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Study on the Optimization of Carbon Sequestration in Shanghai's Urban Artificial Wetlands: The Cases of Shanghai Fish and Dishui Lake

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Abstract: The study focused on optimizing carbon sequestration in urban artificial wetlands, using the Shanghai Fish and Dishui Lake as case studies. As cities like Shanghai experienced rapid urbanization, natural wetland areas diminished, making artificial wetlands essential for carbon storage and ecosystem preservation. The study investigated how various factors—such as plant species, wetland size, and landscape patterns—influenced carbon sequestration. Through field surveys and remote sensing, carbon density changes from 2018 to 2023 were analyzed using grid-based landscape pattern metrics. Results showed significant spatial variation in carbon sequestration, with larger, more fragmented wetland patches contributing more to carbon storage. Emergent plants, particularly *Phragmites australis* and *Typha angustifolia*, demonstrated the highest carbon sequestration potential. The research proposed three optimization models (point, linear, and planar) tailored for different wetland areas, focusing on expanding plant diversity, enhancing landscape complexity, and improving patch distribution. After optimization, carbon storage in the Shanghai Fish wetland was projected to increase by 2.6 times, while Dishui Lake's carbon storage was expected to grow by 3.5 times. The study concluded that carefully planned wetland management, emphasizing plant species selection and spatial design, could significantly enhance carbon sequestration, contributing to Shanghai's carbon neutrality goals. The research provided valuable insights for urban ecological planning, highlighting the role of artificial wetlands in climate regulation.

Keywords: artificial wetlands; carbon sequestration optimization; plant community structure; carbon density distribution; landscape pattern

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1. Introduction

Wetlands, as one of the most important ecosystems in nature, serve multiple functions, including climate regulation, water quality improvement, biodiversity protection, and carbon sequestration. Through plant photosynthesis and organic carbon accumulation in soil, wetlands can sequester carbon dioxide over the long term, reducing the emission of greenhouse gases. Wetlands play a critical role as key carbon sinks in climate regulation [1]. Wetlands are highly productive ecosystems because wetland plants are the most effective agents of carbon assimilation [2], accumulating large amounts of organic matter in the soil, thus serving as significant carbon sinks. Although wetlands only cover 6–8% of freshwater surfaces, it is estimated that they hold one-third of the global organic soil carbon stock [3,4]. Among these, artificial urban wetlands form an important part of terrestrial wetland ecosystems' carbon reserves and are being increasingly adopted internationally [5]. In recent years, as global warming and climate change have intensified, research on the carbon sequestration potential of wetlands has gained increasing attention.

Currently, research on wetland carbon sequestration primarily focuses on the carbon sequestration functions of natural wetlands and the impact of wetland degradation on

the carbon cycle [6]. The carbon sequestration function of artificial wetlands is mainly influenced by factors such as wetland area, vegetation types, and hydrological conditions. Additionally, it is closely related to maintenance and management methods [7–10]. Research on the carbon sequestration patterns and capacity enhancement pathways of urban artificial wetlands is mainly discussed from three scales: firstly, conducting a general analysis at the city-wide scale; secondly, exploring the carbon sequestration capacity of different aquatic plant communities in specific wetlands at the regional scale to reveal the relationship between carbon sequestration patterns and water; and thirdly, studying the influence of specific plant species on the carbon sequestration patterns of wetlands at the local scale.

At the city-wide scale, Rogerson et al. (2021) [11] found that urban artificial wetlands not only contribute to carbon sequestration but also create broad social and ecological value. Fan Zhang et al. (2020) [8] studied the impact of urban land use changes on wetland carbon sinks in Shanghai and found that urbanization led to reduced wetland area and weakened carbon sequestration capacity. Song et al. [12] used the CASA model to estimate carbon sequestration in Wuhan's wetlands, revealing the spatial and temporal variations in wetland carbon sink capacity.

The regional scale focuses on analyzing the carbon sequestration capacity of different aquatic plant communities in specific wetlands. Wang et al. [9] found that changes in plant community structure in Beijing wetlands, particularly under nutrient-rich conditions, enhanced carbon sequestration, with *Phragmites australis* significantly boosting biomass and carbon storage. Bernal and Mitsch [13] studied two 15-year-old artificial wetlands in Ohio, categorizing plants into open water, emergent, and edge communities. They observed higher carbon sequestration in open deep-water communities compared to shallower emergent vegetation.

Finally, at the local scale, studies investigate how specific plant species influence wetland carbon sequestration. Xu et al. [10] examined *Leersia hexandra*, *Canna indica*, *Colocasia esculenta*, and unvegetated plots, revealing considerable seasonal variations in carbon sequestration across flooded and waterless areas. Plant type, growth region, and seasonal changes significantly affect carbon sequestration in artificial wetlands.

The pathways for enhancing the carbon sequestration capacity of urban artificial wetlands are mainly discussed in the following aspects:

Optimizing the carbon sequestration pattern: Studies have shown that the larger the wetland area, the stronger the carbon sequestration capacity; conversely, wetland fragmentation and irregular distribution reduce its carbon sequestration ability [12]. Therefore, changes in the carbon sequestration pattern of urban wetlands are closely related to urbanization and wetland protection measures, and reasonable spatial planning is crucial for enhancing the carbon sequestration capacity of wetlands.

