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Research on Carbon Sink Performance of Blue-Green Spaces in the Wuhan Garden Expo Park

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ABSTRACT: Investigating the carbon sink performance of urban blue-green spaces can help guide reasonable construction of urban carbon pools and enable to scientific assessment of carbon sinks. Among the existing studies, there are few mesoscale studies and comprehensive benefits of blue-green spaces are rarely investigated. Thus, this study attempted to perform a a long-term follow-up investigation of the Wuhan Garden Expo Park, which was built five years ago. In particular, attention was paid to the comprehensive assessment of the carbon sink capacity of blue-green spaces formed by water bodies and green spaces in the Park. Spatial and ecological data on the Park was acquired using ENVI and GIS software and was based on construction drawings and on-site sampling surveys. Vegetation, soil, and water environments in the Park were assessed with reference to the National Tree Benefit Calculator of the USA and the biomass estimation method. The main findings are as follows: (1) The total carbon sink in the blue-green space is about 111,485.4 tons; (2) Vegetation and soil are major contributors to the total carbon sink, accounting for 62.9% and 36.96%; (3) Vegetation with high carbon sink capacity, such as trees with strong carbon sinks, can significantly improve the carbon sink performanc of green spaces; (4) Permeable soils significantly contribute to carbon sinks; (5) Water in the blue-green space only accounts for 0.14% of the carbon sink. However, aquatic vegetation in wetlands can improve the carbon sinking potential of water bodies. This study provides a reference for future mesoscale research on carbon sink performance assessment in urban areas.

KEY WORDS: landscape architecture; landscape performance; carbon sink performance; blue-green spaces; Wuhan Garden Expo Park

Introduction

Against the backdrop of continuously intensifying global warming, research on the carbon sink capacity of urban green spaces has attracted significant attention [1-5]. Carbon sink generallyrefers to the process by which carbon dioxide is removed from the atmosphere—namely, the process and capacity through which various systems (forests, vegetation, soils, wetlands, etc.) absorb and store CO_2 through their ecological functions. When the carbon sequestration within a certain ecosystem exceeds its carbon emissions, the process is a carbon sink; otherwise, it acts as a carbon source [6, 7].

Current research on the carbon sink performance of urban green spaces mainly focuses on: (1) The macro scale, which examines the benefits of carbon sinks provided by urban green space systems [3-5, 8-9]. Models such as *Citygreen* and *i-Tree* Eco developed under the U.S. Landscape Performance Series (LPS) [10-19] are com-

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monly employed; (2) The micro scale, which focuses on the benefits of carbon sinks of different plant species. Methodologies employed in this area include biomass estimation, regression-based estimation, and photosynthesis rate measurement [20-28]; (3) The meso scale, which examines the carbon sink performance of urban Parks, associated green spaces, and various public green spaces. Compared with the macro and micro scales, fewer studies have been conducted at this scale, and they primarily focus on the carbon sink capacity of trees, often resulting in conclusions with substantial uncertainties [29-36, 34, 36-38].

Specifically, in 2015, Wuhan launched a project themed "Eco-Expo, Green Life," transforming the former Jinkou Landfill into a green space through advanced ecological restoration theories and technologies. The site, now known as theWuhan Garden Expo Park (hereafter referred to as 'the Park'), covers a total area of 213.77 hectares (Figures 1-3). This transformation turned the site from a victim of environmental degradation into a beneficiary of ecological restoration. The Park was awarded the "2015 C40 Cities Awards" at the UN Climate Change Conference [39]. Therefore, our team selected the Wuhan Garden Expo Park as its primary case and, based on the blue-green space (i.e., green spaces and water bodies) concept [40, 41], conducted a follow-up investigation on the carbon sink mechanisms and pathways of its vegetation (including trees, shrubs, and herbaceous plants), soils (the soil substrates covered by terrestrial plants in the Park), and water bodies. Our aim is to estimate the comprehensive carbon sink performance of the Park's blue-green spaces five years after its completion, and provide a reference case for studies on comprehensive carbon sink performance of urban green space at the meso scale.

