Construction of Green Space Assessment Indicators for Urban Residential Areas Based on 3D Vegetation Volume: A Case Study of Residential Communities in Wuhan

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Abstract

The current evaluation standards of urban green space are mainly based on 2D indicators, which cannot express the 3D spatial characteristics. Based on leaf area and vegetation volume, this study proposed four 3D green space evaluation indicators to provide a reference for establishing a suitable 3D green space evaluation method. The urban residential areas in Wuhan were then taken as a case study, and the proposed 3D indicators, as well as the 2D indicators, were then calculated and compared to check their applicability. The result showed that the vegetation-volume-based indicators are more prominent than the leaf-area-based indicators, which could be potentially more suitable to express the 3D spatial difference of green space. The 3D green space indicators can also express the temporal variation of plants, including annual growth and seasonal change, which makes them suitable for long-term green space monitoring. The proposed indicators could provide a more comprehensive framework for evaluating ecosystem services in urban residential communities.

Introduction

Urban green space provides a beneficial environment for the residents and provides multiple ecosystem services of the city. In most cities, 45-55% of the living space is dedicated to residential areas (Lu, 2004). As people's demand for the quality of living environment continues to improve, the quality evaluation of urban green space has received more attention. Therefore, a systematic evaluation indicator system will need to be established to guide the green space planning and design process in urban areas.

However, the current evaluation standards of green space in urban areas are mainly based on 2D indicators such as green space rate and vegetation coverage rate, which cannot express the 3D spatial characteristics such as the tree canopy height and spatial volume. As there is a close correlation between 3D green space and its ecological benefits, it is necessary to establish corresponding 3D indicators for quick and accurate assessment.

Background and Literature Review

Several methods for the 3D green space evaluation have been proposed in related research. The current assessment methods can be mainly divided into two categories: leaf-area-based assessment and vegetation-volume-based assessment.

The leaf area index (LAI) is defined as the total area of one-sided leaves per unit of surface area (Monteith and Unsworth, 1973) or as the sum of all the vertical projected leave areas per unit area.

The leaf-area-related factors could express the sunlight utilization status and the canopy structure of plants (Zhou, 2013). A number of green space indicators based on LAI have been discussed in related research. The green plot ratio (GPR) is defined as the average LAI of a plot to provide an indicator for evaluating urban green space, which is similar to the concept of floor area ratio (FAR) in urban planning (Yao and Li, 2015). However, the concept has not been fully tested in different urban areas.

The vegetation-volume-based assessment simplifies the 3D vegetation into simple geometries to estimate the 3D volume of the green space. Tang (2011) calculated the 3D vegetation volume in Beijing based on 3D point cloud samples obtained by LiDAR scanning and remote sensing images. Zheng et al. (2018) calculated the 3D vegetation volume of three parks in Fuzhou by modeling the tree canopies into simple geometries. However, the existing calculations of 3D vegetation volume are usually used for individual projects and lack the explorations as a general-purpose assessment indicator.

In this study, we constructed four different 3D green space assessment indicators and explored the suitability of their application in the residential areas of Wuhan. The distribution patterns of 3D indicators of green space in different residential areas were analyzed and compared. The study could provide a reference for establishing appropriate 3D assessment indicators for urban green space.

Definitions of the 3D Green Space Indicators

The study proposed 4 generalized 3D green space indicators, including 2 leaf-area-based indicators and 2 vegetation-volume-based indicators. The corresponding definition and calculation methods for each indicator are listed below.

Leaf-Area-Based Indicators

The leaf-area-based indicators include the leaf area per unit area and the leaf area per capita. The leaf area distribution can be obtained by public datasets of various remote sensing products, such as LAI products derived from MODIS and Sentinel II. The spatial resolution of the leaf area distribution products varies from 10m to 100m, which can meet the needs of calculation for different scales.

Leaf area per unit area: The leaf area per unit area is the sum of the leaf areas in each unit area, reflecting the average leaf density in the study area. The calculation formula is:

$$A(unit) = \frac{A(sum)}{S}$$

A(sum): the sum of the leaf area within the study area

S: the size of the study area

Leaf area per capita: The leaf area per capita is the amount of leaf area averaged by each resident within the area, which can indicate the average 3D green space resources for each resident. The calculation formula is:

$$A(capita) = \frac{A(sum)}{N}$$

A(sum): the sum of leaf area within the study area

N: the total population of the study area

Vegetation-Volume-Based Indicators

Vegetation-volume-based indicators include 3D vegetation volume per unit area and 3D vegetation volume per capita. The vegetation volume can be obtained by LiDAR scanning or photogrammetry. Various LiDAR datasets with different precisions are available online, which could provide a dataset for large-scale area evaluation.