Refining the plant community structure of wetlands: Refining species composition and regulating hydrology can greatly enhance the carbon storage of artificial wetlands [14]. A three-layer structure of trees, shrubs, and herbaceous plants maximizes space utilization and boosts carbon sequestration [15]. Additionally, selecting high-biomass species can further improve carbon sequestration efficiency.

Improving hydrological management of wetlands: Hydrological conditions, particularly water level changes, significantly influence wetland carbon sequestration by affecting plant growth and organic carbon fixation. Regulating water levels and extending retention time can enhance organic carbon deposition [16]. Wetland restoration projects also help offset urbanization-induced carbon sequestration losses through ecological management [17].

Enhancing wetland layout based on ecological networks: Research shows that improving the clustering efficiency of wetland ecological nodes helps to strengthen the carbon fixation capacity of wetland systems [18]. In coastal wetlands, ecological corridors and 'steps' can promote the functional restoration of wetland systems, thereby boosting carbon sequestration.

As an international metropolis in China, Shanghai is rich in urban wetland resources. Its artificial wetlands play an indispensable role not only in flood prevention, disaster

mitigation, and water supply but also in carbon sequestration [19]. However, over the past 20 years, with the rapid advancement of urbanization, the area of natural wetlands in Shanghai has gradually decreased, and their ecological functions have been weakened. Enhancing the ecological carbon sequestration capacity is a key task in achieving 'carbon peak' and 'carbon neutrality', making it urgent to study how to improve the carbon sequestration functions of urban wetlands.

Addressing the ecological impact of rapid development and enhancing carbon sequestration in urban wetlands is a key strategy in the city's plan to achieve carbon neutrality. According to Shanghai's planning goals, the city aims to become a world-class 'wetland city' and a globally renowned 'eco-city' by 2035 [20]. This study will take the artificial wetlands of 'Shanghai Fish' and 'Dishui Lake' as case studies to explore the spatial and temporal changes in carbon stocks and propose strategies for optimizing carbon sequestration. The goal is to provide scientific guidance for the future planning and development of urban wetlands, thereby contributing to the broader objective of enhancing urban ecological resilience and achieving carbon neutrality.

2. Materials and Methods

2.1. Research Area

The research area includes Shanghai Fish and Dishui Lake of Shanghai, two typical artificial wetlands located in eastern China, near the Pacific Ocean, on the eastern side of the Asian continent, which are part of the Yangtze River Delta. Their geographical coordinates range from 120°52′ E to 122°12′ E and 30°40′ N to 31°53′ N (Figure 1). A variety of wetland plants are planted in both artificial wetlands, and the analysis of carbon sequestration patterns at the initial stage of construction and at present, along with their influencing factors, can provide scientific guidance for improving the carbon sequestration function of urban wetlands.

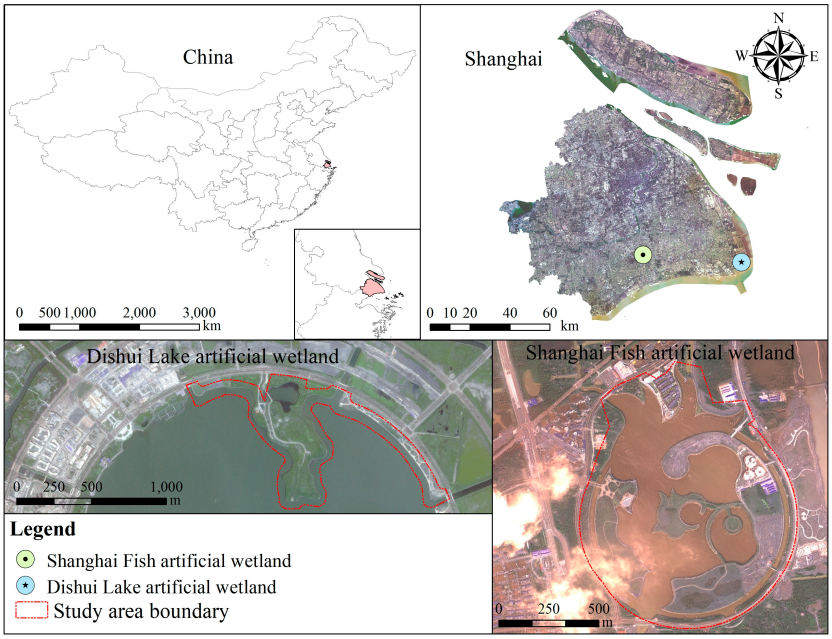


Figure 1. Schematic map of the study area.

2.2. Carbon Density

(1) Field Survey Method for Measuring the Carbon Storage of Wetland Plants

A field survey was conducted in late September 2023. Based on the representativeness of plant species, uniformity of distribution, readability of remote sensing data, and the operability of the field survey, 1 m × 1 m quadrats were set up. The plant density within each quadrat was recorded, ensuring the samples were representative and complete (in-

cluding aboveground parts, underground parts, and soil). Soil samples were dried at a constant temperature of 105 °C until a constant weight was reached to calculate soil bulk density and soil carbon density. Soil bulk density represents the ratio of dry soil mass to the volume of the soil sample, while soil carbon density is derived from the product of soil carbon content, soil bulk density, and sampling depth [21]. The samples were dried, and ground, and their carbon content was measured using an elemental analyzer.