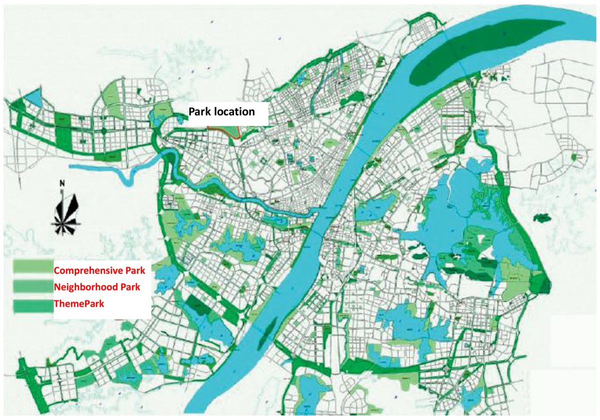

Figure 1 Location of theWuhan Garden Expo Park in Wuhan

Figure 2 Aerial view of theWuhan Garden Expo Park

Figure 3 Ecological bridge in Wuhan Garden Expo Park

1 Research methodology

1.1 Extraction of site information for the Wuhan Garden Expo Park

Satellite remote sensing images of the Park (October 2019, 0.61 m resolution) were processed using ENVI software, including radiometric and atmospheric corrections to enhance classification accuracy. The images were interpreted with GIS software to analyze the coverage of main landscape elements within the Park (Figure 4). Next, construction drawings and on-site sampling surveys of the Park were combined for a comprehensive statistical analysis based on which the Park's vegetation statistics table (covering trees, shrubs, and herbaceous plants), soil table and information on water bodies were compiled.

For extraction of vegetation data, the site was divided by 100m x 100m grids into 190 numbered sample plots, each covering an area of 1 hectare (Figure 5). Plots smaller than 1 hectare at the corners and edges (some of which were omitted) were generally treated as individual sample plots and marked with red boundary lines. Field investigations were conducted in each plot to record species of trees and shrubs growing outdoors, along with measurements such as diameter at breast height (DBH), tree height, canopy spread, and health condition. These were supplemented with the research team's earlier findings on site, the Park's construction drawings, and the statistical analysis of 50 randomly selected subplots based on site surveys and construction drawings.

