Enhancing Sustainable Cities Through Comparative Carbon Sink Benefits of Blue-Green Spaces: Evidence from Multi-Source Data

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Abstract
Cities, characterized by the coexistence of carbon emissions and sinks, face escalating climate challenges. This study advances carbon sink research by examining integrated blue-green space benefits, emphasizing neighbourhood scales as critical nexus points for intervention, combining ArcGIS and quantitative methods, we measured carbon contributions from green (e.g., vegetation) and blue spaces (e.g., water bodies), identifying green spaces—particularly arboreal vegetation—as dominant carbon sinks. Spatial aggregation of blue-green elements was identified as key determinants. We propose neighborhood-scale climate-adaptive strategies to enhance carbon sink performance and support sustainable urban development..

Keywords: Blue-Green Infrastructure, Sustainable Cities, Carbon Sinks, Climate-Adaptive Planning

1.Introduction

Urban areas constitute primary sources of carbon emissions whilst concurrently retaining substantial carbon sink potential. As complex spatial systems wherein emissions and sinks coexist, advancing sustainable urban development through emission mitigation and sink enhancement represents a critical pathway towards achieving China's "dual carbon" goals [1-5]. Contemporary research on urban carbon emissions predominantly focuses on building lifecycle energy consumption [6], extending analyses across multiple scales through interdisciplinary methodologies [7] and has yielded mature technical approaches. Nevertheless, high-density urban development has fragmented natural carbon sink spaces—primarily vegetated areas—diminishing their efficacy.

Scholarly investigations into urban carbon sinks face limitations arising from scale-induced methodological inconsistencies and intricate operational mechanisms, resulting in a "multi-dimensional dilemma": challenges in identifying sink components, delineating sink processes, and quantifying sink benefits. Within this context, targeted research has addressed carbon sink identification and performance. Zhou et al. [8] examined forest carbon sinks and storage in Guangzhou, whilst Liu et al. [9] quantified carbon sequestration capacity within Beijing's central urban parks, revealing that urban green space sink efficiency is influenced by vegetation typologies, habitat composition, and various determinants. Regional-scale carbon sink studies benefit from robust theoretical foundations, enabling established measurement and simulation techniques including the CITYgreen and i-Tree Eco models [10-19], alongside biomass methodologies and regression-based calculations [20-28]. These contributions have significantly advanced urban carbon sink research [29-30].

However, amidst escalating global warming and extreme weather phenomena, singular carbon sink spaces prove inadequate to address contemporary complexities. Research has consequently evolved from isolated examinations of green or blue spaces towards integrated analyses of composite urban blue-green space systems [31,33]. As fundamental ecological carriers for carbon sequestration, blue-green spaces demonstrate pronounced sink potential, extensively validated within the existing literature [31-33].

Collectively, current scholarship exhibits three salient characteristics:
(1) Prevailing studies compartmentalise blue and green spaces [34], overlooking synergistic carbon sink benefits [4];
(2) Technical constraints (e.g., limited data precision, ambiguous boundaries) and theoretical limitations (e.g., complex influencing mechanisms) impede accurate quantification of the carbon sink efficiency of blue-green spaces;
(3) Urban carbon sinks constitute a multi-scale challenge wherein measurement criteria—detection methods, computational formulae, and evaluation standards—diverge significantly across macro-, meso-, and micro-scales, necessitating explicit calibration of scale-induced variations.

Consequently, developing scientifically rigorous, high-precision carbon sink measurement methodologies that account for scalar heterogeneity forms the principal focus of this research.

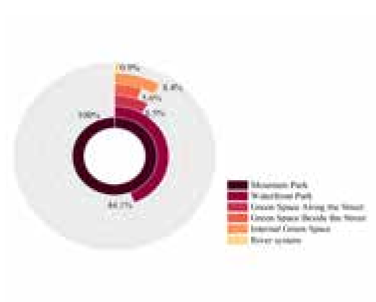
Neighbourhoods—the minimal spatial units holistically encompassing blue-green infrastructure elements and built infrastructure—are prioritised as the optimal scale for urban carbon sink investigation. Functionally, neighbourhoods integrate city-wide carbon sink systems whilst informing site-specific components, serving as critical spatial nexuses. This study therefore adopts the neighbourhood scale, integrating macro-scale remote sensing with micro-scale field data to mitigate single-source limitations. We quantify integrated carbon sink benefits and influencing factors within Nanjing's Yuejianglou neighbourhood. Subsequently, we propose climate-adaptive optimization strategies for blue-green space planning at this scale.

