban forest planning and design (He et al., 2013; Chi et al., 2022; Sun et al., 2022). Researchers and scholars have argued that three-dimensional green biomass used to characterize urban vegetation greenness is significantly better than two-dimensional indicators, and that three-dimensional spatial structure can more accurately assess vegetation greenness than two-dimensional indicators (Qiu et al., 2017). Some scholars have used remote sensing imagery or LiDAR to estimate the three-dimensional green biomass of vegetation (Anderson et al., 2018; Zheng et al., 2021), but it is difficult to accurately assess the complex vegetation patches in urban areas (Zheng et al., 2016, 2018a). Other scholars estimated the total three-dimensional green volume

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according to the geometry of crown shape in plant communities, which makes up for the lack of two-dimensional quantification of remote sensing satellites. Compared with LiDAR measurements, this method has a lower workload, fewer requirements on the measuring device, and can quickly determine the ecological benefits of three-dimensional green volume; It is a highly practical and innovative tool (Liu et al., 2008; Zheng et al., 2018b). The influencing factors of three-dimensional green volume per square meter (PGB) are still controversial (Zheng et al., 2018a; Su et al., 2020; Wang et al., 2023). The current study will reveal the influencing factors of PGB, which will help to improve the ecological efficiency of urban parks.

Plant communities which are basic components of vegetation can effectively characterize the ecological benefits of vegetation (Zheng et al., 2022). The three-dimensional green volume was estimated by the crown morphology of plant communities, and its ecological service capacity and ecological benefit value were assessed to provide a basis for the scientific management of urban green space (Li and Xie, 2012; Zheng et al., 2018b; Li et al., 2022). The three-dimensional green volume is closely related to air quality (Shi et al., 2023) and plays an important role in mitigating the urban heat island effect (Qiu et al., 2017). Three-dimensional green biomass can also alleviate the thermal discomfort index of urban residents (Bao et al., 2022). Previous studies related to three-dimensional green biomass have mainly focused on urban parks (Su et al., 2020), nursing homes (Wang et al., 2013), and so on. However, less literature has focused on the three-dimensional green volume of mountain parks and the ecological benefits they generate. Nanping is a city in China with high forest coverage, ecological benefits and various types of parks. This study was carried out with urban green space in Nanping City as the research object. Seven parks in Yanping District of Nanping City were selected as sample sites to determine the three-dimensional green biomass of typical plant communities in the parks, to reveal the influencing factors of the PGB, and to provide scientific suggestions for the enhancement of the three-dimensional green biomass of park vegetation and the construction of a green and ecological smart city.

Materials and method

Study area and study design

Nanping is situated in Fujian, China, at coordinates ranging from 117°00′ to119°25′ E, and 26°30′ to28°20′ N, with the terrain dominated by hills and mountains (*Fig. 1*). It has a humid monsoon climate in the central subtropics, with an average annual temperature of 18.1~20.8°C, and an annual rainfall of 1960.4 mm; Nanping City is rich in forest resources and is an important forest area in southern China. The area of forest land is 21,684 km^2, with a forest coverage rate of 78.89% (Nanping City Annals compilation Committee, 2004).

According to geographic location and park area, seven representative parks were selected as the sample site (*Table 1*). Each sample plot is 20 m × 20 m in size. The number of sample plots selected was based on a number of selection principles, i.e., species in the community with high climatic adaptation, plant applied with high frequency, and community with local distinctiveness. On the basis of investigation of the entire park, representative and stable artificial plant communities are selected along the visiting routes of the park. A total of 60 sample plots in seven parks were surveyed. The sampling sites and habitats can be seen in *Figure 2*.