3D vegetation volume per unit area: The 3D vegetation volume per unit area is the amount of leaf area averaged by each resident within the area. The calculation formula is:

$$V(unit) = \frac{V(sum)}{S}$$

V(sum): total 3D vegetation volume of the study area

S: the total size of the study area

3D vegetation volume per capita: The 3D vegetation volume per capita is the amount of 3D vegetation volume averaged by each resident within the area, the 3D vegetation volume per capita can reflect the average vegetation volume for each person. The calculation formula is:

$$V(capita) = \frac{V(sum)}{N}$$

V(sum): total 3D vegetation volume of the study area

N: the total population of the study area

Method and Data

Study Area

The study took the residential districts in the central urban area (within the third ring road) of Wuhan, China as the study area (Figure 1). The areas are distributed in 7 municipal districts: *Jiangan*, *Jianghan*, *Qiaokou*, *Hanyang*, *Wuchang*, *Qingshan*, and *Hongshan*.

Figure 1. Site location

Data Sources

Datasets for the assessment of 3D vegetation volume in residential areas, including canopy heights, residential boundaries, and population data. The study used an LAI dataset with a 6m resolution obtained by the GLASS LAI product (Ma and Liang, 2022) and a high-resolution 1m global canopy height mapping extracted on Google Earth Engine (Meta and WRI, 2023).

The Area of Interest(AOI) polygons of different residential areas were extracted from the Gaode Map, a map service provider in China. The attributes of the different residential areas were based on the Point of Interest(POI) dataset from Anjuke, a real estate transaction platform in China.

The population data were obtained from the 7th National Census Bulletin. To estimate the number of residents in each residential area, the city's average population per household (2.47) (Wuhan Municipal Bureau of Statistics, 2021), was multiplied by the total households in each residential area extracted from Anjuke to get the total population.

Data Processing

The acquired datasets were then imported into ArcGIS Pro. The AOI data were cropped to the study area by the boundary of Wuhan's third ring road. To eliminate the fragments of the AOI dataset, the AOI polygons were screened by the "Select By Attribute" tool with the condition: AOI residential area ⩾1000m^2, number of households ⩾500. 1227 residential areas within the study were then obtained.

To obtain the attributes for each residential area, the POI points within the AOI range were extracted by the "Select By Location" tool and then merged with the residential area AOI data by the "Dissolve" tool. The "Extract by Mask" tool was used to clip the vegetation height and LAI data within the residential area to obtain the crown height and LAI data within the residential area.

5.3 Green Space Indicators Calculation

Based on ArcGIS Pro Model Builder, an automated calculation pipeline was built to obtain each residential area's 2D and 3D green indicators.

The 2D green space indicators were calculated for comparison with the results of the proposed 3D green space indicators. The green space in the residential area was calculated using the 1m canopy Height data, the pixel points with non-zero values in the dataset are regarded as green space. The calculation process in the GIS model builder is shown in Figure 2.

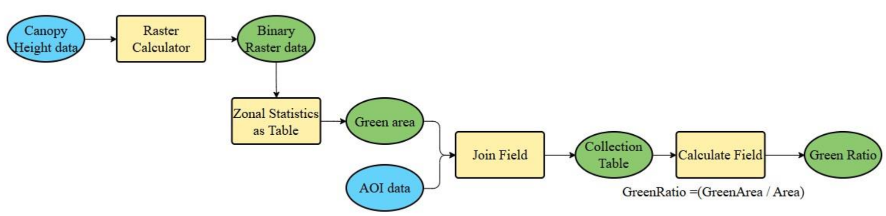


Figure 2 2D Green Volume Calculation Process

The two types of 3D green space indicators were calculated separately with different data sources in ArcGIS Model Builder. In terms of vegetation-volume-based indicators, the 3D vegetation models were simplified as a number of cuboid geometries with the height value set to the corresponding canopy height. The 1m canopy height dataset was used to calculate the 3D vegetation volume. The calculation process in ArcGIS Model Builder is shown in Figure 3.

