iForest
Biogeosciences and Forestry

Research Article
doi: 10.3832/ifor4268-016
vol. 16, pp. 136-143

Evaluation of urban forest spatial distribution characteristics in Guangdong - Hong Kong - Macao Greater Bay Area

Qing Zhao [(1)], Chi Zhang [(1)], Rouxuan Hu [(1)], Wanhui Qian [(1)], Yuhan Wei [(2)]

To understand the health and ecological benefits of scenic recreational forests, we elucidated their spatial distribution characteristics, which can be used to create guidelines and reveal strategic issues regarding the spatial distribution of tree species. We randomly set up 900 m^2 quadrats in scenic recreational forest communities in Guangzhou, Foshan, and Zhuhai, and surveyed each tree using LiDAR. We then calculated the living vegetation volume (LVV) and amount of recreational space on the forest floor (RSFF), and analyzed the differences in spatial distribution characteristics across cities, locations, and forest types. The spatial distribution characteristics of trees differed between different cities, but were similar among different locations and forest types. Urban scenic recreational forest areas are thus configured based on aesthetics, recreational functions, and the spatial distribution characteristics of different tree species. Additionally, the relationship between the tree crown LVV and the RSFF was generally synergistic, yet contradictory. Although an increase in LVV can effectively improve ecological benefits, it may also reduce RSFF and other benefits provided by tree crowns to urban residents.

Keywords: Urban Forests, Living Vegetation Volume, Forest Floor Recreational Space, Spatial Distribution Strategy

Introduction

The urban heat island effect is being exacerbated by the increase in impervious surfaces caused by the rapid expansion of urbanization (Oke 1989, Grimmond & Oke 1999, Müller et al. 2014, Deilami et al. 2018). This is leading to high energy consumption (Santamouris et al. 2001) and changes in the habitats of animals and plants, and is adversely affecting the physiology and psychology of urban residents (Santamouris et al. 2007, Akitt 2018), resulting in psychological anxiety, respiratory and skin diseases, and even death. In particular, the Guangdong – Hong Kong – Macao Greater Bay Area (GBA), located at a low latitude, is frequently exposed to extreme weather events, such as consistently high temperatures, periodic droughts, and floods. According to the latest monitoring data, the average temperature recorded in the months of January, July, and November in 2020 was 23.5 °C, which is 1.0 °C higher than the usual value recorded, marking the highest recorded temperature since 1961 (2021 GBA Climate Bulletin – August 10, 2021). The number of hot days in 2021 was 39.0, 19.6 days more than that recorded in typical years, also marking the highest number of hot days recorded since 1961 (2021 GBA Climate Bulletin – August 10, 2021).

As an important component of green infrastructure (He et al. 2004) and a nature-based solution (Escobedo et al. 2019), urban forests can mitigate the urban heat island effect and reduce ambient temperatures (Bowler et al. 2010, Rahman et al. 2011, Rötzer et al. 2019). Urban forests have aesthetic value, create recreational space on the forest floor (RSFF), and contribute to thermal buffering, shading, and transpiration (Li et al. 2012, Yang et al. 2022). The forest canopy layer is the most direct and dynamic interface between a forest and the external environment (Meng et al. 2007). The canopy structure and its changes have a crucial impact on several ecological factors and processes, such as forest lighting conditions, microclimates, hydrology, nutrient cycles, health, and biodiversity (Zhou et al. 2017, Fu et al. 2021, Zhang et al. 2022). The canopy layer is a complex, three-dimensional spatial structure, and the canopy leaf area index can well reflect the heterogeneity in the spatial structure of urban greening. These structural characteristics objectively reflect the utilization of spatial resources in forests (Huang et al. 2019) and can also be applied to optimize ecological functions, such as the cooling and heat reduction benefits of urban forests (Liu et al. 2013). While the ecological landscape functions of urban forests are manifested through the main canopy, they are also demonstrated through the forest floor structure. Therefore, it is essential to study both the living vegetation volume (LVV) of the tree canopy and the RSFF.

Previous forest canopy research has mainly focused on evaluating the vegetation volume of the urban forest canopy (Dong et al. 2004, Zheng et al. 2016, 2018, Casalegno et al. 2017), studying the differences in the light environment (Huang et al. 2019, Xu et al. 2019) and the microclimate differences (Zhao et al. 2012, Shen et al. 2017, Liu et al. 2020, Gao et al. 2021) between the canopy and understory, among others. However, relatively few studies have examined the relationship between the canopy structure and the RSFF. There-

(1) Guangdong Academy of Forestry, Guangdong Provincial Key Laboratory of Silviculture Protection and Utilization, Guangzhou 510520 (China); (2) Guangdong Lingnanyuan Exploration and Design Co., Ltd., Guangzhou 510663 (China)

@ Qing Zhao (22306040@qq.com)

Received: Nov 19, 2022 - Accepted: Feb 26, 2023

Citation: Zhao Q, Zhang C, Hu R, Qian W, Wei Y (2023). Evaluation of urban forest spatial distribution characteristics in Guangdong - Hong Kong - Macao Greater Bay Area. iForest 16: 136-143. – doi: 10.3832/ifor4268-016 [online 2023-05-16]

Communicated by: Raffaele Lafortezza

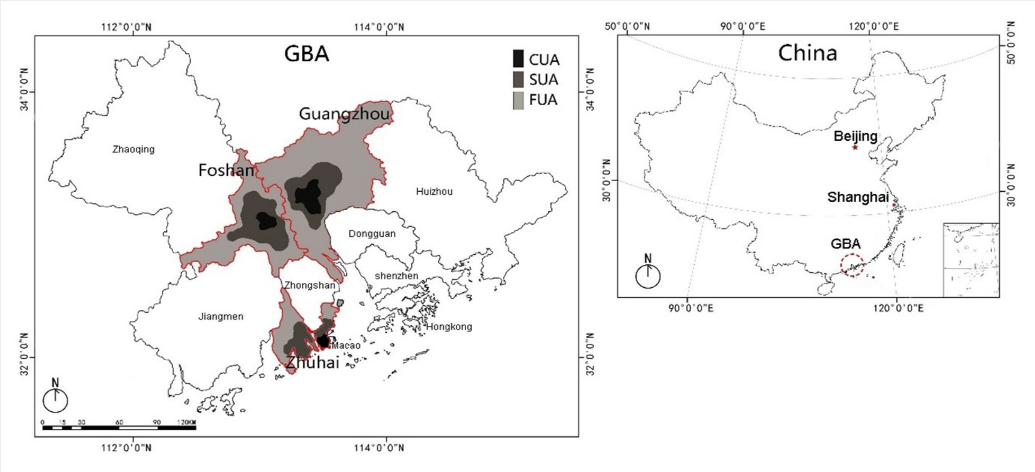

Fig. 1 - Schematic illustration of location of the study areas. The core urban area (CUA), semi urban area (SUA), and urban fringe area (UFA) of Guangzhou, Foshan, and Zhuhai are represented by black, dark gray, and light gray colors, respectively.

fore, in this study, we focused on urban forest communities. We quantified the relationship between the LVV and RSFF for different forest types in the core urban areas (CUA), semi-urban areas (SUA), and urban fringe areas (UFA) of three cities (Guangzhou, Foshan, and Zhuhai) and optimized the spatial distribution of trees in urban forests to guide the effective development of ecological service functions. This was achieved by addressing three main research questions: (i) What are the spatial distribution characteristics of different tree species in urban forests? (ii) What are the spatial distribution characteristics of urban forests in different cities, locations, and forest types? (iii) How can the spatial distribution strategy be optimized according to the characteristics of different tree species to obtain more ecological benefits?