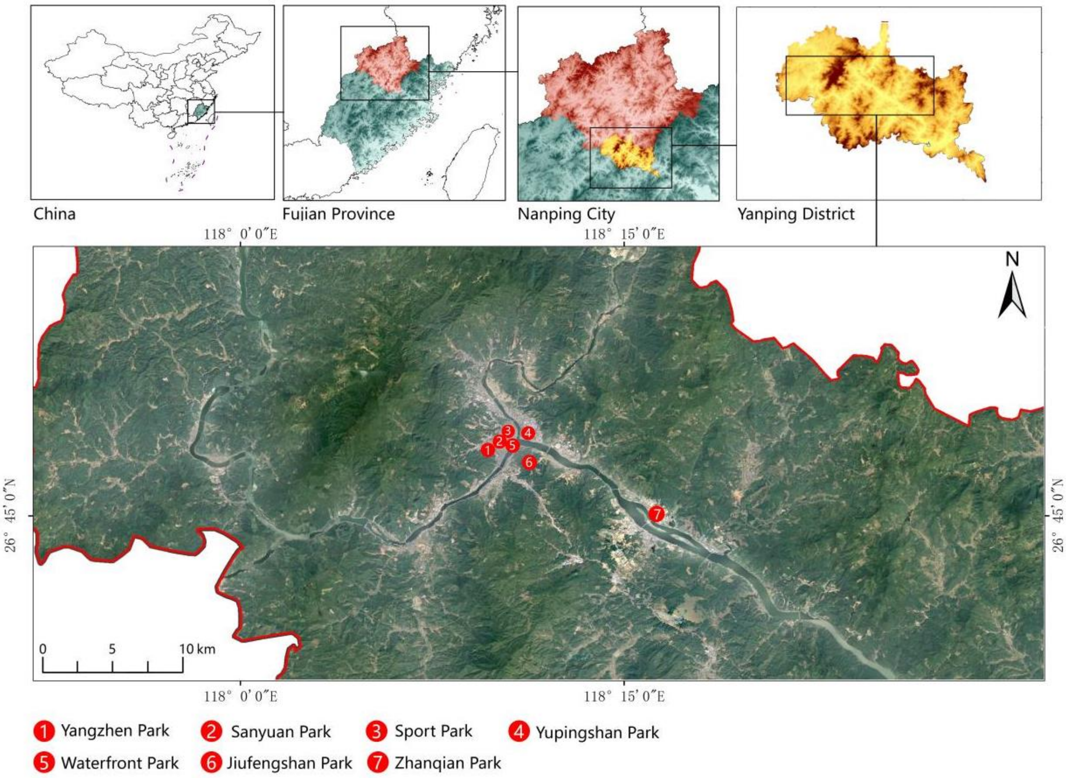

Figure 1. *Distribution of sample site in Nanping City, China*

Table 1. *Description of the park and sample plot setting*

Park name	Park area/hm²	Longitude	Latitude	Sampling quantity	Sampling area/m²
Jiufengshan Park	107.44	118°11’0″	26°37’34″	20	8000
Yupingshan Park	40.31	118°11’28″	26°38’36″	10	4000
Waterfront Park	6.19	118°11’11″	26°38’24″	8	3200
Sanyuan Park	3.02	118°10’23″	26°38’5″	8	3200
Yangzhen Park	0.93	118°10’4″	26°37’59″	6	2400
Sport Park	0.49	118°10’18″	26°38’45″	4	1600
Zhanqian Park	0.52	118°10’39″	26°37’23″	4	1600

Figure 2. *Sampling sites and habitats. (a) Zhanqian Park; (b) Sanyuan Park; (c) Yupingshan Park*

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The characteristics of plant community measurements

The investigation of plant community characteristics was conducted in July-August 2023. A stratified sampling method was conducted to record species names in different layers (tree, shrub, grass) in the sample plots. The structural characteristics are shown in *Figure 3*. The structural characteristics of plant communities which include tree number, height, diameter at breast height (DBH), tree crown width, and tree crown height were determined by Leica Laser Rangefinder D81 (Leica-DISTO D5, Switzerland) and tape measure. The tree height, tree crown width, DBH means the average number, height, crown width, and DBH of tree layer in sample plots. The shrub height and shrub crown width mean average shrub number, height, and shrub crown width of shrub layer in sample plots. The coverage was calculated by the photogrammetric method (Fan et al., 2021).

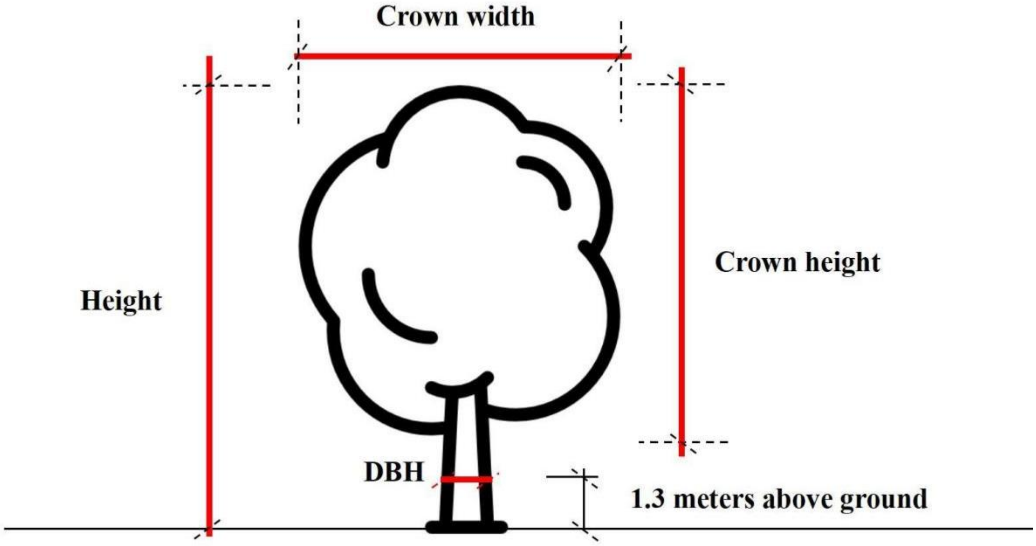

Figure 3. *Diagram of the structural characteristics*

The layer was delineated according to the complexity of the plant hierarchy with the number of complex layers for a single tree, shrub, or herb layer being 1, the number of complex layers for an arboreal-shrub structure being 2, and the number of complex layers for an arboreal-shrub-grass structure being 3. The ratio is the ratio of the number of trees to the number of shrubs. The layer and ratio were performed as described in Zheng et al.(2018a). Berger-Parker dominance index, Margalef richness index, Simpson diversity index, Shannon diversity index, and Pielou evenness index were selected to assess community diversity, and these indexes were calculated according to Greig-Smith (1983).