2.Materials and Methods

2.1 Study Area and Data Sources

This study selected the Yuejianglou neighborhood in Nanjing, China—a representative hot-summer/cold-winter climate zone—as the research case study. Nanjing possesses superior natural conditions as one of China's inaugural National Garden Cities, with built-up areas attaining 45.04 per cent green coverage by the end of 2023, establishing a robust carbon sequestration foundation. The Yuejianglou neighborhood exemplifies typical urban characteristics, incorporating blue-green infrastructure components including mountain parks (Shizishan Park), waterfront parks (Xiuqiu Park), street greenery (green space along the street), pocket greens (green space beside the street), community internal greens, and hydrological features (river system) (Table 1). Its significant low-carbon development potential renders it a representative case for investigating urban neighborhood-scale blue-green infrastructure carbon sinks.

Table 1: Spatial Types and Areas of Carbon Sink Elements in the Yuejianglou neighborhood of Nanjing

Spatial type	Vegetation type	Land area (m^2)	Area proportion
Mountain Park	Trees,	140,000	
Green Space Along the Street	shrubs,	24,300	
Internal Green Space	grasslands,	123,000	
Waterfront Park	Trees,shrubs, grasslands,	95,600	
Green Space Beside the Street	aquatic plants	13,000	
River system	Aquatic plants	135,355	

We extracted urban green space data using a generic deep learning framework [33] integrated with remote sensing. ENVI software facilitated preprocessing of green space elements, encompassing boundary delineation and area calculation, supplemented and validated through field surveys to ensure data completeness and accuracy. Vegetation typologies were catalogued via on-site investigations and statistical records; hydrological data originated from OpenStreetMap, with coordinate transformation and boundary extraction executed in ArcGIS. Carbon sink components comprised two categories: green spaces including mountain parks, waterfront parks, street greenery, pocket greens, and internal greens exhibiting point, linear, and areal spatial configurations; and blue spaces including lakes and rivers (e.g., the moat) displaying areal and linear distribution patterns. All data were standardised to uniform coordinates and units, culminating in a foundational geospatial dataset for the Yuejianglou neighbourhood's blue-green spaces (Figure 1).