Materials and methods

Study areas

Three cities in the GBA, *i.e.*, Guangzhou, Foshan, and Zhuhai, were selected as the study areas (Fig. 1). Guangzhou City (22° 26′ - 23° 56′ N, 112° 57′ - 114° 03′ E), located in the south-central part of Guangdong Province and the north-central edge of the Pearl River Delta, is large and located at the confluence of three rivers, the Xijiang, Beijiang, and Dongjiang. It has a subtropical monsoon climate characterized by warm weather and rain, abundant sunshine, long summers, and short winters. The annual average temperature is 21.9 °C, having the smallest annual average temperature difference compared with the other two cities studied. Foshan City (22° 38′ - 23° 34′ N, 112° 22′ -113° 23′ E) is located in the south-central part of Guangdong Province, in the hinterland of the Pearl River Delta, adjacent to Guangzhou in the east and Zhongshan in the south. It has a subtropical monsoon climate characterized by a mild climate and abundant rainfall, with an annual average temperature of 23.2 °C. Zhuhai City (21° 48′ - 22° 27′ N, 113° 03′ - 114° 19′ E) is located in the southern part of Guangdong Province on the west bank of the Pearl River Delta, facing Hong Kong across the sea in the east and Macao in the south. It has a subtropical monsoon oceanic climate, with high annual temperatures and abundant rainfall. The average annual temperature is 22.5 °C and the annual average rainfall can reach up to 2061.9 mm.

Sampling method

Each city was divided into CUA, SUA, and UFA based on the distance from the target area to the city center. Using a random sampling method, 100 sample plots (30 × 30 m) were established in each area of the three cities. Most of the selected sample plots primarily included urban forests, and those with mainly buildings, roads, or lakes were excluded. A total of 193 quadrats were studied (Tab. 1). For CUA, 15 plots were located in Guangzhou, 20 in Foshan, and 26 in Zhuhai; for SUA, 25 were in Guangzhou, 40 in Foshan, and 14 in Zhuhai; and for UFA, 20 were in Guangzhou, 20 in Foshan, and 13 in Zhuhai.

Based on the classification principle of forest parks, the quadrats in the forest areas were classified as core or edge forest according to the different distributions of the sample plots. The core forest was further divided into core closed forest and core open woodland (hereafter referred to as closed forest and open woodland), and the edge forest was divided into forest areas close to water bodies and forest areas adjacent to buildings. In the closed forest, the furthest side of the quadrat was more than 50 m away from water bodies or buildings, and the quadrat had a canopy density of more than 0.20. In the open woodland, the furthest side of the quadrat was at a distance greater than 50 m from water bodies or buildings, and the quadrat had a canopy density between 0.10 and 0.19. In the forest areas close to water bodies, the side of the quadrat closest to the water's edge was less than 50 m away from the water body. In the forest area adjacent to buildings, the quadrat closest to the edge of the building was less than 50 m away from the building (Zhao et al. 2020a).

For all species, each tree with a diameter at breast height (DBH) ≥ 5 cm within the opposite quadrat was examined, and a total of 4216 trees were surveyed across the three cities. The species names were recorded and matched with the data obtained using a handheld SLAM-100 LiDAR scanner (see below).

Tab. 1 - City population (million) and area (km²) of Guangzhou, Foshan, and Zhuhai, respectively. The core urban area (CUA), semi urban area (SUA), and urban fringe area (UFA) were classified based on their distances to the city center in each city. The numbers of the sample plots containing urban forests are provided for all specified areas.

Cities	Population (million)	Area (km²)	CUA		SUA		UFA	
			Scope (km)	Plots	Scope (km)	Plots	Scope (km)	Plots
Guangzhou	15.3	7434	< 7	15	7-14	25	> 14	20
Foshan	7.9	3797	< 4	20	4-8	40	> 8	20
Zhuhai	2.0	1711	< 3	26	3-6	14	> 6	13

Index evaluation method

LVV

All samples were scanned using a handheld SLAM-100® LiDAR scanner (Feima, Shenzhen, China) according to the following procedure: (i) after activation, the scanner powered up for 10 s. When the status indicator turned green, the scanner was held in front of the body, directing the laser head upwards, and the area was scanned while walking steadily and slowly around the quadrat. (ii) We set the vertices of four quadrats as the control points, aligned the center of the crosswire of the scanner base with the center of the control point, and oriented the head of the scanner in multiple directions to ensure that the elapsed time was more than 10 s. (iii) We avoided human facial obstructions at the laser emission area and vigorous movement of the scanner during the data collection process.

All data from the laser scans were stored on SD cards and retrieved in the laboratory. The LiDAR360 system (Beijing GreenValley Technology Co., Ltd., Beijing, China) was used for analysis. First, noise was removed from the point cloud, ground points were obtained, and a digital elevation model (DEM) was generated. Using point cloud computing tools to normalize the DEM, high-precision point cloud seed points of the quadrat were generated. The error and interference points in the seed points were deleted using the TLS editor included in the system, and the batch processing function was used to separate all individual trees in the sample plot. After separating all individual trees in the quadrat, their tree height, DBH, crown width, height, projection area, volume, and other data were calculated using the individual tree detection tool included in the system. Thereafter, the above data parameters could be used to calculate the crown volume of a single tree, also referred to as the LVV.

RSFF

The amount of RSFF reflects the size of the space provided by the forest for human movement and recreational use. Based on relevant research (Zhao et al. 2021), we defined the amount of RSFF as the product of the vertical projection area of the tree crown and the clearance under the tree branches (the clearance under the branches higher than 2.2 m). The specific formula is (eqn. 1):

$$V_C = \sum_{i=1}^{n} M_i H_i \qquad (1)$$

where V_C refers to the amount of RSFF (m^3), n refers to the number of trees with a clearance of more than 2.2 m under the branches, M_i is the vertical projection coverage area of the i-th tree's crown (m^2), and H_i refers to the clearance under the branch of the i-th tree (m). The M_i and H_i data were acquired using a handheld SLAM-100 LiDAR scanner.