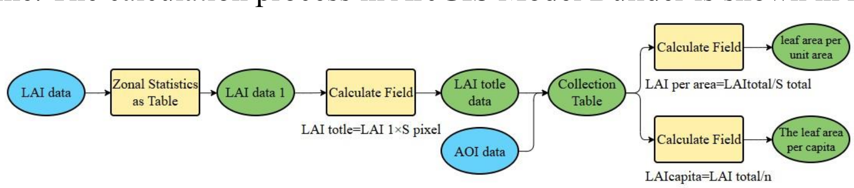


Figure 3 The calculation process of vegetation-volume-based indicators

In terms of leaf-area-based indicators, the LAI dataset was used as the main data source. The total leaf area was obtained by multiplying the total leaf area per unit area by the area of each pixel. The calculation process in the ArcGIS model builder is shown in Figure 4.

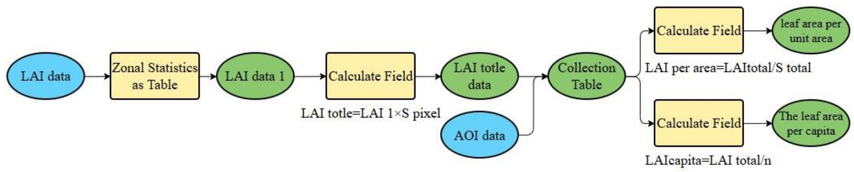


Figure 4 The calculation process of leaf-area-based indicators

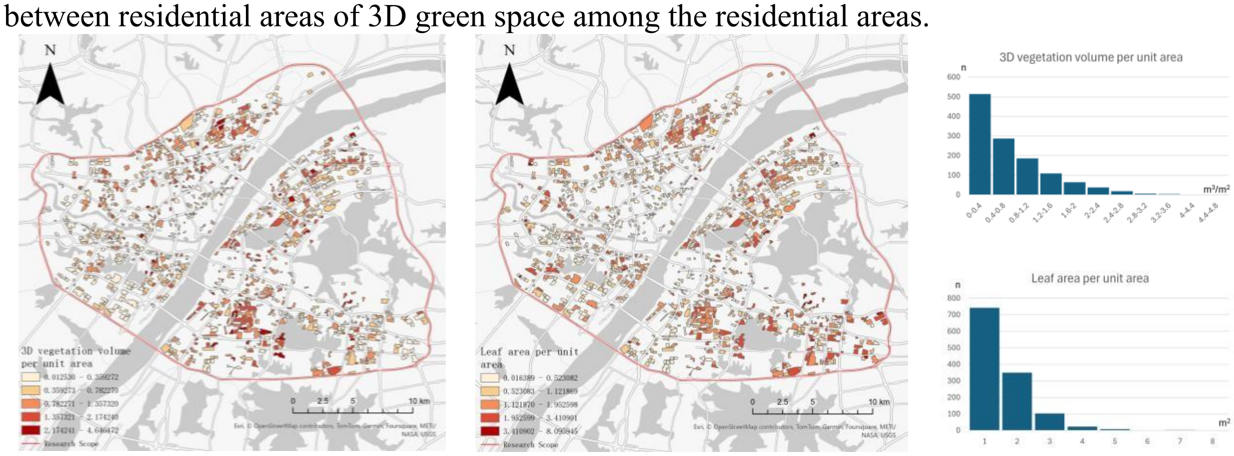
Results

3D Green Space Per Unit Area in Different Residential Areas

The average value of 3D vegetation volume per unit area among the 1227 residential areas is $0.72m^3/m^2$. The spatial distribution shows that the residential areas with higher 3D vegetation volume per unit area are mostly located in *Wuchang District* and *Jiangan District*, while the 3D vegetation volume per unit area of residential areas in *Hanyang District* is generally at a lower level.

The residential area with the highest 3D vegetation volume per unit area is *Qiyiersuo Community* ($3.41\ m^3/m^2$). Its large green space and multi-layered vegetation have contributed to a high-density 3D green space. The residential area with the lowest 3D vegetation volume per unit area is *Huasheng Hankou Plaza* ($0.03\ m^3/m^2$), which has a large area but consists mainly of small trees and lawns with low canopy height and low density (Figure 5).

The average value of leaf area per unit area among the 1227 residential areas is 0.99. The spatial distribution shows that the residential areas with a higher amount of leaf area per unit area are mainly located in *Wuchang District*, with a maximum value (*Meteorological Bureau Community*) of 4.42. The values of leaf area per unit area in *Qiaokou District* and *Jianghan District* are relatively low, with a minimum value (*Wufuli Community*) of 0.05, which shows a significant difference between residential areas of 3D green space among the residential areas.



3D vegetation volume per unit area Leaf area per unit area

Figure 5 3D green space per unit area in different residential areas

The 4 sample residential areas are shown in Figure 6.