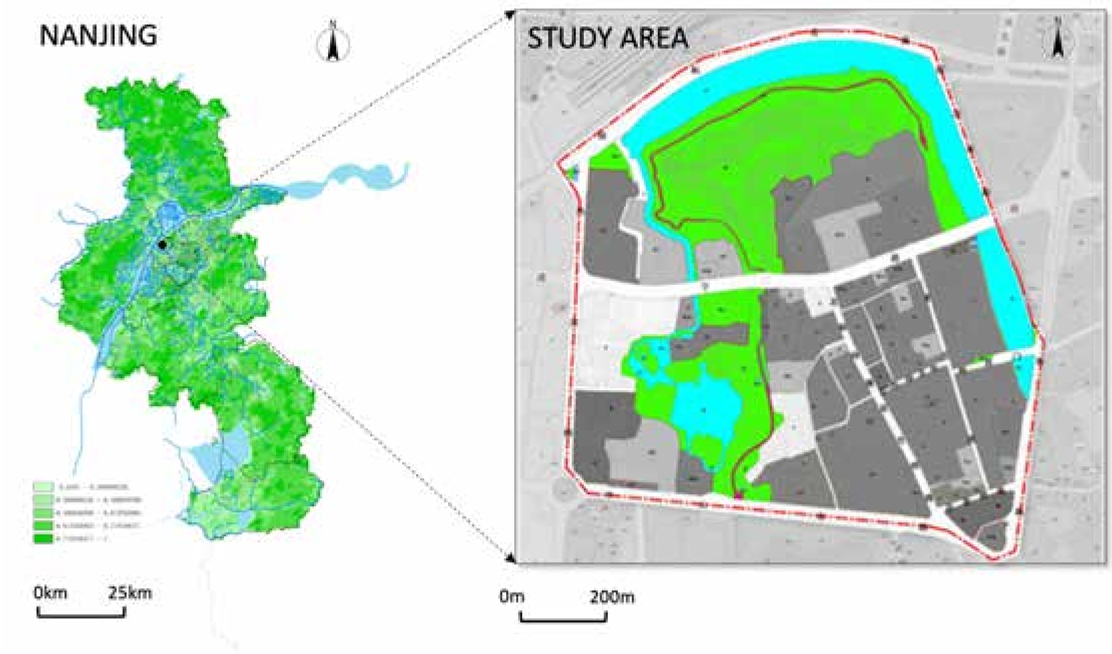


Figure 1: Distribution of Blue-Green Spaces in the Yuejianglou neighbourhood

2.2 Carbon Sink Calculation for Distinct Elements

Carbon sink quantification for neighborhood blue-green infrastructure encompassed two components.

1) Arboreal carbon sequestration: Calculated using the Landscape Performance Series (LPS) National Tree Benefit Calculator (NTBC) .

2) Shrub/herbaceous layer sequestration: Derived from established methodologies [35].

3) Aquatic carbon sinks: Computed using lake carbon sink methodologies [36-37], distinguishing contributions from water bodies and hydrophytes, with unit area sequestration rates categorised by waterbody type.

Spatial overlay analysis integrated biomass-based methods to quantify synergistic carbon sink enhancement in blue-green spatial interfaces. This approach incorporated vegetation-specific carbon sink coefficients and coverage areas, formalised as:

$$E = PVxBxVS$$

where:

E = Vegetation carbon sink (kg)

VS = Vegetation coverage area (m²)

B = Carbon sequestration per unit area (kg/m²)

PV = CO∆potential value (standardised to 1)

2.3 Influencing Factors of Blue-Green Space Carbon Sinks

We compiled carbon sink components (green spaces, water systems, soil, vegetation) and influencing factors, constructing a correlation model to examine their interrelationships. Influencing factors emphasised spatial patterns and configurations of components (Table 2) to inform design strategies. Pearson correlation analysis generated matrix of correlations between components and influencing factors, with statistical validation ensuring analytical objectivity.

Table 2: Constituent Elements and Influencing Factors of Blue-Green Space Carbon Sinks

Constituent elements		Influencing factors	Abbreviation
Green space	park green space area street green space area internal green space area	Green space concentration degree	GSCD
Water system	Water system area	Concentration degree of water system	CDWS
Soil	Permeable ground area	Vegetation richness	VR
Vegetation	Vegetation canopy width	Permeable ground coverage rate	PGCR

Note: Constituent elements refer to the elements that generate carbon sinks in the space, and the influencing factors refer to the elements that affect carbon sinks in the space

3.Results

3.1 Carbon Sink Benefits and Comparisons of Blue-Green Spaces

As illustrated in Figure 2, Shizishan Park—a mountainous park within the neighborhoods—exhibits rich vegetation communities, yielding an annual carbon sink of 806.92 t (tons), representing Yuejianglou's primary carbon sequestration zone. Street trees (predominantly Platanus spp., Cinnamomum camphora, and Celtis sinensis) contribute 79.50 t annually. Pocket greens generate 45.55 t/yr(tons/year), with vegetation including trees (Cinnamomum camphora, Celtis sinensis), shrubs (Pittosporum tobira, Loropetalum chinense, Photinia spp.), and herbaceous cover (Lolium perenne). Internal neighbourhood greens (residential greenspaces, flower beds) yield 56.24 t/yr, dominated by shrubs, herbs, and sparse trees.