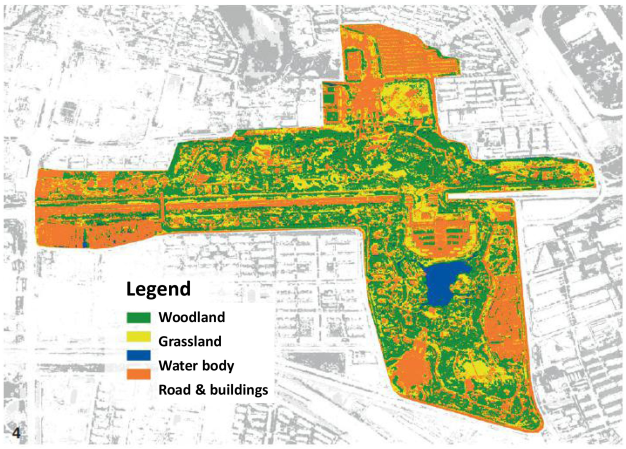

Figure 4 GIS data extraction for theWuhan Garden Expo Park

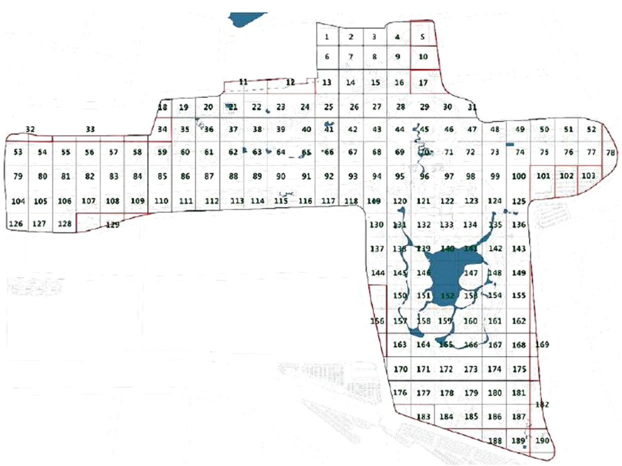

Figure 5 Site subdivision into 1-hectare sample plots using GIS software

1.2 Calculation of carbon sink performance

1.2.1 Calculation of carbon sink performance of vegetation

Vegetation in the Park was categorized into three groups—trees, shrubs, and ground cover (including herbaceous plants)—for separate carbon sink calculations. The total vegetation carbon sequestration is the sum of the carbon sinks of these three categories. Among them, the carbon sequestration of trees was calculated using the National Tree Benefit Calculator (NTBC) from the Landscape Performance Series (LPS)[42]. The calculation of carbon sequestration performance for shrubs and herbaceous ground cover was based on the method proposed by Dong Nannan et al. [43], combined with the findings of Zhao Yanling et al. [34], to derive the annual average carbon sink per unit area for each vegetation type (see Table 1). The formulas used to calculate the carbon sink performance of shrubs and ground cover [43] are as follows:

$$W_{annual\_mean\_carbon\_sequestration\_shrub\_herb} = M_{shrub\_herb} \times A_{shrub\_herb} \quad (1)$$

$$W_{total\_carbon\_sequestration\_shrub\_herb} = N \times W_{annual\_mean\_carbon\_sequestration\_shrub\_herb} \quad (2)$$

Table 1 Average carbon Sequestration rate of shrubs and herbaceous ground covers

Vegetation Type	Carbon Sequestration Rate	Unit
Shrubs	10.9	kg/(m² · a)
Herbaceous Ground Cover	0.4	kg/(m² · a)

Where:

$W_{annual\_mean\_carbon\_sequestration\_shrub\_herb}$ denotes the annual mean carbon sequestration of shrubs or herbaceous ground cover (unit: kg);

M_{shrub_herb} refers to the annual mean carbon sequestration rate per unit area for different types of vegetation (Table 1), unit: kg/(m^2 · a).

A_{shrub_herb} stands for the total planted area of shrubs or herbaceous ground cover in the Park (unit: m^2);

N represents the number of years since the completion of the Park (unit: year); as the Wuhan Garden Expo Park was completed in 2015, so N= 5;

$W_{total\_carbon\_sequestration\_shrub\_herb}$ refers to the total carbon sequestration of shrub or herbaceous ground cover over N years since the Park was built (unit: kg).

Table 3 Carbon sequestration per unit water area by type

Item	Value	Unit
Carbon Sequestration Rate of Water Body	0.06	kg/m²
Carbon Sequestration Rate of Aquatic Plants	0.09	kg/(m² · a)
Carbon Sequestration Rate of Sediments	0.38	kg/(m² · a)

1.2.2 Calculation of carbon sink performance of soil

The soil area considered in this study refers to the regions covered by vegetation. Soils under impervious surfaces and water bodies are excluded. A method proposed by Wu Wenting et al.[44] for calculating the soil carbon sequestration in urban green space in Hangzhou was used. The calculation results were organized to derive the annual mean carbon sequestration of soils under different vegetation types (see Table 2).

Table 2 Annual mean carbon sequestration rate of soil by type of vegetation community

Community Type	Annual Mean Carbon Sequestration Rate	Unit
Evergreen Broadleaf Forest	4.2	kg/(m² • a)
Deciduous Broadleaf Forest	5.0	kg/(m² • a)
Coniferous Forest	4.8	kg/(m² • a)
Bamboo	4.9	kg/(m² • a)

With reference to the study of Wu Wenting et al.[44], the carbon sink performance of soils inWuhan Garden Expo Park was calculated using the following formula:

$$W_{annual\_carbon\_sequestration\_soil} = Z_{soil} \times A_{soil} \quad (3)$$

$$W_{total\_carbon\_sequestration\_soil} = N \times W_{total\_carbon\_sequestration\_soil} \quad (4)$$

Where:

$W_{annual\_carbon\_sequestration\_soil}$ refers to the annual mean carbon sequestration of soil per unit area in the Park (unit: kg/a);

Z_{soil} indicates the annual mean carbon sequestration rate of soil under different vegetation communities (see Table 2), unit: kg/(m^2 • a);

A_{soil} refers to the total area of soil under different vegetation communities in the Park, (unit: m^2);

N refers to the number of years since the completion of the Park (unit: year);

$W_{total\_carbon\_sequestration\_soil}$ refers to the total carbon sequestration of soil in the Park (unit: kg).