Spatial distribution characteristics

The LVV and RSFF are the main functions provided by different forest tree species occupying a particular space. We defined the values of the spatial distribution characteristics based on S_A, which is the ratio of the LVV (V_G) to the amount of RSFF (V_C – eqn. 2):

$$S_A = \frac{V_G}{V_C} \qquad (2)$$

where S_A is the value of the spatial distribution characteristic, V_G represents the LVV (m^3), and V_C represents the amount of RSFF (m^3). S_A < 1.0 indicates that the tree species of the forest will tend toward having more RSFF than LVV. S_A < 0.5 indicates that the RSFF has an absolute advantage. S_A between 0.5 and 1.0 shows that RSFF has a slight advantage over the LVV. S_A ≥ 1.0 indicates that the LVV has an advantage over the RSFF. S_A between 0.5 and 3.0 indicates a strong diversity in the spatial distribution of urban forests.

Results

S_A in different cities

S_A was compared by analyzing the top 30 tree species in the study areas of the three cities.

S_A in Guangzhou

As shown in Fig. 2, among the top 30 tree species in urban forests in Guangzhou, the proportion of individual trees with S_A < 1.0 was 78%. This finding indicates that the RSFF was relatively large in the forests of urban parks.

The tree species with S_A ≥ 1.0 included white champaca (*Michelia alba*), African mahogany (*Khaya senegalensis*), council tree (*Ficus altissima*), sea hibiscus (*Hibiscus tiliaceus*), Moluccan albizia (*Albizia falcataria*), sacred fig (*Ficus religiosa*), herba ficus (*Ficus concinna*), and Java apple (*Syzygium samarangense*). This indicates that the LVV of these tree species was more advantageous than their RSFF. However, the S_A of Kashi holly (*Ilex rotunda*), African tulip tree (*Spathodea campanulata*), and camphor tree (*Cinnamomum camphora*) ranged from 0.5 to 3.0, indicating that the spatial distribution of these tree species on the forest floor was diverse.

S_A in Foshan

The proportion of the individual trees among the top 30 tree species in urban forests in Foshan with S_A < 1.0 was 80% (see Fig. S1 in Supplementary material for S_A of different tree species in Foshan). This indicates that the RSFF was relatively large in the urban forest parks.

The tree species with a ratio of S_A > 1.0 included weeping paperbark (*Melaleuca leucadendron*) and Moluccan albizia, indicating that the LVV of these tree species was slightly more advantageous than their RSFF. However, S_A values of African mahogany, council tree, eugenia cumini (*Syzygium hainanense*), bishop wood (*Bischofia javanica*), and herba ficus were generally between 0.5 and 2.0, indicating that the spatial distribution of these tree species on the forest floor was diverse.

S_A in Zhuhai

The proportion of the individual trees among the top 30 tree species in urban forests in Zhuhai with S_A < 1.0 was 94% (see Fig. S2 in Supplementary material for S_A of different tree species in Zhuhai), indicating that most RSFFs were relatively large in urban forest parks.

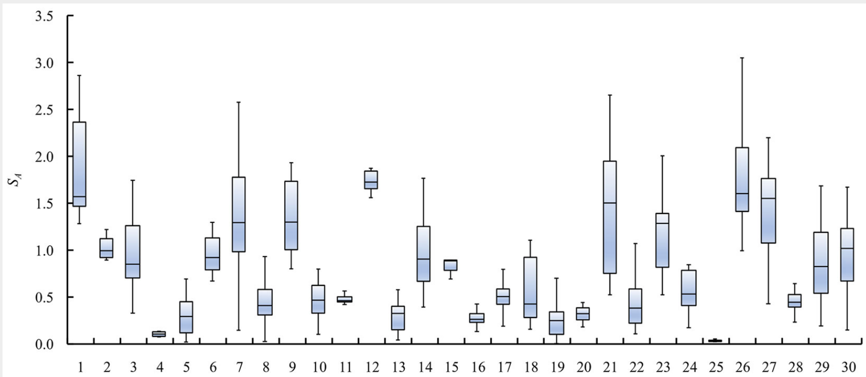

Fig. 2 - S_A of different tree species in Guangzhou. The numbers on the *x*-axis represent tree species: 1, white champaca (*Michelia alba*); 2, tiger's claw (*Erythrina variegata*); 3, giant crepe-myrtle (*Lagerstroemia speciosa*); 4, Cuban royal palm (*Roystonea regia*); 5, earleaf acacia (*Acacia auriculiformis*); 6, Kashi holly (*Ilex rotunda*); 7, African mahogany (*Khaya senegalensis*); 8, royal poinciana (*Delonix regia*); 9, council tree (*Ficus altissima*); 10, Hong Kong orchid tree (*Bauhinia blakeana*); 11, araguaney (*Handroanthus chrysanthus*); 12, sea hibiscus (*Hibiscus tiliaceus*); 13, Changkhen (*Heteropanax fragrans*); 14, African tulip tree (*Spathodea campanulata*); 15, cockspur coral tree (*Erythrina crista-galli*); 16, hairy-fruited elaeocarpus (*Elaeocarpus apiculatus*); 17, golden shower tree (*Cassia fistula*); 18, Indian mahogany (*Chukrasia tabularis*); 19, floss silk tree (*Ceiba speciosa*); 20, cotton tree (*Bombax ceiba*); 21, Moluccan albizia (*Albizia falcataria*); 22, blackboard tree (*Alstonia scholaris*); 23, sacred fig (*Ficus religiosa*); 24, burflower-tree (*Neolamarckia cadamba*); 25, Timor white gum (*Eucalyptus urophylla*); 26, herba ficus (*Ficus concinna*); 27, Java apple (*Syzygium samarangense*); 28, mountain ebony (*Bauhinia variegata*); 29, Indonesian cinnamon (*Cinnamomum burmannii*); and 30, camphor tree (*Cinnamomum camphora*). The numbers on the *y*-axis represent the value of S_A.

Tab. 2 - S_A of respective tree species in different cities. Classes: I, S_A < 0.5; II, S_A 0.5-1.0; III, $S_A \geq 1.0$; IV, S_A 0.5-3.0.

Common name	Scientific name	Spatial distribution characteristics S_A			Deciduous/ evergreen	Flowering period	Flowering/foliage
		Guangzhou	Foshan	Zhuhai			
White champaca	*Michelia* × *alba*	III	II	II	Evergreen	Apr-Sept	Flowering (white), foliage
Giant crepe-myrtle	*Lagerstroemia speciosa*	II	II	II	Deciduous	May-Jul	Flowering (purple)
Royal poinciana	*Delonix regia*	I	II	I	Deciduous	Jun-Jul	Flowering (red)
Araguaney	*Handroanthus chrysanthus*	I	I	I	Deciduous	Mar-Apr	Flowering (yellow)
Floss silk tree	*Ceiba speciosa*	I	II	I	Deciduous	Oct-Dec	Flowering (pink)
Cotton tree	*Bombax ceiba*	I	II	I	Deciduous	Mar-Apr	Flowering (red)
Blackboard tree	*Alstonia scholaris*	I	II	I	Evergreen	Jun-Sept	Foliage
Herba ficus	*Ficus concinna*	III	IV	II	Evergreen	Mar-Jun	Foliage
Mountain ebony	*Bauhinia variegata*	I	II	I	Deciduous	May-Apr	Flowering (pink)
Camphor tree	*Cinnamomum camphora*	IV	II	II	Evergreen	Apr-May	Foliage

Chinese fan palm (*Livistona chinensis*) presented S_A > 1.0, indicating that the LVV of this tree species was slightly more advantageous than its RSFF. However, the S_A of the flame bottletree (*Brachychiton acerifolius*) was between 0.5 and 3.0, indicating that the spatial distribution of this tree species on the forest floor was diverse.