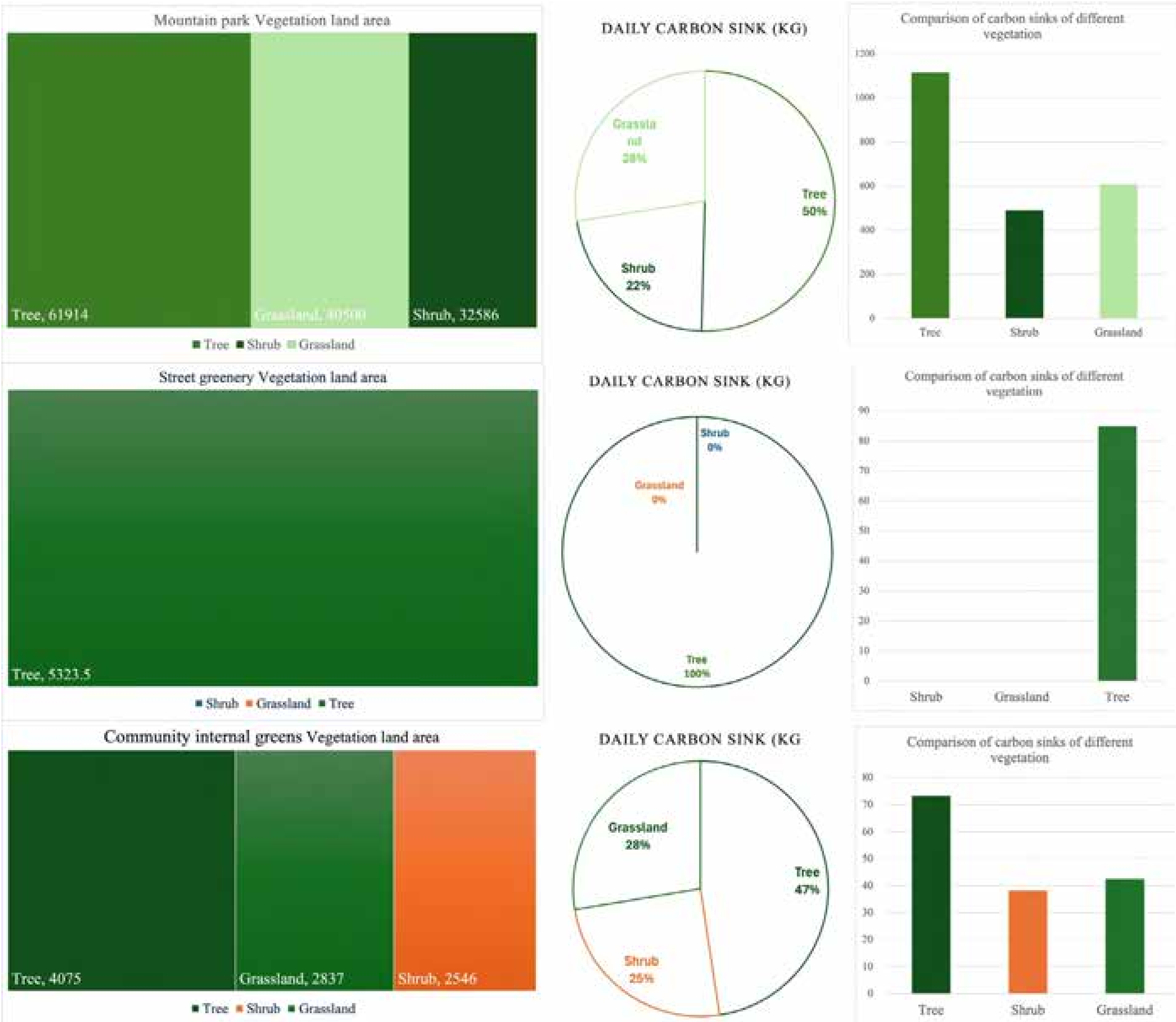


Figure 2: Area Proportion and Carbon Sink Benefits of Green Space Types (Mountain Park, Street Greenery, Internal Greens))

Blue space carbon sinks comprise lakes and rivers. Xiuqiu Park (Figure 3), a waterfront park, achieves 355.64 t/yr through integrated blue-green sequestration. However, its lake carbon sinks (79.05 t/yr) derive primarily from hydrophytes (Lythrum salicaria, Schoenoplectus tabernaemontani, Pontederia cordata, Phragmites australis), with negligible contributions from the water body itself. The moat's ecological ponds sequester 27.20 t/yr Hydrophytes account for 51% of aquatic carbon sinks despite occupying only 17% of water surface area, indicating their dominant role.