1.2.3 Calculation of carbon sink performance of water bodies

According to related studies[45], there were no large water bodies on the site before the Park was constructed. Therefore, the total post-construction carbon storage in the Park's Chushui Lake represents the entire carbon sink performance of the Park's water bodies.

With reference to the methods used by Liu Bo[46] and Wang Huaxiang[47] in their studies on carbon sinks in lake ecosystems, we calculated and sorted out the carbon sequestration per unitarea for different types of water bodies (see Table 3).

The carbon sink performance of water bodies here include: (1) inorganic carbon and organic carbon dissolved within the water bodies; (2) carbon sequestration by aquatic plants in the water; and (3) carbon sequestration in sediment deposits. Based on the formulas proposed by Liu Bo et al. [46] for calculating lake carbon sequestration, we obtain the formulas for calculating carbon sequestration of water bodies in the Park as follows:

$$W_{carbon\_sequestration\_of\_water\_body} = Z_{water\_body \times A\_water\_body} \quad (5)$$

$$W_{annual\_carbon\_sequestration\_of\_aquatic\_plants} = Z_{aquatic\_plants} \times A_{aquatic\_plants} \quad (6)$$

$$W_{annual\_carbon\_sequestration\_sediment} = Z_{sediment} \times A_{sediment} \quad (7)$$

$$W_{total\_carbon\_sequestration\_water\_body} = W_{carbon\_sequestration\_water\_body} + N \times (W_{annual\_carbon\_sequestration\_aquatic\_plants} + W_{annual\_carbon\_sequestration\_sediment}) \quad (8)$$

Where:

$W_{carbon\_sequestration\_water\_body}$ refers to the carbon sequestered by dissolving in water bodies of the Park (unit: kg);

$W_{annual\_carbon\_sequestration\_aquatic\_plants}$ refers to the annual carbon sequestration rate of aquatic plants (unit: kg/a);

$W_{annual\_carbon\_sequestration\_sediment}$ refers to the annual carbon sequestration rate of sediment deposits (unit: kg/a);

Z_{water_body} refers to the carbon sequestration rate of water body per unit area (for both inorganic and organic carbon) (unit: kg/m^2);

$Z_{aquatic\_plants}$ refers to the annual mean carbon sequestration rate of aquatic plants per unit area (unit: kg/(m^2 • a));

$Z_{sediment}$ refers to the annual mean carbon sequestration rate of sediment per unit area (unit: kg/(m^2 • a));

A_{water_body} refers to the total area of water bodies in the Park (unit: m^2);

$A_{aquatic\_plants}$ refers to the total area of aquatic plants in the Park (unit: m^2);

$A_{sediment}$ refers to the total area of sediment deposits (unit: m^2);

N refers to the number of years since the Park's completion (unit: year);

$W_{total\_carbon\_sequestration\_water\_body}$ refers to the total carbon sequestration of water bodies in the Park (unit: kg).

Table 4 General information of Wuhan Garden Expo Park

Type	Area (hm²)	Coverage (%)
Green Space	176.4	82.55
Water Body	6.6	3.09
Buildings, Roads & Pavement	30.7	14.36
Total	213.7	100

Table 5 Vegetation information for of Wuhan Garden Expo Park

Vegetation Type	Quantity	Unit
Arbor Trees	53480	Each
Shrubs	60.8	hm²
Herbaceous Ground Cover	115.6	hm²

Table 6 Annual carbon sequestration of trees in Wuhan by type and size (unit: kg/plant · year)