Three-dimensional green biomass measurements

The estimation of three-dimensional green biomass is based on the geometric form of the green tissue of the plant community. The total three-dimensional green biomass was the sum of the green volumes of trees, shrubs, and grass layers in the sample plot (Zheng et al., 2018a). The three-dimensional green biomass of tree species was based on the estimation of tree the crown geometry (see *Table 2*), and the formulae of different crown types were described by Zhou et al. (2001). The three-dimensional

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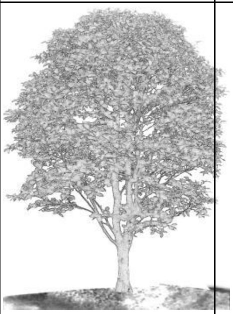
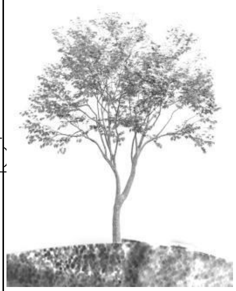
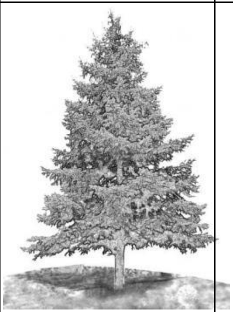
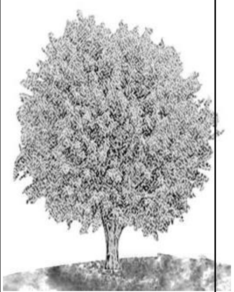
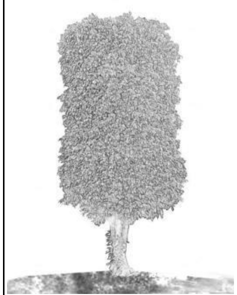
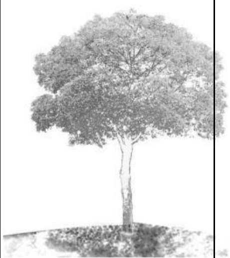
green biomass of the shrub and herb layers was estimated based on the product of the projected area and height of the plants.

Table 2. *Three-dimensional green biomass calculation formula*

No	Crown shape	Formulas	Diagram	No	Crown shape	Formulas	Diagram
1	Oval	$\frac{\pi x^2 y}{6}$	 Case: *Casuarina equisetifolia*	5	Spherical sector	$\frac{\pi(2y^3 - 2y^2\sqrt{4y^2 - x^2})}{6}$	 Case: *Koelreuteria paniculata*
2	Cone	$\frac{\pi x^2 y}{12}$	 Case: *Chamaecyparis hodginsii*	6	Spherical cap	$\frac{\pi(3xy^2 - 2y^3)}{6}$	 Case: *Osmanthus fragrans*
3	Sphere	$\frac{\pi x^2 y}{6}$	 Case: *Cinnamomum bodinieri*	7	Cylinder	$\frac{\pi x^2 y}{4}$	 Case: *Juniperus chinensis*
4	Semisphere	$\frac{\pi x^2 y}{6}$	 Case: *Schima superba*				

x means tree crown width; y means tree crown height

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The ecological benefit value of three-dimensional green biomass determination

The vegetation was divided into evergreen and deciduous according to the vegetation type. The amount of O_2 release, CO_2 sequestration, SO_2 absorption amount, dust absorption amount, and summer transpiration humidifying amount (STHA) were calculated according to Dong et al. (2019). The cost release amount and CO_2 sequestration amount were calculated concerning the 'China Biodiversity National Situation Research Report' (The Writing Group of the National Research Report on Biodiversity in China, 1998). The costs of SO_2 absorption amount, dust absorption amount, and summer transpiration humidifying amount were calculated concerning the 'Specifications for assessment of forest ecosystem services' (Ecology and Nature Conservation Institute, 2008). The ecological benefit value can be seen in *Table 3*. Due to the lack of data, SO_2 absorption capacity, dust absorption amount, and STHA were converted using the data of mixed coniferous and broad-leaved forests.

Table 3. *Ecological benefit value*

Item	O_2 release amount ($kg \cdot m^{-3}$)	CO_2 sequestration amount ($kg \cdot m^{-3}$)	SO_2 absorption capacity ($kg \cdot m^{-3}$)	Dust absorption amount ($kg \cdot m^{-3}$)	STHA ($kg \cdot m^{-3}$)
Evergreen plant	3.52	4.85	3.03	1.10	0.55
Deciduous plant	1.90	2.62	3.03	1.10	0.55
Cost/$CNY \cdot kg^{-1}$	0.3697	0.2733	1.2	0.15	0.0016

Data analysis

Nonparametric tests were used to analyze the difference in plant community structural features, three-dimensional green biomass, and ecological benefit values among parks. Pearson's correlation was used to analyze the correlation between community structural characteristics and PGB, and correlation coefficient $r < 0.2$ and P values > 0.05 were excluded. The statistics were performed on the R 4.2.2 with RandomForest package, rfPermute package, EasyStat package, and ggplot2 package.

Results

Structural characterization of the plant community and three-dimensional green biomass

Twenty typical plant communities were screened in the seven parks (see *Table 4*). The layer of plant communities is mainly a tree-shrub-grass structure. Some of the plant communities in Jiufengshan Park, Yupingshan Park, and Sanyuan Park were constructed as semi-natural plant communities mixed with natural plants. The composition of the plant communities in other parks has more ornamental plants for greening.

The PGB ranged from 0.697 $m^3 \cdot m^{-2}$ ~ 6.954 $m^3 \cdot m^{-2}$, the coverage from 41.89% to 88.95%, the tree height ranged from 5 m ~ 15.19 m, and the number of layers ranged from 2 to 3 layers (*Fig. 4*). There are no significant differences in shrub width, shrub height, and layers among parks ($P > 0.05$). Coverage and PGB were 83.62% and 5.60 $m^3 \cdot m^{-2}$, respectively, which were significantly greater ($P < 0.05$) in Jiufengshan

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Park than the other parks. The DBH in Jiufengshan Park, Sanyuan Park, Yangzhen Park, and Yupingshan Park was significantly higher than that in the other parks ($P < 0.05$).