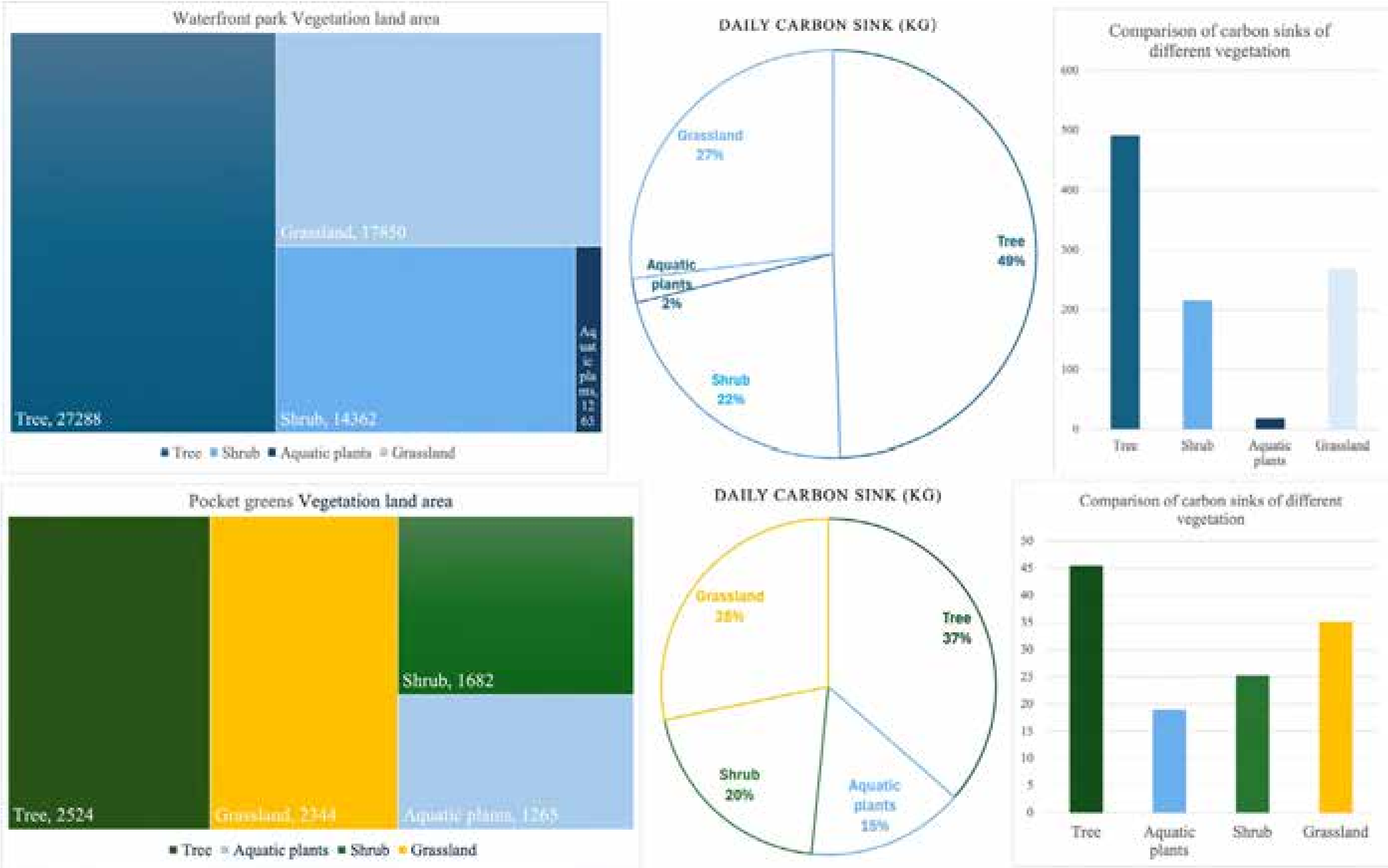


Figure 3: Area Proportion and Carbon Sink Benefits of Blue Space and Associated Riparian Greenspaces (Xiuqiu Park, Moat Riparian Zone))

Figure 4 illustrates the integrated relationship between spatial coverage and carbon sink benefits across diverse carbon sink typologies within the Yuejianglou neighbourhood.

Our analysis reveals two distinct carbon sink modalities: singular and composite systems. Shizishan Park, street trees, pocket greens, and internal neighbourhood greens constitute singular sinks predominated by green infrastructure, whilst the moat represents a singular blue-dominated system. Conversely, Xiuqiu Park and riparian green spaces along the moat exemplify composite blue-green systems, integrating lakes, hydrophytes, and terrestrial vegetation.