Tree Type \ DBH (D, cm)	5< D ⩽10	10< D ⩽20	20< D ⩽30	30< D ⩽40
Deciduous Broadleaf Trees	32. 65	82.53	144.45	205.65
Evergreen Broadleaf Trees	26.76	68.93	143.76	227.20
Evergreen Coniferous Trees	20.41	56.69	122.46	195.46
Evergreen Palms	6.35	6.80	7.26	7.71

Table 7 Soil information by vegetation community type

Community Type	Proportion of Type (%)	Area of Soil (hm^2)
Deciduous Broadleaf Forest	49.55	87.4
Evergreen Broadleaf Forest	38.2	67.4
Coniferous Forest	10.48	18.5
Bamboo & Palms	1.77	3.1

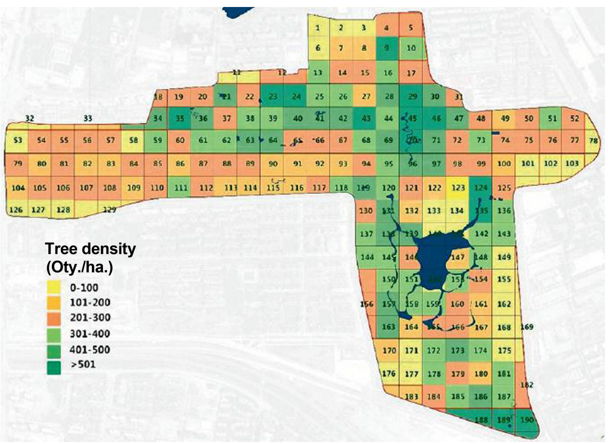

Figure 6 Tree density analysis of the Wuhan Garden Expo Park

Figure 7 Chushui lake and shanshan wetlands in Wuhan Garden Expo Park

2 Results and analysis

2.1 Land use statistics of blue-green spaces in Wuhan Garden Expo Park

(1)Land Use Statistics of Wuhan Garden Expo Park

The blue-green spaces in Wuhan Garden Expo Park consist of green spaces, water bodies, and built environments (including roads and paved areas). Detailed statistics are shown in Table 4.

(2)Vegetation Statistics

According to the analysis, the 190 sample plots had an average tree density of 230 trees/ha. Among these plots, 14 had a tree density of over 500 trees/ha, while the lowest recorded density was 2 trees/ha. Specifically, 30 plots had 0-100 trees/ha, 31 plots had 101-200 trees/ha, 56 plots had 201-300 trees/ha, 36 plots had 301-400 trees/ha, and 23 plots had 401-500 trees/ha (Figure 6).

The Park had over 410 species of plants, including 90-100 native species (Celtis sinensis, Metasequoia glyptostroboides, Acer buergerianum, Ulmus parvifolia, and Choerospondias axillaris) and 30-40 species native to Hubei (Cornus kousa, Cornus officinalis, Citrus ichangensis, Euonymus hamiltonianus, Cornus controversa, Prunus sibirica L., Prunus pseudocerasus, Cercis glabra Pamp, and Fraxinus hupehensis). Native species account for approximately two-thirds of the total vegetation[39]. With reference to the NTBC, we conducted comprehensive analysis and obtained vegetation statistics (Table 5) and reference carbon sequestration data on annual carbon sequestration by tree type and size (Table 6) in Wuhan Garden Expo Park.

There were approximately 35 species of evergreen trees, accounting for 36.9% of the total vegetation, and about 95 species of deciduous trees (with morphologically similar species counted as one), accounting for 63.1%. The ratio of evergreen to deciduous vegetation was approximately 1:1.7. The ten dominant species are Cinnamomum camphora, Koelreuteria paniculata, Osmanthus fragrans, Ginkgo biloba, Celtis sinensis, Cedrus deodara, Bischofia polycarpa, Photinia serratifolia, Sapium sebiferum, and Platanus acerifolia. Together, they accounted for 39.64% of all plants[38].

(3)Soil Statistics of the Park

Based on comprehensive analysis, the soil statistics across different vegetation community types in Wuhan Garden Expo Park are summarized in Table 7.