The Berger-Parker dominance index ranged from 1.0 to 5.0, the Margalef species richness index ranged from 0 to 2.15, the Simpson diversity index ranged from 0 to 0.89, the Shannon-Wiener diversity index ranged from 0 to 2.19, and the Pielou evenness index ranged from 0 to 1.0 (*Fig. 5*). When the Margalef richness index, Simpson diversity index, Shannon-Wiener diversity index, and Pielou evenness index were 0, indicating that the species composition of the plant community was only one species.

Correlation analysis

There was a highly significant correlation between tree height, tree crown width, tree number, and coverage with PGB ($r = 0.35, 0.29, 0.55, 0.92$, $P < 0.01$, see *Fig. 6*). There was a highly significant positive correlation between tree crown width and DBH with tree height ($r = 0.53, 0.51$, $P < 0.01$). Shrub crown width was significantly and positively correlated with shrub number ($r = 0.56$, $P < 0.05$).

Table 4. *Typical plant community patterns*

No	Community composition	Layer	Park name
1	*Liquidambar formosana**, *Schima superba, Michelia maudiae, Cycas revoluta, Rhododendron simsii, Philodenron selloum*	Tree-shrub-grass	Jiufengshan Park
2	*Casuarina equisetifolia**, *Koelreuteria paniculata**, *Lagerstroemia indica, Camellia japonica*	Tree-shrub-grass	Jiufengshan Park
3	*Phyllostachys edulis**, *Osmanthus fragrans**, *Ligustrum lucidum, Excoecaria cochinchinensis, Bougainvillea glabra, Ligustrum sinense*	Tree-shrub-grass	Jiufengshan Park
4	*Pinus massoniana**, *Schima superba, Chamaecyparis hodginsii, Callicarpa bodinieri, Pseudocydonia sinensis**, *Cibotium barometz*	Tree-shrub-grass	Jiufengshan Park
5	*Juniperus chinensis**, *Magnolia denudata**, *Ligustrum sinense, Loropetalum chinense*	Tree-shrub	Jiufengshan Park
6	*Cinnamomum japonicum**, *Juniperus chinensis**, *Pinus massoniana**, *Photinia × fraseri, Ligustrum × vicaryi*	Tree-shrub	Jiufengshan Park
7	*Schima superba**, *Ligustrum lucidum, Loropetalum chinense, Dicranopteris pedata*	Tree-shrub-grass	Jiufengshan Park
8	*Cinnamomum bodinieri**, *Rhododendron simsii, Loropetalum chinense, Zoysia matrella*	Tree-shrub-grass	Yupingshan Park
9	*Dendrocalamopsis oldhami**, *Osmanthus fragrans**, *Ligustrum lucidum, Photinia × fraseri, Rhododendron simsii*	Tree-shrub-grass	Yupingshan Park
10	*Cinnamomum bodinieri**, *Eriobotrya japonica, Indocalamus latifolius*	Tree-grass	Yupingshan Park
11	*Schima superba**, *Cunninghamia lanceolata, Shibataea chinensis, Pteriscretica*	Tree-grass	Sanyuan Park
12	*Dendrocalamopsis oldhami**, *Ficus microcarpa, Osmanthus fragrans, Calliandra haematocepha, Ophiopogon japonicus*	Tree-shrub-grass	Sanyuan Park
13	*Cinnamomum bodinieri**, *Osmanthus fragrans, Zoysia japonica*	Tree-shrub-grass	Yangzhen Park
14	*Cinnamomum bodinieri**, *Lagerstroemia indica, Rhododendron simsii*	Tree-shrub	Yangzhen Park
15	*Ficus microcarpa**, *Loropetalum chinense, Excoecaria cochinchinensis*	Tree-shrub	Waterfront Park
16	*Bauhinia purpurea**, *Osmanthus fragrans, Rhododendron simsii*	Tree-shrub	Waterfront Park
17	*Osmanthus fragrans**, *Phoenix hanceana, Ligustrum quihoui, Zoysia matrella*	Tree-shrub-grass	Zhanqian Park
18	*Trachycarpus fortunei**, *Osmanthus fragrans, Zoysia matrella*	Tree-grass	Zhanqian Park
19	*Osmanthus fragrans**, *Ligustrum quihoui*	Tree-shrub	Sport Park
20	*Trachycarpus fortunei**, *Loropetalum chinense, Ligustrum quihoui*	Tree-shrub	Sport Park