Qiyiersuo community (3.533/3.411)

Huasheng Hankou Plaza (0.030/0.043)

Meteorological Bureau Community (2.784/4.423)

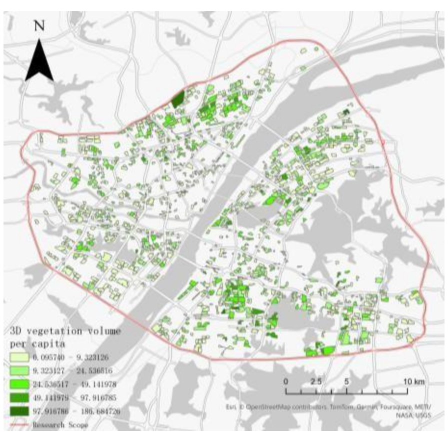
Wufuli Community (0.038/0.045)

Figure 6 Sample residential areas and indicators (3D vegetation volume per unit area/leaf area per unit area)

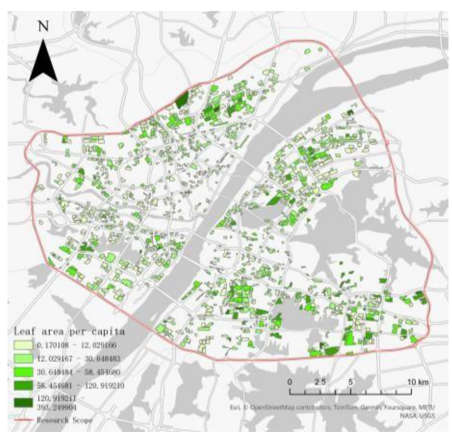
3D Green Space per Capita in Different Residential Areas

The average 3D vegetation volume per capita of the 1227 residential areas is 11.94 m^2. The spatial distribution shows that residential areas with higher 3D vegetation volume per capita are mostly located in *Wuchang District* and *Jiangan District*, while the 3D vegetation volume per capita of residential areas in *Hanyang District* is relatively lower. The residential area with the largest amount of 3D vegetation volume per capita is *Menghuxiangjun*, with a value of 220, and the smallest is *Wenhaoyuan*, with a value of 22.

The leaf area per capita of the 1227 residential areas is 17.64m^2. The spatial distribution shows that the values of leaf area per capita in *Jiangan District* are relatively higher, with a maximum value in the *Menghuxiangjun* of 393.25m^2. The values in *Hanyang District* are generally lower, with the lowest one in the *Zhongcheng Yuecheng Community* at 0.17 m^2. The residents of different residential areas share a significant difference in green space. Low-density residential areas have relatively higher leaf areas per capita values due to the low population and large green space, while high-rise residential areas have relatively low leaf area per capita values due to high population density and limited green space (Figure 7). The 3 sample residential areas are shown in Figure 8.



3D vegetation volume per capita



Leaf area per capita

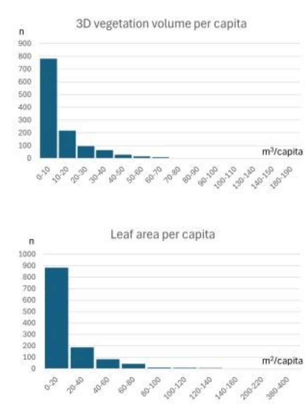


Figure 7 3D green space per capita in different residential areas

Menghuxiangjun (186.685/393.250)

Zhongcheng Yuecheng (2.063/0.170)

Wenhaoyuan (0.096/1.438)

Figure 8 Sample residential areas and indicators (3D vegetation volume per capita/leaf area per capita)

Differences between the 3D and 2D indicators

The average green coverage rate of the residential areas is 24%, with most of the values between 10% and 40%. The green coverage area per capita of residential areas is 3.78m^2, with most of the values between 0-5m^2. The correlation between the 3D vegetation volume, leaf area indicator and green space rate distribution in residential areas is shown in Figure 9.