Differences in S_A in different cities

In this study, we analyzed tree species present in all three cities and found that the S_A of the same tree species differed between different urban forests (Tab. 2).

The white champaca, a flowering foliage tree, was dominant in the LVV in Guangzhou and RSFF in Foshan and Zhuhai. Herba ficus, a foliage plant, showed differences in dominance across the three cities. The camphor tree, a foliage tree species, exhibited strong diversity in spatial distribution in Guangzhou, and was dominant in the RSFF in Foshan and Zhuhai. The flowering tree species of giant crepe-myrtle (*Lagerstroemia speciosa*), royal poinciana (*Delonix regia*), araguaney (*Handroanthus chrysanthus*), floss silk tree (*Ceiba speciosa*), cotton tree (*Bombax ceiba*), and mountain ebony (*Bauhinia variegata*), as well as the foliage species of the blackboard tree (*Alstonia scholaris*), were dominant in the RSFF.

S_A in different regions

The top 30 tree species in the forest land located in CUA, SUA, and UFA were analyzed to compare the S_A values of different tree species.

S_A values of different tree species in the CUA

As shown in Fig. 3, the proportion of individual trees among the top 30 tree species in the forest communities in CUA with an S_A < 1.0 was 78%, indicating that the RSFF of most trees in the urban forest was relatively large. The tree species with S_A > 1.0 were Moluccan albizia and Java apple. This indicates that the LVV of these tree species was slightly more dominant than their RSFF. The S_A for the flame bottletree, African mahogany, and herba ficus was 0.5 to 3.0, indicating that the vertical spatial distribution of these tree species was diverse.

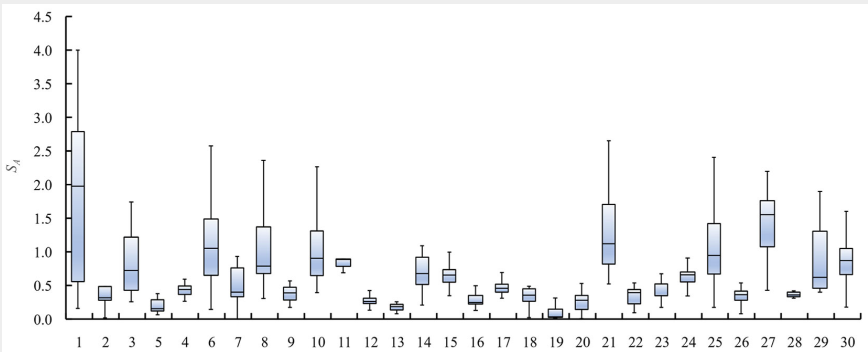

Fig. 3 - S_A of different tree species in CUA. The numbers on the *x*-axis represent tree species: 1, flame bottletree; 2, Australian umbrella tree (*Brassaia actinophylla*); 3, giant crepe-myrtle; 4, earleaf acacia; 5, Cuban royal palm; 6, African mahogany; 7, royal poinciana; 8, eugenia cumini; 9, araguaney; 10, African tulip tree; 11, cockspur coral tree; 12, hairy-fruited elaeocarpus; 13, blue jacaranda (*Jacaranda mimosifolia*); 14, Queensland peppermint (*Eucalyptus exserta*); 15, Indian mahogany; 16, Masson's pine (*Pinus massoniana*); 17, mango (*Mangifera indica*); 18, floss silk tree; 19, pygmy date palm(*Phoenix roebelenii*); 20, cotton tree; 21, Moluccan albizia; 22, blackboard tree; 23, Chinese fan palm; 24, bishop wood; 25, herba ficus; 26, purple bauhinia (*Bauhinia purpurea*); 27, Java apple; 28, mountain ebony; 29, narra (*Pterocarpus indicus*); and 30, camphor tree. The numbers on the *y*-axis represent the value of S_A.

S_A of different tree species in SUA

The proportion of individual trees among the top 30 tree species in the forest communities in the SUA with S_A < 1.0 was 94% (see Fig. S3 in Supplementary material for S_A of different tree species in SUA), indicating that the RSFF of most trees in the urban forest was relatively large. The only tree species with S_A > 1.0 was the sacred fig. This indicates that the LVV of this tree species was slightly more dominant than its RSFF. The S_A was 0.5 to 3.0 for white champaca, indicating that the vertical spatial distribution for this tree species was diverse.

S_A of different tree species in UFA

The proportion of individual trees with an S_A < 1.0 was 83% among the top 30 tree species in the forest communities in UFA (see Fig. S4 in Supplementary material for S_A of different tree species in UFA), indicating that the RSFF of most trees in the urban forest was relatively large. The tree species with S_A > 1.0 were weeping paperbark, lofty fig (*Ficus virens*), African mahogany, sea hibiscus, and Moluccan albizia, indicating that the LVV of these tree species was slightly more dominant than their RSFF. The S_A was 0 to 1.5 for Kashi holly and herba ficus, indicating that the vertical spatial distributions of these tree species were diverse.

S_A values of the same tree species in different areas

We analyzed tree species in CUA, SUA, and UFA and found that the S_A values of the same tree species were very similar in different areas (Tab. 3). African mahogany, a foliage tree, was more spatially diverse in

Tab. 3 - S_A of respective tree species in core urban areas (CUA), semi-urban areas (SUA), and urban fringe areas (UFA). Classes: I, S_A < 0.5; II, S_A 0.5-1.0; III, S_A ≥ 1.0; IV, S_A 0.5-3.0.