*Indicates dominant species

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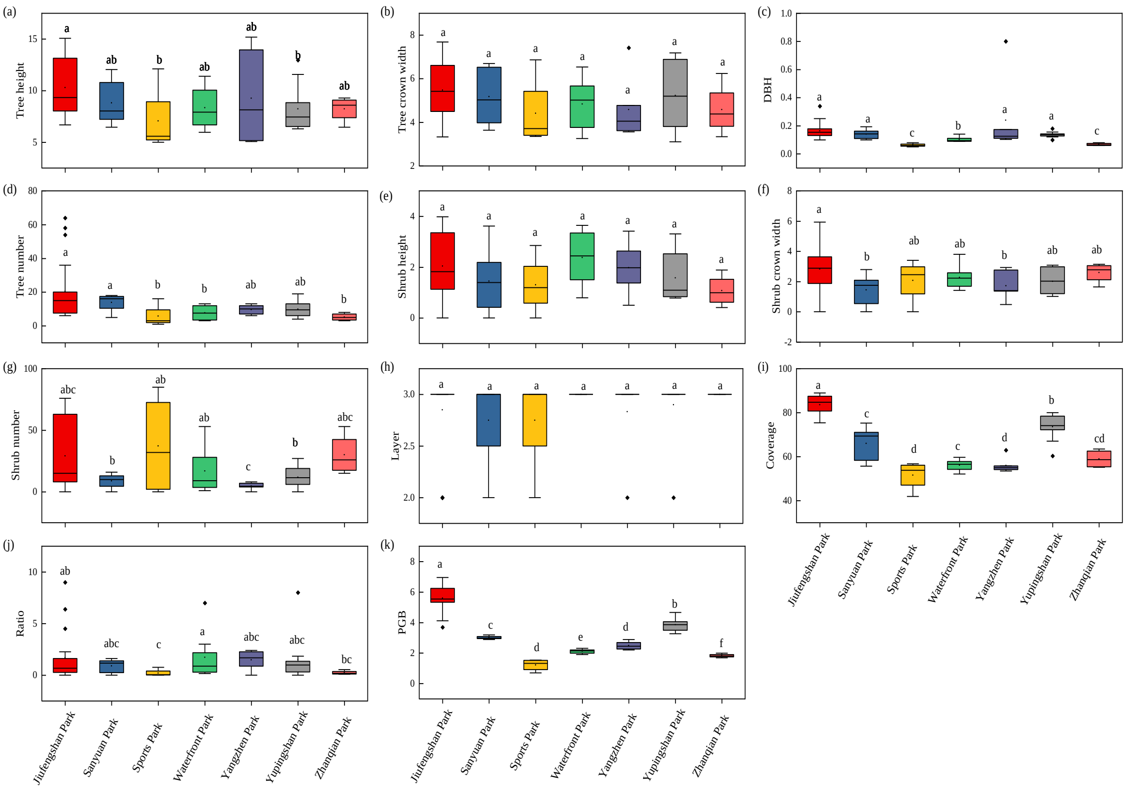

Figure 4. *Structural characteristics of park plant communities. Different letters indicate significant differences between parks (P < 0.05). Tree height: average crown width of trees; tree crown width: average crown width of trees; DBH: diameter at breast height; Shrub height: average crown width of trees; Shrub crown width: average crown width of trees; PGB: three-dimensional green biomass per square meter.*

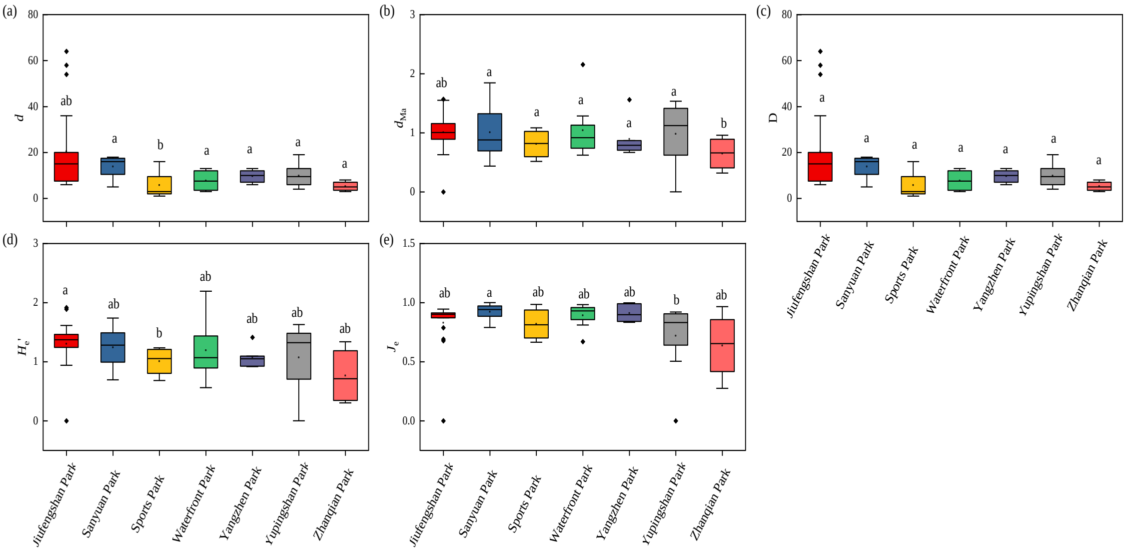

Figure 5. *Species diversity of plant communities. *Different letters indicate significant differences between parks (P < 0.05). d: Berger-Parker dominance index, d_{Ma}: Margalef species richness index, D: Simpson diversity index, H_e': Shannon-Wiener diversity index, J_e: Pielou evenness index*