(4)Water Body Statistics of the Park

The water surface area in the Park was approximately 6.6 ha in total. Of this total, Chushui Lake covered about 6 ha, and the water area in Shanshan Wetland covered approximately 6,400 m^2(Figure 7).

2.2 Carbon sink benefit assessment of the Park

(1)Carbon sink benefit of vegetation

Based on aggregated calculations, the estimated carbon sink benefits generated by vegetation in the Park after its completion, as shown in Table 8, was approximately a total of 70,122.85 tonnes When the internationally recognized Swedish carbon tax rate of USD 150/tonne (approximately RMB 1,050/tonne) was applied, the overall carbon sink benefits of vegetation in the five years following the Park's completion amounted to RMB 73.629 million.

Table 8 Carbon sink benefits of vegetation in the Park

Vegetation Type	Annual Mean Carbon Sequestration (t)	Five-Year Carbon Sequestration after Completion (t)	Economic Value (RMB 10,000)
Arbor Trees	6934.97	34674.85	3640.86
Shrubs	6627.2	33136	3479.28
Herbaceous Ground Cover	462.4	2312	242.76
Total	14024.57	70122.85	7362.9

As shown in Table 8, arbor trees contributed the highest proportion of carbon sink, followed by shrubs. In urban landscape planning and design, selecting tree and shrub species with higher carbon sink capacity could significantly improve the carbon sink performance and value of the green spaces.

(2)Carbon sink benefits of soil

After the Park was built, it reached a total soil carbon sequestration of 41,203.5 tonnes, creating overall carbon sink benefits of approximately RMB 43.2637 million (Table 9).

(3)Carbon sink benefits of water bodies

Upon completion of the Park, its water bodies created a carbon sequestration of 159.06 tonnes in total. When expressed in economic terms, the carbon sink benefits of water bodies in the five years since completion were estimated at RMB 1.671 million (Table 10). Compared with vegetation and soil, water bodies contributed less carbon sink benefits.

(4)Overalrl carbon sink benefits of the park

By integrating the statistics of vegetation, soil, and water bodies, we obtained the statistics of total five-year carbon sink benefits of Wuhan Garden Expo Park upon its completion, as shown in Table 11.

Table 9 Carbon sink benefits of soil in the Park

Community Type	Annual Mean Carbon Sequestration (t)	Five-Year Carbon Sequestration after Completion (t)	Economic Value (RMB 10,000)
Evergreen Broadleaf Forest	2830.8	14154	1486.17
Deciduous Broadleaf Forest	4370	21850	2294.25
Coniferous Forest	888	4440	466.2
Bamboo & Palms	151.9	759.5	79.75
Total	8240.7	41203.5	4326.37

Table 10 Carbon sink benefits of water bodies in the park

Type	Annual Mean Carbon Sequestration (t)	Five-Year Carbon Sequestration after Completion (t)	Economic Value (RMB 10,000)
Carbon Sink of Water	0.79	3.96	0.42
Carbon Sink of Aquatic Plants	5.94	29.7	3.12
Carbon Sequestration of Sediments	25.08	125.4	13.17
Total	31.81	159.06	16.71

Table 11 Overall carbon sink benefits of the park

Carbon Sink Type	Five-Year Carbon Sequestration after Completion (t)	Percentage (%)	Economic Value (RMB 10,000)
Carbon Sink Benefits of Vegetation	70122.85	62.9	7362.9
Carbon Sink Benefits of Soil	41203.5	36.96	4326.37
Carbon Sink Benefits of Water Bodies	159.06	0.14	16.71
Total	111485.41	100	11705.98

Since its completion in 2015, the Park has sequestered a total of 111,485.41 tonnes of carbon, with vegetation contributing the most, followed by soil and water bodies contributing the least. Expressed in economic terms, the Park's integrated carbon sink benefits are valued at RMB 117.0598 million.

3 Conclusion and discussion

3.1 Urban blue-green spaces contribute substantial carbon sinks, though they are unevenly distributed

Urban blue-green spaces make significant contribution to carbon sinks, though the contributions from vegetation, soil and waterbodies vary.