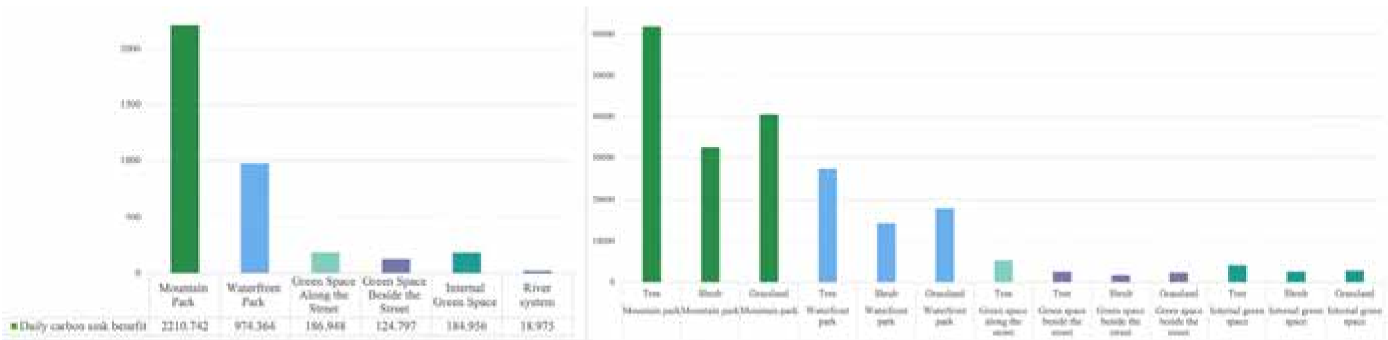


Figure 4: Relationship between Spatial Coverage Area and Carbon Sink Benefit by Space Type