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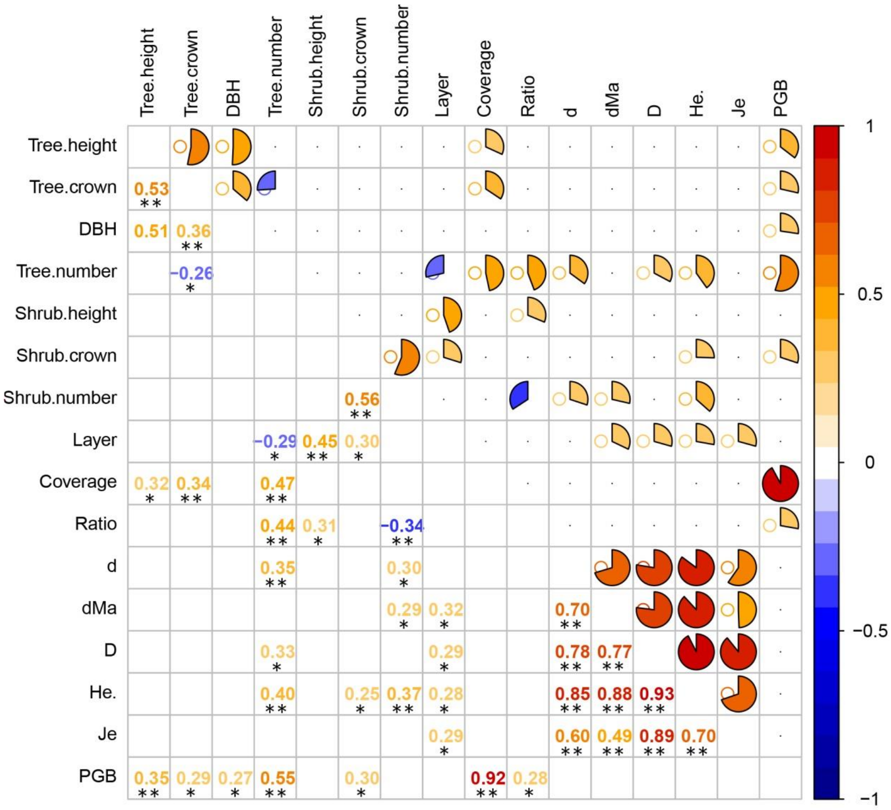

Figure 6. *Pearson correlation analysis between plant community structural characteristics and three-dimensional green biomass. The font color depth indicates the degree of correlation coefficients, where red indicates a positive correlation, and blue indicates a negative correlation. Tree height: average crown width of trees; tree crown width: average crown width of trees; DBH: diameter at breast height; Shrub height: average crown width of trees; Shrub crown width: average crown width of trees; d: Berger-Parker dominance index, d_{Ma}: Margalef species richness index, D: Simpson diversity index, H_e': Shannon-Wiener diversity index, J_e: Pielou evenness index; PGB: three-dimensional green biomass per square meter*

Factors affecting PGB

The 15 variables explained 81.65% of PGB, and the mean of squared residuals was 0.4903, which had a high explanation rate. The coverage, DBH, and tree number had highly significant effects on PGB ($P < 0.01$, *Fig. 7*), and tree crown width had significant effects on PGB ($P < 0.05$).

There was a highly significant relationship between tree number, coverage with PGB ($P < 0.01$, *Fig. 8*), and the DBH and tree crown width were significantly correlated with PGB ($P < 0.05$). With the increase in coverage, DBH, tree number, and tree crown width, PGB showed an increasing trend.

Comparison of ecological benefit values of different parks

CO_2sequestration amount, O_2 release amount, SO_2absorption capacity, dust absorption amount, and summer transpiration humidifying amount (STHA) in Jiufengshan Park are higher than in the other parks ($P < 0.05$, *Fig. 9*), and the ecological benefit value of PGB in Jiufengshan Park was the highest at 35.13 CNY, while the ecological benefit value of PGB in the Sports Park was the lowest at only 7.67 CNY.

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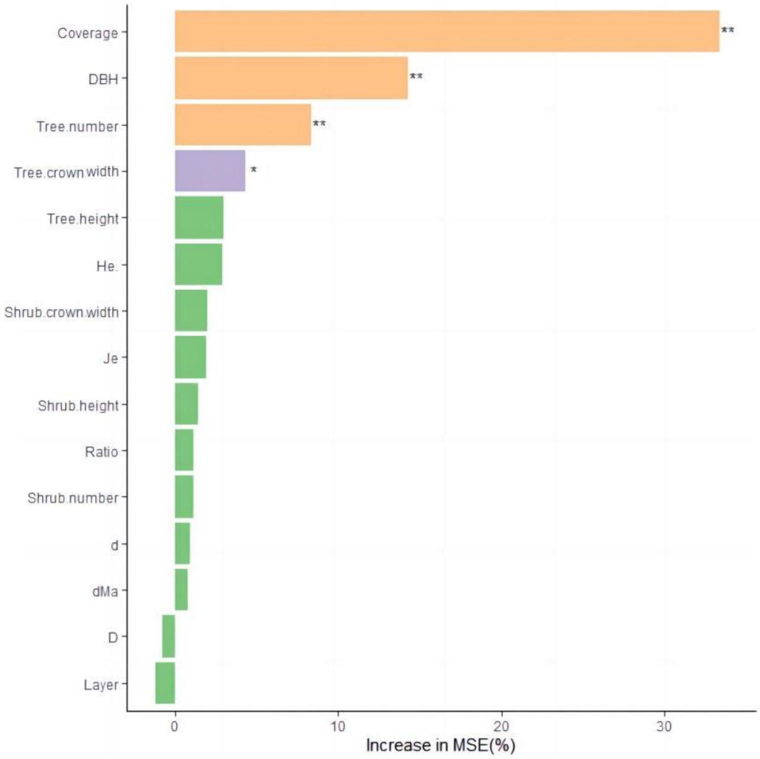