(1) Vegetation contributed nearly two-thirds of the total carbon sink in our case study. The major reason is that vegetation acts as the dominant contributor to overall carbon sink capacity. Among all vegetation types, arbor trees, especially the larger ones, are the most effective in sequestrating carbon. According to NTBC, trees' capacity to capture carbon is generally proportional to their size. Moreover, different types of trees require different conversion factors. Large trees that are very capable of capturing carbon can significantly increase the overall carbon sink efficiency and value of an urban green space.

(2) Soil ranks second only to vegetation in terms of carbon sequestration benefits. It contributed about one-third of the overall benefits in this case. However, its role in carbon sequestration is often overlooked when urban green spaces are assessed for carbon sink performance. Although the carbon sequestration rates among soils under different vegetation types vary little, loose and porous planting soils have better carbon sequestration performance and support the carbon sink capacity of urban green spaces.

(3) In our case, the carbon sink benefits of water bodies were relatively limited, possibly attributable to the small proportion of water surface area in the Park. However, it also indicates that the majority of carbon sequestration of water bodies came from the carbon captured by sediments, which is consistent with the carbon sequestration characteristics of wetlands. We could infer indirectly that most of the carbon storage in wetlands came from the organic matter accumulated in silt. Planting aquatic vegetation in water bodies helps improve their carbon sink performance, which indicates a close relationship with green plants.

3.2 The localization of tools for calculating carbon sink benefits is in urgent need, and support for substantial fundamental research in this area is required

Some limitations remain in this study. For instance, the mean value estimation method was employed to estimate the carbon sink benefits of shrubs and herbaceous ground covers, so the outcomes may differ from the actual conditions. Reference data provided by NTBC and LPS were mainly used to estimate the carbon sink benefits of arbor trees. However, due to the different geographic and climatic conditions between China and the U.S., the carbon sequestration capacity of tree species may vary. Such limitations highlight the need for more fundamental data on carbon sink benefits of Chinese trees, so that conversion coefficients can be established, enabling more accurate and realistic assessments.

3.3 Awareness about carbon sink performance is essential in green space planning and design

The concept of carbon sink performance should be incorporated into urban green space planning and design from the outset. This requires a holistic approach that considers spatial layout, types of plants, buildings and structures, water bodies, site conditions, and landscape aesthetics to highlight the ecological benefits of green spaces. Particularly in built urban areas where land is scarce, enhancing carbon sink performance per unit area can better support low-carbon urban development and help mitigate the greenhouse effect.

3.4 Post-completion maintenance and management of blue-green spaces could improve overall carbon sink performance

Proper post-construction maintenance and management of blue-green spaces—especially the care of vegetation such as trees, shrubs, and herbaceous ground cover—can significantly enhance carbon sink benefits. This can reduce poor maintenance practices, such as inadequate pest and disease control, improper irrigation and fertilization, and poor planting techniques, which could lead to plant mortality or stunted growth. Additionally, compacted soils due to trampling, poor water infiltration and water pollution leading to large-scale die-off of aquatic vegetation can all adversely affect the carbon sink performance of green spaces. Conversely, sound maintenance and management can optimize the carbon sink performance of blue-green spaces.

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Sources of Figures and tables

Figure 1: Provided by Wuhan Landscape construction development Co., Ltd.

Figure 2: Provided by Yang Niandong.

Table 1: Adapted based on work by Dong Nannan[43] and Zhao Yanling[34].

Table 2: Adapted based on work by Wu Wenting[44].

Table 3: Calculated and adapted based on average values and rates derived from research on lake carbon sinks by Liu Bo [46] et al.

Table 6: Converted using reference data from the NTBC. Considering the applicability of the NTBC is limited to North America, the authors selected Chicago, a region similar in latitude, longitude, and climate to Wuhan, for conversion; for tree species selection, those similar (deciduous broadleaf, evergreen broadleaf, evergreen coniferous, etc.) or within the same family were chosen.

Table 7: Derived from remote sensing image analysis, interpretation and calculation using ENVI and GIS software. All other figures and tables were jointly prepared by the authors.

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