Common name	Scientific name	Spatial distribution characteristics S_A			Deciduous/ evergreen	Flowering period	Flowering/ foliage
		CUA	SUA	UFA			
Giant crepe-myrtle	*Lagerstroemia speciosa*	II	II	II	Deciduous	May-Jul	Flowering (purple)
African mahogany	*Khaya senegalensis*	IV	I	III	Evergreen	Mar-May	Foliage
Royal poinciana	*Delonix regia*	I	II	I	Deciduous	Jun-Jul	Flowering (red)
Araguaney	*Handroanthus chrysanthus*	I	I	I	Deciduous	Mar-Apr	Flowering (yellow)
African tulip tree	*Spathodea campanulata*	II	II	II	Deciduous	Apr-May	Flowering (red)
Floss silk tree	*Ceiba speciosa*	I	II	I	Deciduous	Oct-Dec	Flowering (pink)
Cotton tree	*Bombax ceiba*	I	II	I	Deciduous	Mar-Apr	Flowering (red)
Blackboard tree	*Alstonia scholaris*	I	II	I	Evergreen	Jun-Nov	Foliage
Chinese fan palm	*Livistona chinensis*	I	I	I	Evergreen	Apr	Foliage
Bishop wood	*Bischofia javanica*	II	I	I	Evergreen	Apr-May	Foliage
Mountain ebony	*Bauhinia variegata*	I	II	I	Deciduous	Mar-Apr	Flowering (pink)
Camphor tree	*Cinnamomum camphora*	IV	II	II	Evergreen	Apr-May	Foliage

CUA. It was dominant in the RSFF in SUA and in the LVV in UFA. Other tree species were relatively dominant in the RSFF.

S_A of different types of urban forests

S_A of different tree species in closed forests

Fig. 4 shows that the proportion of individual trees with S_A < 1.0 was 84% among the top 30 tree species in closed forests, indicating that the RSFF of most tree forests in the urban forest was relatively large. The tree species with S_A > 1.0 were council tree and Moluccan albizia, suggesting that their LVV was more dominant than their RSFF. S_A was 0 to 2.0 for the sausage tree, African mahogany, eugenia cumini, and herba ficus, indicating that the vertical spatial distribution of these tree species was diverse.

S_A of different tree species in open woodlands

The proportion of individual trees among the top 30 tree species in open woodland with S_A < 1.0 was 90% (see Fig. S5 in Supplementary material for S_A of different tree species in open woodlands), indicating that the RSFF of most trees in the urban forest was relatively large. The S_A of golden jasmine tree (*Radermachera hainanensis*) was > 1.0. This suggested that the LVV of this tree species was more dominant than its RSFF. The S_A for the flame bottletree, African mahogany, and council tree was 0 to 2.5, indicating that the vertical spatial distributions of these tree species were diverse.

S_A of different tree species in forest areas close to water bodies

The proportion of individual trees among the top 30 tree species in forest areas close to water bodies with S_A < 1.0 was 88% (see Fig. S6 in Supplementary material for S_A of different tree species in forest areas close to water bodies), indicating that the RSFF of most trees in the urban forest was relatively large. The tree species with S_A > 1.0 were the Cuban royal palm (*Roystonea regia*), lofty fig, the blackboard tree, and Chinese fan palm, suggesting that the LVV of these tree species was more dominant than their RSFF. The S_A for weeping paperbark was 0 to 2.0, indicating that the vertical spatial distribution of this tree species was diverse.

S_A of different tree species in forest areas beside buildings

The proportion of individual trees among the top 30 tree species in forest areas beside buildings with S_A < 1.0 was 83% (see Fig. S7 in Supplementary material for S_A of different tree species in forest areas beside buildings), indicating that the RSFF of most trees in the urban forest was relatively large. The tree species with S_A > 1.0 were white champaca, weeping paperbark, African mahogany, and eugenia cumini. This indicates that the LVV of these tree species was slightly better than their RSFF. The S_A for tiger's claw (*Erythrina variegata*) and sacred fig was 0 to 2.0, indicating that the vertical spatial distribution of these tree species was diverse.

S_A of same tree types in different urban forests

Analyzing the tree species in the closed forest, open woodland, forest areas close to water bodies, and forest areas beside buildings revealed that the S_A values of the same tree species were very similar in different types of urban forests (Tab. 4). The LVV of the forest areas close to water bodies was dominated by Cuban royal palm and the blackboard tree, which are foliage tree species. The closed forest, open woodland, and forest areas beside buildings primarily contributed to the RSFF. Different tree species were relatively domi-

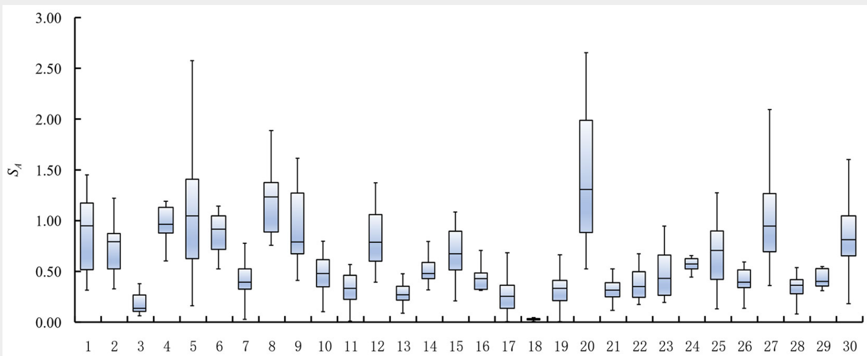

Fig. 4 - S_A of different tree species in closed forests. 1, white champaca; 2, giant crepe-myrtle; 3, Cuban royal palm; 4, sausage tree (*Kigelia africana*); 5, African mahogany; 6, Taiwanese sweet gum; 7, royal poinciana; 8, council tree; 9, eugenia cumini; 10, Hong Kong orchid tree; 11, araguaney; 12, African tulip tree; 13, hairy-fruited elaeocarpus ; 14, golden shower tree; 15, Queensland peppermint; 16, mango; 17, floss silk tree; 18, pygmy date palm; 19, cotton tree; 20, Moluccan albizia; 21, blackboard tree; 22, Chinese fan palm; 23, bishop wood; 24, Hainan oil-fruit tree; 25, burflower-tree; 26, Madagascar almond tree (*Terminalia neotaliala*); 27, dieng-kachiri; 28, purple bauchinia; 29, mountain ebony; and 30, camphor tree. The numbers on the *y*-axis represent the value of S_A.

Tab. 4 - S_A of the same tree species in different types of forests. Classes: I, S_A < 0.5; II, S_A 0.5-1.0; III, S_A ≥ 1.0; IV, S_A of 0-3.0.

Common name	Scientific name	Spatial distribution characteristics S_A				Deciduous/ evergreen	Flowering period	Flowering/ foliage
		Closed forest	Open woodland	Forest areas close to water bodies	Forest areas beside buildings			
Giant crepe-myrtle	*Lagerstroemia speciosa*	II	II	II	II	Deciduous	May-Jul	Flowering (purple)
Cuban royal palm	*Roystonea regia*	I	I	III	I	Evergreen	Mar-Apr	Foliage
Araguaney	*Handroanthus chrysanthus*	I	I	I	I	Deciduous	Mar-Apr	Flowering (yellow)
Mango	*Mangifera indica*	I	I	II	I	Evergreen	Jan-Feb	Foliage
Floss silk tree	*Ceiba speciosa*	I	I	II	I	Deciduous	Oct-Dec	Flowering (pink)
Cotton tree	*Bombax ceiba*	I	I	I	I	Deciduous	Mar-Apr	Flowering (red)
Blackboard tree	*Alstonia scholaris*	I	I	III	I	Evergreen	Jun-Nov	Foliage
Bishop wood	*Bischofia javanica*	I	II	I	I	Evergreen	Apr-May	Foliage
Madagascar almond tree	*Terminalia neotaliala*	I	I	I	I	Evergreen	-	Foliage
Mountain ebony	*Bauhinia variegata*	I	I	I	I	Deciduous	Mar-Apr	Flowering (pink)
Camphor tree	*Cinnamomum camphora*	II	II	II	II	Evergreen	Apr-May	Foliage

nant in the RSFF in different types of urban forests.