Figure 7. *Ranking of the importance of influencing factors of PGB based on random forest model. *P < 0.05; **P < 0.01. Tree height: average crown width of trees; tree crown width: average crown width of trees; DBH: diameter at breast height; Shrub height: average crown width of trees; Shrub crown width: average crown width of trees; d: Berger-Parker dominance index,* d_{Ma}*: Margalef species richness index, D: Simpson diversity index,* H_e*': Shannon-Wiener diversity index,* J_e*: Pielou evenness index; PGB: three-dimensional green biomass per square meter*

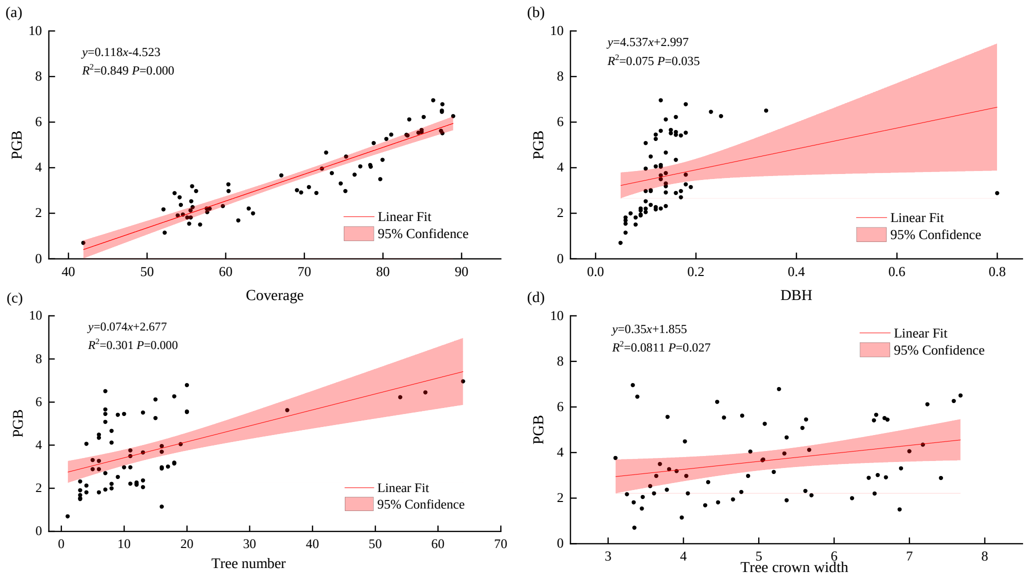

Figure 8. *Regression analysis of coverage, DBH, tree number, and tree crown width with PGB. DBH: diameter at breast height; tree crown width: average crown width of trees. PGB: three-dimensional green biomass per square meter*

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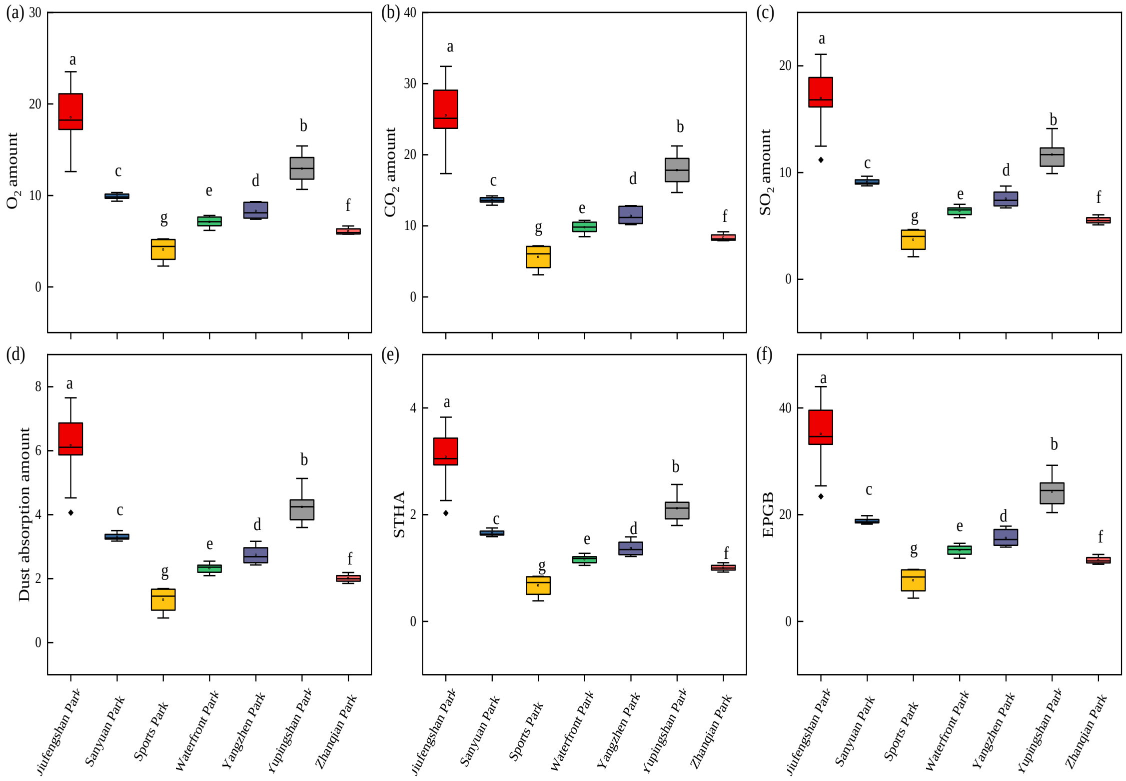