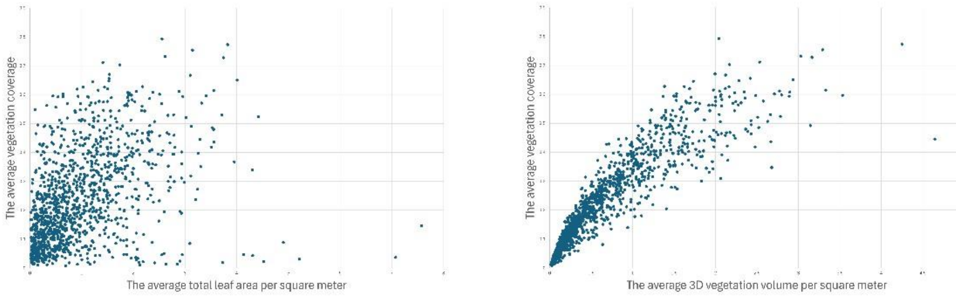


Figure 9 Differences between 3D and 2D indicators

The evaluation results show a certain difference between the 2D and 3D indicators. Some of the residential areas have shown a match between their 2D and 3D indicators, such as *Meteorological Honggangcheng* and *Chutianliyuan*, while some of them show noticeable differences. For example, *Jingyueyuan* has relatively low green coverage, while the leaf area per unit area is relatively high; *Fenghuangcheng* has a higher green coverage rate, but its leaf area per unit area is relatively low. The combination of 3D and 2D indicators can more holistically express the characteristics of green space. The 4 sample residential areas are shown in Figure 10.

Honggangcheng
(2.935/0.650)

Chutianliyuan
(2.663/0.530)

Fenghuangcheng
(2.484/0.595)

Jingyueyuan
(0.034/0.010)

Figure 10 Sample residential areas and indicators (3D vegetation volume per unit area/Vegetation coverage)

Discussion and Conclusion

Applicability of Different Indicators

The calculation results show that according to the spatial differences among the residential areas in Wuhan, the vegetation-volume-based indicators are a bit more prominent than the leaf-areabased indicators, which could be potentially more suitable to express the 3D spatial difference of green space.

Moreover, 3D green space indicators can express the temporal variation of plants, including annual growth and seasonal change, which makes them suitable for long-term green space monitoring. The leaf-area-based indicators can better reflect the seasonal difference of the plants, while the vegetation-volume-based indicators can express the growth change of the plants over time.

By combining both 3D and 2D green space indicators, as well as other ecological indicators, a more comprehensive analysis framework can be provided for the measurement of ecosystem service performance of urban green space such as water retention or microclimate regulation.

Accuracy Verification and Further Refinements

The increasing LiDAR and remote sensing open data have provided a basis for the calculation and assessment of both 2D and 3D green space indicators, which makes the calculation more feasible for quick assessments. However, due to the limited data acquisition methods and the variations in spatial and temporal resolution, the results obtained from different calculation methods often have some differences from each other. A unified calculation standard for various scales will need to be discussed and verified.

The crown height and leaf area data adopted in this study are from global open-access datasets, which may need further accuracy verification in the local context. The accuracy of the AOI boundaries will also affect the accuracy of the calculation. The satellite images may contain shadows cast on the green space, resulting in a certain gap between the recognized green space areas and the real areas. For a more accurate calculation result, field visits and collect on-site data collection will be necessary.

References

Lu, Sheng. 2004. "Preliminary Study on 3D Modeling Methods of Landscape Plants." *Journal of Beijing Agricultural College* 19 (3): 49–54.

Zhou, Jianmin. 2013. *Soil Science Encyclopedia*. Beijing: Science Press.

Monteith, J. L., and M. H. Unsworth. 1973. *Principles of Environmental Physics*. London: Edward Arnold Ltd.

Yao, Chonghuai, and Dexi Li. 2015. "Green Volume Ratio and Its Determination Mechanism." *Chinese Landscape Architecture* 31 (9): 5–11.

Tang, Xuehai. 2011. *Study on Estimation and Analysis of 3D Green Volume in the Six Urban Districts of Beijing.* Master's thesis, Beijing: Beijing Forestry University.

Zheng, Junming, Dandan Zhu, Mengying Jiang, et al. 2018. "Study on 3D Green Volume and Its Influencing Factors of Three Mountain Parks in Fuzhou City." *Chinese Landscape Architecture* 34 (2): 89–93.

Ma, H., & Liang, S. 2022. Development of the GLASS 250-m leaf area index product (version 6) from MODIS data using the bidirectional LSTM deep learning model. Remote Sensing of Environment, 273, 11298

Meta, and World Resources Institute (WRI). 2023. *High-Resolution Canopy Height Maps (CHM).* Source imagery for CHM © 2016 Maxar.Accessed [14 12 2024].

Wuhan Municipal Bureau of Statistics. 2021. *The Seventh National Population Census Bulletin of Wuhan City.* Published September 16, 2021. Accessed [14 12 2024].https://tjj.wuhan.gov.cn/ztzl_49/pczl/202109/t20210916_1779157.shtml.

Ministry of Housing and Urban-Rural Development of the People's Republic of China. 2018. *Urban Residential Area Planning and Design Standards.* Accessed [14 12 2024]. http://www.mohurd.gov.cn.