Discussion

Point cloud generated by LiDAR scanner can obtain LVV and RSFF

In this study, we used a handheld SLAM-100 LiDAR scanner to survey every tree in the quadrats. Compared with the research time and cost of previous research methods (Zhou & Sun 1995, Wang et al. 2013, Dong & Wan 2019, Wei et al. 2020, Chen et al. 2021) that used empirical formulas to calculate the LVV and RSFF using tree crown and branch height data, the research time and cost in this study were greatly reduced (Zhou et al. 2020, Zhu et al. 2020). Using LiDAR to generate point cloud data, without considering tree shape, reduced the requirement for personnel and the research accuracy was improved (Xu et al. 2021). The LiDAR scanner was used to monitor LVV and RSFF for a prolonged period and to analyze the temporal pattern of the spatial distribution characteristics of trees. This would allow the Urban Landscaping Department to formulate corresponding strategies to consider the LVV and RSFF in order to achieve ecological and social benefits. However, the LiDAR scanner still had some limitations in terms of tree recognition, similar to the conclusion of research based on the use of backpack LiDAR (Li et al. 2022). In this study, the tree species identification method involved artificial statistics, and a fully automatic process for calculating the LVV and RSFF was not achieved. When the sample size of trees was large or the density of shade was high, the calculation efficiency was limited. Therefore, a tree species identification algorithm should be used in the future to produce a rich database of the basic morphology of different tree species so that they can be identified intelligently and accurately, and the LVV and RSFF of urban forests can be obtained fully automatically.

Regional differences affect the spatial distribution characteristics of urban forests

The spatial allocation strategy for urban forests in cities did not only fully elucidate and efficiently utilize the limited urban land resources, but improved the landscapes of urban forests and provided high-quality environments for citizens and animals (Liu et al. 2008). The spatial distribution characteristics of urban forests changed with the climate environments and greening management strategies of different cities. This study indicated that the proportion of LVV of royal poinciana, floss silk tree, cotton tree, blackboard tree, and mountain ebony in Guangzhou and Zhuhai was less than 0.5, whereas the proportion of LVV in Foshan was greater than 0.5. The vertical structural distributions of these trees in different cities may differ due to various factors, such as planting time and soil conditions. The distribution of foliage tree species, such as herba ficus and camphor tree, was more diverse in the LVV than in the RSFF in different cities. This may occur because these tree species are strongly disturbed by human activity in urban forests. In the process of forest community development, the vertical structure of trees will be affected by factors such as competition and trees in the understory. Additionally, spatial heterogeneity, human disturbance, disasters, and other environmental factors also affect the vertical structural distribution of trees. The main influencing factors of the RSFF are the crown projection area and the lowest point of branching.

Assessing the potential of social media for estimating the RSFF of urban forests

Similar to previous research, this study took the size of the RSFF as a proxy to estimate the recreational potential of urban forests. The main factor influencing the RSFF observed in this study was the relationship between the canopy projection area and the lowest branch point. In the urban environment, the empty understory, small trees, and shrubs together constitute the RSFF (Zhao et al. 2020b). The small trees and shrubs play an important role in regulating the RSFF and LVV. Chen et al. (2018) studied the LVV of artificial green spaces in a rehabilitation hospital, reporting that trees and shrubs should be reasonably allocated in developing the plant configuration of small-scale artificial green spaces and that the vertical coverage area of greenery should be expanded. In addition, trees with a large crown should be planted, and indiscriminate tree planting should be avoided. However, the focus of the above research was the size of the RSFF. People are the key users of urban forests. The quality and function of the RSFF cannot be accurately evaluated without monitoring people's recreational activities (Wartmann et al. 2021). Such monitoring data was often difficult to obtain in previous large-scale RSFF assessments. Owing to the rapid development of social media, such as WeChat, Weibo, and 2bulu, we can evaluate the utilization of the RSFF with the aid of relevant positioning data. It is possible to conduct a comprehensive evaluation of the size and usage frequency of the RSFF using social media, and it can more reasonably reflect and estimate the RSFF of urban forests. This is also the mainstream direction of recreational urban forest use estimation worldwide (Komossa et al. 2020).

Dynamic assessment of the spatial distribution characteristics and their impact on the ecological function of urban forests

Dynamic temporal changes in the spatial distribution of LVV and RSFF are caused by forest succession, growth, and phenology; evaluating these changes is one of the most effective strategies to further explore the ecological and landscape services provided by urban forests. By considering the LVV and RSFF, this study focused on factors such as tree size, spatial distribution, and distribution strategy, providing static research results; however, we did not consider the effect of time in relation to the spatial distribution of the LVV and RSFF. This remains a limitation of this research – the dynamics of the LVV and RSFF change over time with changes in forest succession, growth, and phenology. Therefore, the construction of index parameters reflecting this dynamic process can aid in scientifically evaluating the ecological and recreational landscape functions of urban forests, such as the temporal stability of the LVV and RSFF. In addition to the visual landscape of the LVV and recreational effects of the RSFF mentioned in this study, the spatial distribution characteristics and forms of urban forests will also affect ecological functioning, such as the thermal comfort and cooling effects of tree shading (Sabrin et al. 2021). Therefore, it is necessary to study the characteristics and forms of LVV and RSFF in detail in the future and conduct correlation analysis of the functions of urban forests in order to maximize their ecological benefits.

Conclusions

Comparing the LVV with the RSFF revealed the following: the LVV of flowering tree species, such as giant crepe-myrtle, royal poinciana, araguaney, floss silk tree, cotton tree, blackboard tree, and mountain ebony, was relatively small in different cities. The LVVs of foliage trees, such as white champaca, herba ficus, and camphor tree, were relatively large in Guangzhou, whereas they were relatively small in Zhuhai. In the CUA, SUA, and UFA of urban forests, the same tree species accounted for small proportions of the LVV. Among them, African mahogany, a foliage tree, showed a highly diverse spatial distribution in CUA; its RSFF was dominant in SUA, while its LVV was dominant in UFA. The proportion of the LVV of foliage trees, such as Cuban royal palm and blackboard tree, in the forest areas close to water was relatively large, whereas the proportions of the LVVs of araguaney, mango, floss silk tree, cotton tree, blackboard tree, bishop wood, Madagascar almond tree, mountain ebony, and camphor tree in the closed forest, open woodland, forest areas close to water bodies, and forest areas beside buildings were relatively small.