Figure 9. *Comparison of ecological benefit values of different parks. Different letters indicate significant differences between parks (P < 0.05); CO_2 amount: CO_2 sequestration amount; O_2 amount: O_2 released amount; SO_2 amount: SO_2 absorption amount; STHA: Summer transpiration humidifying amount; EBGB: three-dimensional green biomass ecological benefits per unit area*

Discussion

The three-dimensional green biomass of plant communities is closely related to the structure of plant communities (Zheng et al., 2022; Yang et al., 2022; Shi et al., 2023). A higher Increase in MSE (%) in the random forest model indicates that the variable has a higher importance than the dependent variable (Kuhn et al., 2008). Random forest model results showed that the order of importance of the factors that significantly influenced the PGB was coverage, DBH, tree number, and tree crown width (see *Fig. 6*). The tree layer plays a decisive role in the construction of plant communities, and the structural characteristics of the tree layer largely determine the three-dimensional green volume of the plant community.

The differences in species selection and community structure during plant configuration in parks affect the three-dimensional green volume (Chen et al., 2012). In this study, coverage is an important factor affecting PGB, and the conclusions of this current study are consistent with those of previous studies (Zheng et al., 2018a; Su et al., 2020). In addition to coverage, DBH, tree number, and tree crown width did not remain consistent with the findings of previous studies. For example, the tree height and layers played an important role in urban parks in Quanzhou City (Su et al., 2020), the ratio was a determining factor influencing the PGB of mountain parks in Fuzhou City (Zheng et al., 2018a), and the main influences on the PGB of plant communities in Fuzhou City’s beach parks were the crown height of the tree layer, the tree height, DBH

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and the Shannon diversity index (Zheng et al., 2016). The main reasons for the inconsistent findings of influencing factors of PGB were location, park type, species composition, and community configuration.

The PGB is closely related to ecological benefits (Bao et al., 2022). In this study, the PGB of Nanping City Park ranged from 0.697 $m^3 \cdot m^{-2}$~ 6.954 $m^3 \cdot m^{-2}$, with a mean value of 3.64 $m^3 \cdot m^{-2}$. Compared to the previous studies, the PGB of urban parks in Quanzhou City (0.05 ~ 0.54 $m^3 \cdot m^{-2}$) (Su et al., 2020), mountain parks in Fuzhou City (0.41 ~ 4.79 $m^3 \cdot m^{-2}$) (Zheng et al., 2018a), and Shanghai Lingang New City (0.46 $m^3 \cdot m^{-2}$) (Zheng et al., 2021), the PGB of Nanping Park was significantly higher than that of the other study sample sites. However, it was significantly lower than the PGB of 6.51 in the Shanghai Botanical Garden (Luo et al., 2022). On the one hand, it originated from the different urban green space system planning of the cities, Nanping is a mountain city with high native plant coverage and relatively little anthropogenic interference, while other study sites such as Quanzhou City, Fuzhou City, and Shanghai Lingang New City are plain cities with high intensity of anthropogenic activities and relatively low three-dimensional green biomass, and the plant communities in urban parks are rich in diversity, and the types of plant configurations such as sparsely forested meadows and large lawns also reduce the density of three-dimensional greening. On the other hand, there is a significant difference in the three-dimensional green biomass between different park types (Li et al., 2021), and the urban park in this current study is a comprehensive park for the public, which is not the same as the Shanghai Botanical Garden’s specialized park. It can provide a more complete ecological niche for plant communities due to its high intensity of manual management in the Shanghai Botanical Garden. The plant community of the urban park in Nanping City will die due to ecological niche competition (light, water, etc.), and finally form a natural and stable plant community.

The three-dimensional is of great significance to the regulation of urban ecosystems (Dai et al., 2022), and evergreen trees play an important contribution to the ecological benefits of plant communities (Chen et al., 2012). At least 200 m^3 of three-dimensional green biomass (PGB, 0.5 $m^3 \cdot m^{-2}$) in a residential neighborhood is required for a cooling effect. More than 300 m^3 of three-dimensional green biomass (PGB, 0.75 $m^3 \cdot m^{-2}$) can have a maximized climate-regulating effect (Li et al., 2011). When PGB ranges from 4-6 m^3, green biomass can maximize human thermal comfort (Bao et al., 2022). The mean value of PGB in parks in Nanping City is 3.64 m^3, and the ecological benefit value is 22.88 CNY, which can provide a strong ecological benefit value. Estimating the ecological benefit value of three-dimensional green volume can effectively measure the ecological benefit of urban park vegetation and provide a scientific basis for plant configuration.

Conclusion

The three-dimensional is of great significance to the regulation of urban ecosystems. The results showed that the PGB of Jiufengshan Park was the highest, reaching 5.60 $m^3 \cdot m^{-2}$. The Random forest model revealed that the coverage, diameter at breast height (DBH), and tree number had a highly significant effect on PGB ($P < 0.01$), and tree crown width had a significant effect on the PGB ($P < 0.05$). Therefore, the PGB of parks can be improved by improving the coverage, DBH, tree number, and tree crown width. Future research should take the light transmission of tree species into account in canopy geometry modeling. This study would help to increase the ecological benefit value and well-being of human beings.

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