3.2 Correlation Between Blue-Green Space Components and Carbon Sink Benefits

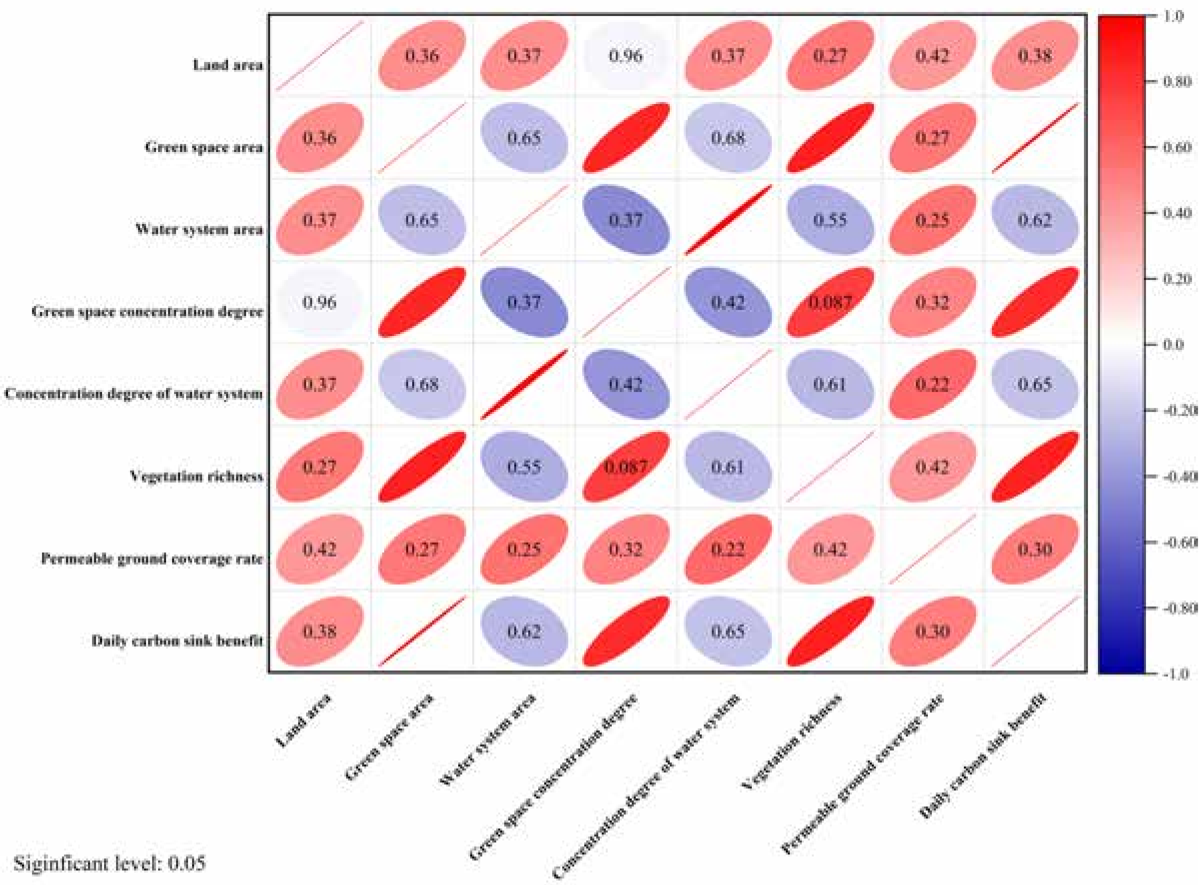


Figure 5: Correlation Analysis of Carbon sink Benefits of Blue and Green Spaces in the Yuejianglou Block

Correlation analysis (Figure 5) reveals carbon sink efficiency is jointly influenced by water system aggregation (as measured by CDWS) (r = 0.65) and green space aggregation (as measured by GSCD) (r = 0.62). Concentrated distributions of water bodies (e.g., lake-river connectivity) and green patches positively enhance overall carbon sequestration. Aggregated blue-green configurations promote efficient carbon sink functionality, with water aggregation (CDWS) exhibiting marginally stronger effects than green aggregation (GSCD).

Key correlations include:
1) Green space area and aggregation (GSCD): Strongest correlation (r = 0.96), indicating larger areas facilitate clustered green patches.
2) Total study area: Weak positive effects on water coverage and carbon sinks, but is less significant than green aggregation.
3) Water coverage: Marginal positive impact on carbon sinks.
4) Vegetation richness (VR) and water aggregation (CDWS): Moderately weak correlation (r = 0.55), suggesting aquatic clustering may mildly enhance plant diversity.
The neighbourhood's total annual carbon sink (1,314.36 t) displays significant spatial heterogeneity.

Key findings:
1) Green Spaces Dominate: Shizishan Park contributes 61.4% (806.92 t), confirming green infrastructure as the primary carbon sink component.
2) Blue Space Enhancements: Hydrophytes and riparian zones significantly boost aquatic sinks. Xiuqiu Park's water body contributes only 6% (79.05 t), but ecological riparian zones exhibit higher carbon density (1.2 t/h(tons/ha)) than hardened banks (0.4 t/h). Riparian interfaces correlate positively with terrestrial vegetation.

3) Linear Street Greenery Optimisation: Street trees (79.50 t) demonstrate a strong "tree size-carbon sequestration" relationship (R^2 = 0.73). As arboreal vegetation yields the highest per-unit sequestration, streetscapes—particularly tree-lined corridors—constitute critical optimisation spaces in high-density urban contexts.

4. Discussion

Our findings indicate that vegetation carbon sinks within green spaces predominantly contribute to overall carbon sink benefits (e.g., Shizishan Park's annual carbon sequestration of 806.92 t surpasses all other spatial types). Among vegetation categories, arboreal species—particularly large-specimen trees—demonstrate superior carbon sequestration capacity. This substantiates the principle posited by the National Tree Benefit Calculator that tree carbon sink potential correlates positively with dimensions. Concurrently, vegetation type significantly influences carbon sink efficiency, with distinct tree species exhibiting variable carbon sink coefficients. Consequently, trees characterised by high coefficients and substantial dimensions markedly enhance integrated green space carbon sink performance. Nevertheless, this remains contingent upon total green space area. Street tree selection and optimisation should therefore prioritise large-specimen trees with elevated carbon sink coefficients.