Urban forests should be configured according to the spatial distribution characteristics of different tree species. For example, the S_A of giant crepe-myrtle was stable and ranged between 0.5 and 1.0 in different cities, regions, and types of urban forests, whereas the LVV of araguaney was less than 0.5, suggesting that external interference did not considerably affect these two species. Araguaney is a flowering tree; its yellow flowers are highly ornamental when in full bloom. However, its crown width is small after the flowering period, and the LVV is small as well. Therefore, this tree is suitable for planting in areas with ornamental landscaping requirements, but not in areas that require shade for recreational purposes.

The LVV and RSFF are both complementary and contradictory. An increase in the LVV can effectively improve ecological benefits. However, it may also decrease the RSFF and reduce the cooling benefits of the tree crown for urban residents. Therefore, the spatial distribution strategy of tree species should be carefully considered according to the main functional requirements when allocating urban trees.

Abbreviations

CUA: Core urban areas; DBH : Diameter at breast height; DEM: Digital elevation model; GBA: Greater Bay Area; LVV: Living vegetation volume; RSFF: Recreational space on the forest floor; SUA: Semi urban areas; UFA: Urban fringe areas.

Author contributions

QZ: conceptualization, methodology, formal analysis, writing the original draft, review and editing; CZ: writing, review, editing and supervision; RH: investigation; WQ: investigation; YW: software and investigation.

Acknowledgments

We are grateful to all the participants who generously shared their opinions. We are thankful to Editage (https://www.editage.cn) for English language editing.

Funding

This study was supported by the Forestry Science and Technology Innovational Specific Project of Guangdong Province (grant no. 2022KJCX009 and no. 2021KJCX009).

References

Akitt JW (2018). Some observations on the greenhouse effect at the Earth's surface. Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy 188: 127-134. - doi: 10.1016/j.saa.2017.06.051

Bowler DE, Buyung-Ali L, Knight TM, Pullin AS (2010). Urban greening to cool towns and cities: a systematic review of the empirical evidence. Landscape and Urban Planning 97 (3): 147-155. - doi: 10.1016/j.landurbplan.2010.05.006

Casalegno S, Anderson K, Cox DTC, Hancock S, Gaston KJ (2017). Ecological connectivity in the three-dimensional urban green volume using waveform airborne lidar. Scientific Reports 7 (1): 45571. - doi: 10.1038/srep45571

Chen H, Liu RB, Li SX, Zhou LP, Guo CA, Zhang HP (2018). Study on the canopy density and the three-dimensional green quantity of the artificial green space in the Rehabilitation Hospital. Journal of Chongqing University of Technology (Natural Science) 32 (8): 121-129. - doi: 10.3969/j.issn.1674-8425(z).2018.08.019

Chen JX, Huang RR, Lin JB, Xi RC (2021). Characteristics and evaluation of plant landscape resources in Huangpu ancient village of Guangzhou City. Forestry and Environmental Science 37 (3): 47-53.

Deilami K, Kamruzzaman M, Liu Y (2018). Urban heat island effect: A systematic review of spatio-temporal factors, data, methods, and mitigation measures. International Journal of Applied Earth Observation and Geoinformation 67: 30-42. - doi: 10.1016/j.jag.2017.12.009

Dong Y, Zhao L, Zhao Y (2004). Quantity of plant leaf area on three major public squares in Kunming City, China. Journal of Forestry Research 15 (04): 291-294. - doi: 10.1007/BF02844955

Dong YJ, Wan FX (2019). Ecological benefits and value assessment of forest stands based on three-dimensional green volume - A case study of Pujiang country park of Shanghai. Research of Soil and Water Conservation 26 (3): 347-352.

Escobedo FJ, Giannico V, Jim CY, Sanesi G, Lafortezza R (2019). Urban forest, ecosystem services, green infrastructure and nature-based solutions: nexus or evolving metaphors? Uraban Forestry and Urban Greening 37: 3-12. - doi: 10.1016/j.ufug.2018.02.011

Fu Q, Wang N, Xiao M, Xi LL, Shao YZ, Jia HR, Chen Y, Yuan Z, Ye YZ (2021). Canopy structure and illumination characteristics of different man-made interference communities in Baiyun Mountain National Forest Park. Acta Ecologica Sinica 41 (19): 7830-7837.

Gao XY, Li C, Cai Y, Ye L, Xiao LD, Zhou GM, Zhou YF (2021). Influence of scale effect of canopy projection on understory microclimate in three subtropical urban broad-leaved forests. Remote Sensing 13 (18): 3786. - doi: 10.3390/rs13183786

Grimmond CSB, Oke TR (1999). Heat storage in urban areas: local-scale observations and evaluation of a simple model. Journal of Applied Meteorology and Climatology 38 (7): 922-940. - doi: 10.1175/1520-0450(1999)038<0922:HSIUAL>2.0.CO;2

He XY, Liu CF, Chen W, Guan ZJ, Zhao GL (2004). Discussion on urban forest classification. Chinese Journal of Ecology 23 (5): 175-178.

Huang LZ, Yang JL, Xu QH, Zhang XY, Kan L, Zhang L (2019). Relationship between canopy structures and understory light availability in urban forest communities. Journal of Central South University of Forestry and Technology 39 (9): 53-58.

Komossa F, Wartmann FM, Kienast F, Verburg PH (2020). Comparing outdoor recreation preferences in peri-urban landscapes using different data gathering methods. Landscape and Urban Planning 199: 103796. - doi: 10.1016/j.land