Regarding spatial correlations, water system aggregation (CDWS) (r = 0.65) and green space aggregation (GSCD) (r = 0.62) constitute primary determinants of integrated carbon sink benefits, further evidencing that carbon sink research necessitates combined analysis of blue and green spaces. More aggregated spatial configurations of water bodies and green patches enhance carbon sink functionality. Notably, water aggregation (CDWS) exerts marginally stronger effects than green aggregation (GSCD). Additionally, blue and green spaces exhibit synergistic spatial patterning, evidenced by a significant moderate positive correlation between water aggregation (CDWS) and green aggregation (GSCD) (r=0.68).This reveals that clustered aquatic areas frequently coexist with aggregated green zones (or vice versa), potentially influenced by shared topographic, planning or ecological processes. Spatial design should thus strategically adjust blue-green ratios to optimise carbon sinks within constrained areas.

Concerning influencing factors, vegetation structure and composition principally govern singular carbon sinks. For instance, broadleaf trees (e.g., Platanus spp.) sequester 12.6 kg/m² annually, which is 4.1 times the capacity of grasslands.[31] Secondly, spatial connectivity critically influences integrated sinks; blue-green ecological corridors (>30m width) elevate carbon density by 18–22%. Moreover, soil carbon sink contributions warrant attention: permeable surfaces exhibit 40% higher efficiency than impervious surfaces, while each 1% increase in organic matter boosts sequestration by 7.3%. These findings advocate incorporating "grey space" (permeable surfaces) into integrated sink frameworks, extending analysis from blue-green to blue-green-grey systems. Future research should quantify permeable soil carbon sinks and integrate them as design elements to substantially enhance neighbourhood-scale sequestration.

Optimisation Strategies focus on two dimensions: Sink enhancement: Blue spaces: Introduce hydrophytes (Lythrum salicaria, Phragmites australis) to augment aquatic contributions. Green spaces: Increase neighborhoods tree coverage from 30% to 50%, projecting 15–20% annual sink gains. Prioritise aggregated, interconnected blue-green spatial configurations.

Multifunctional synergy: Transform moat riparian zones into "carbon-neutral landscape corridors" integrating ecological, aesthetic, and recreational functions. Implement community carbon sink trading mechanisms to incentivise public engagement.

Technological advancements—particularly AI-enabled dynamic carbon flux monitoring, automated vegetation identification, and high-resolution data analytics—will refine future research precision, enabling robust, objective conclusions.

5.Conclusions

This study employed multi-source datasets to identify spatial distributions of carbon sink components in Nanjing's Yuejianglou neighbourhood, utilising ArcGIS and quantitative calculations to evaluate carbon sink benefits from green and blue spaces, establish correlations among influencing factors, and analyse determinants across spatial typologies. Climate-adaptive optimisation strategies were subsequently formulated. Key findings demonstrate that green spaces constitute the primary carbon sink domain, with arboreal vegetation exhibiting superior sequestration capacity. Spatial aggregation of blue-green elements and green space area emerged as dominant influencing factors, with water aggregation (CDWS) exerting marginally stronger effects than green aggregation (GSCD). Notably, soil contributions—exhibiting sink benefits analogous to green spaces—were identified as a significant yet previously underemphasised dimension. Consequently, spatial design strategies are proposed: optimising blue-green ratios, enhancing street tree efficiency, adjusting aquatic plant communities, expanding riparian green areas, and establishing carbon-neutral landscape corridors.

Nevertheless, limitations persist regarding the precision of blue-green infrastructure component identification and the exclusion of carbon emission calculations during sink processes. Future research should integrate artificial intelligence algorithms for digital vegetation recognition to improve survey efficiency and accuracy. Concurrently, dynamic models capturing temporal variations in emission-sink processes would enhance the objectivity and scientific rigour of blue-green space assessments. Furthermore, incorporating microclimatic influences (e.g., urban heat island effects) through multi-scale validation via atmospheric inversion data (e.g., CO∆ monitoring stations) presents a critical avenue for advancement.

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Appendices
Not included in this excerpt

Acknowledgements
Zhihan Zhang completed the framework and data measurement of the entire thesis, as well as the writing of the entire article and the drawing of the figures

Yuyue Huang completed the data research and organization of the Yuejianglou neighbourhood and participated in the drawing of the figures

Xun Zhang completed the basic data research and organization of the Yuejianglou neighbourhood and participated in the drawing of the figures

Qingxin Yang completed the plant data research and organization of the Yuejianglou neighbourhood and participated in the drawing of the figures

Junyan Yang provided guidance and supervision for this research