urbplan.2020.103796
Li XW, Chen QX, Zheng J, Lu X, Xia HT (2012). Classification system of subtropical scenic-recreational forest in South Zhejiang. Journal of Chinese Urban Forestry 10 (5): 32-35.
Li XX, Tang LY, Peng W, Chen JX, Ma X (2022). Estimation method of urban green space living vegetation volume based on backpack light detection and ranging. Chinese Journal of Applied Ecology 33 (10): 2777-2784. - doi: 10.13287/j.1001-9332.202210.020
Liu CF, Li L, Zhao GL, He XY, Chen W (2008). Vertical distribution of tridimensional green biomass in Shenyang urban forests. Journal of Northeast Forestry University 36 (3): 18-21. - doi: 10.13759/j.cnki.dlxb.2008.03.017
Liu CF, Shang Y, Zhao GL (2013). Quantitative difference analysis of three-dimensional green biomass of urban forest based on the types and influencing factors. Journal of Northwest University 28 (4): 55-60.
Liu HX, Wu J, Xu LJ, Xu CY (2020). Selection of canopy structure index of urban forest associated with comfort degree of microclimate within the forest. Scientia Silvae Sinicae 56 (2): 32-39.
Meng C, Xu MC, Li JX, Gao SP (2007). Spatial heterogeneity of photo synthetic characteristics of *Castanopsis fargesii* canopy. Chinese Journal of Applied Ecology 18 (9): 1932-1936.
Müller N, Kuttler W, Barlag AB (2014). Counteracting urban climate change: adaptation measures and their effect on thermal comfort. Theoretical and Applied Climatology 115 (1-2): 243-257. - doi: 10.1007/s00704-013-0890-4
Oke TR (1989). The micrometeorology of the urban forest. Philosophical Transactions of the Royal Society B 324: 335-349.
Rahman MA, Smith JG, Stringer P, Ennos AR (2011). Effect of rooting conditions on the growth and cooling ability of *Pyrus calleryana*. Urban Forestry and Urban Greening 10 (3): 185-192. - doi: 10.1016/j.ufug.2011.05.003
Rötzer T, Rahman MA, Moser-Reischl A, Pauleit S, Pretzsch H (2019). Process based simulation of tree growth and ecosystem services of urban trees under present and future climate conditions. Science of the Total Environment 676: 651-664. - doi: 10.1016/j.scitotenv.2019.04.235
Sabrin S, Karimi M, Nazari R, Pratt J, Bryk J (2021). Effects of different urban-vegetation morphology on the canopy-level thermal comfort and the cooling benefits of shade trees: case-study in Philadelphia. Sustainable Cities and Society 66: 102684. - doi: 10.1016/j.scs.2020.102684
Santamouris M, Papanikolaou N, Livada I, Koronakis I, Georgakis C, Argiriou A, Assimakopoulos DN (2001). On the impact of urban climate on the energy consumption of buildings. Solar Energy 70 (3): 201-216. - doi: 10.1016/S0038-092X(00)00095-5
Santamouris M, Paraponiaris K, Mihalakakou G (2007). Estimating the ecological footprint of the heat island effect over Athens, Greece. Climate Change 80 (3-4): 265-276. - doi: 10.1007/s10584-006-9128-0
Shen H, Cai JN, Li MJ, Chen Q, Ye W, Wang Z, Lian J, Song L (2017). On Chinese forest canopy biodiversity monitoring. Biodiversity Science 25 (3): 229-236. - doi: 10.17520/biods.2016294
Wang DL, Jin HX, Fan LK, Tang YL (2013). Distribution and influencing factors of three-dimensional green biomass for artificial greenbelts in sanatoriums. Journal of Zhejiang A&F University 30 (4): 529-535.
Wartmann FM, Baer MF, Hegetschweiler KT, Fischer C, Hunziker M, Purves RS (2021). Assessing the potential of social media for estimating recreational use of urban and peri-urban forests. Urban Forestry and Urban Greening 64: 127261. - doi: 10.1016/j.ufug.2021.127261
Wei CL, Xie ZS, He XH, Deng LH, Kong LH (2020). Spatial structure and three-dimensional green quantity of *Cratoxylum cochinchinense* population. Journal of Southwest Forestry University 40 (2): 71-78.
Xu QH, Yang JL, Huang LZ, Zhang XY, Tan XL, Zhang L (2019). Influence of canopy structure on understory vegetation of secondary evergreen broadleaf forest communities. Journal of Zhejiang A&F University 36 (6): 1151-1157.
Xu Y, Zhang CL, Jiang RJ, Wang Z, Zhu M, Shen G (2021). UAV-based hyperspectral images and monitoring of canopy tree diversity. Biodiversity Science 29 (5): 647-660. - doi: 10.17520/biods.2021013
Yang C, Wang YR, Tang ZY, Wang Q, Duan MJ, Qi LH (2022). Ecological health care effects of scenic recreational forests with different community structures: a case study of Beijing Xishan National Forest Park. Acta Ecologica Sinica 42 (16): 1-15.
Zhang J, Zhang Z, Lutz JA, Chu C, Hu J, Shen G, Li B, Yang Q, Lian J, Zhang M, Wang X, Ye W, He F (2022). Drone-acquired data reveal the importance of forest canopy structure in predicting tree diversity. Forest Ecology and Management 505: 119945. - doi: 10.1016/j.foreco.2021.119945
Zhao ZY, Du AP, Shu QT (2012). Study on microclimate characteristics at different heights within a Eucalyptus plantation. Eucalypt Science and Technology 29 (3): 15-18.
Zhao Q, Hu RX, Xu DX, Wei YH (2020a). Community structure characteristics for landscape-recreational forests in the urban parks of Foshan City. Journal of Zhejiang A&F University 37 (3): 447-455.
Zhao Q, Xu DX, Qian WH, Hu RX, Chen XC, Tang HH, Zhang C (2020b). Ecological and landscape perspectives on urban forest planning and construction: a case study in Guangdong - Hong Kong - Macao Greater Bay area of China. Frontiers in Sustainable Cities 2: 44. - doi: 10.3389/frsc.2020.00044
Zhao Q, Zhang C, Hu RX, Xu DX, Qian WH, Wei YH (2021). Characteristics of the three-dimensional green quantity and recreation space for landscape-recreational forests in Zhuhai City. Journal of Zhejiang A&F University 38 (3): 534-540.
Zheng JM, Fang X, Zhu XP, Zhu DD (2016). Research on correlation between plant communities and tridimensional green biomass in Fuzhou Beach park. Journal of Chinese Urban Forest 14 (2): 48-52.
Zheng JM, Zhu DD, Jiang MY, Fang X, Deng CY (2018). Tridimensional green biomass and its impact factors of three mountain parks in Fuzhou. Chinese Landscape Architecture 34 (2): 89-93.
Zhou JH, Sun TZ (1995). Study on remote sensing model of three-dimensional green biomass and the estimation of environmental benefits of greenery. Remote Sensing of Environment 10 (3): 162-174.
Zhou XG, Wen YG, Zhu HG, Wang L, Li XC (2017). Canopy vertical structure and understory plant regeneration of an evergreen broadleaved forest in Damingshan, Guangxi, China. Chinese Journal of Applied Ecology 28 (02): 367-374.
Zhou XC, Liao HY, Cui YJ, Wang KF (2020). UAV remote sensing estimation of three-dimensional green volume in landscaping: a case study in the Qishang campus of Fuzhou University. Journal of Fuzhou University (Natural Science Edition) 34 (10): 160-165.
Zhu SM, Wang ZX, Pei Y, Lü JC, Ge Y (2020). Crown extraction and volume inversion of *Picea schrenkiana* var. *tianshanica* forest based on UAV image. Journal of Arid Land Resources and Environment 34 (10): 160-165.

Supplementary Material

Fig. S1 - S_A of different tree species in Foshan.

Fig. S2 - S_A of different tree species in Zhuhai.

Fig. S3 - S_A of different tree species in SUA.

Fig. S4 - S_A of different tree species in UFA.

Fig. S5 - S_A of different tree species in open woodlands.

Fig. S6 - S_A of different tree species in forest areas close to water bodies.

Fig. S7 - S_A of different tree species in forest areas beside buildings.

Link: Zhao_4268@suppl001.pdf