(2) Remote Sensing Data Analysis and Carbon Density Estimation

The remote sensing data for the two wetlands, Shanghai Fish and Dishui Lake, were sourced from the Land Observation Satellite Data Service (https://data.cresda.cn (accessed on 4 September 2018)) and Today's Earth Imagery on Xingtu Earth (https://daily.geovisearth.com (accessed on 5 August 2018)) for 2018, with resolutions of 0.8 m and 0.9 m, respectively. The 2023 remote sensing data were captured using a DJI Mavic 3M drone with a resolution of 0.03 m.

Image preprocessing in remote sensing involves correcting systematic errors and calibrating remotely sensed imagery to ensure consistent and comparable data. The typical steps involved in remote sensing image preprocessing include radiometric calibration, atmospheric correction, geometric correction, image fusion, mosaic, and clipping [22,23].

The theoretical basis for image preprocessing lies in the need to correct sensor-related biases and environmental interferences, thereby improving data quality and feature expression. Radiometric calibration aims to adjust the radiometric values recorded by sensors to real-world reflectance values, allowing comparison across different dates and sensors. Atmospheric correction is performed to eliminate the effects of atmospheric scattering and absorption. Geometric correction is employed to rectify any spatial distortions and to align images with true geographical coordinates, making it possible to accurately compare images over time. Image fusion and mosaic are used to merge images with different spatial resolutions or spectral bands, enhancing feature identification capabilities, while clipping ensures that only the study area of interest is analyzed, thus removing unnecessary information.

The measured carbon sequestration data of wetland plants and vegetation indices obtained from remote sensing images were used to establish a model for estimating the carbon sequestration of wetland plants. The normalized difference vegetation index (NDVI) and the ratio vegetation index (RVI) were utilized to estimate the carbon sequestration of wetland plants [24]. Based on the carbon density values of wetland plants and the corresponding quadrat's RVI, SPSS and Excel were used to perform correlation analysis and model construction for the two sets of data. The carbon density values in the study area were calculated using the established vegetation carbon density inversion model.

2.3. Grid-Based Calculation and Extraction of Carbon Sequestration Zones

The research area was divided into different grid units, and the carbon density of each unit was calculated and evaluated independently [25]. Grid-based calculations facilitate regional management and detailed assessments, which not only enable comparison and analysis of the carbon sequestration capacity across different areas but also help identify key areas with high carbon sequestration potential. This serves as a basis for developing targeted carbon sequestration management strategies. The selected grids should meet two criteria: first, they should not be boundary grids, as some areas within boundary grids may lack data; second, they should ideally include multiple types of wetland plants, which allows for exploration of the relationship between wetland plant landscape patterns and changes in carbon stock.

Grid-based analysis relies on the theoretical principle of spatial heterogeneity, which recognizes that variations in landscape elements (such as plant species and soil conditions) are critical to understanding ecological functions. By using grids, the study aims to systematically assess spatial patterns of carbon density and to determine how landscape metrics relate to carbon storage changes. This method facilitates a detailed examination of the influence of different landscape configurations on carbon sequestration.

This study used grid-based analysis to extract the changes in carbon stock and landscape pattern indices from multiple grids based on the spatial distribution of carbon density changes in the two artificial wetlands from 2018 to 2023. Fragstats 4.3 was used to calculate the landscape pattern indices [26], and SPSS 22 and Origin 8.0 software were used to analyze the correlation between landscape patterns and carbon sequestration effects. The correlation between these factors was explored to guide the design of wetland plant carbon sequestration models. If the grid scale is too small, it may cause further fragmentation of the original wetland plant landscape, thereby obscuring the spatial characteristics of the plant landscape pattern and carbon sequestration performance. On the other hand, if the grid scale is too large, it may overlook spatial heterogeneity at smaller scales. To ensure the capture of grid samples with unique landscape pattern structure characteristics, and considering the size of the study area and the existing scale of wetland vegetation planting, a grid scale of 50 m was chosen for this study. In ArcMap 10.7, a 50 m × 50 m grid was created by using the research area outline as a mask, and the changes in carbon stock for each grid were extracted.

3. Results

3.1. Distribution of Carbon Stock Changes in Different Grids

The changes in carbon stock within each grid are shown in Figures 2 and 3. The grid with the largest reduction in carbon stock in Shanghai Fish decreased by 5.66 kg, while the grid with the largest increase in carbon stock increased by approximately 4.25 tons. In Dishui Lake, the grid with the smallest increase in carbon stock increased by 2.25 kg, while the grid with the largest increase in carbon stock increased by approximately 4.25 tons. The total number of grids in Shanghai Fish was 474, of which 306 were effective grids; in Dishui Lake, the total number of grids was 269, with 181 effective grids.

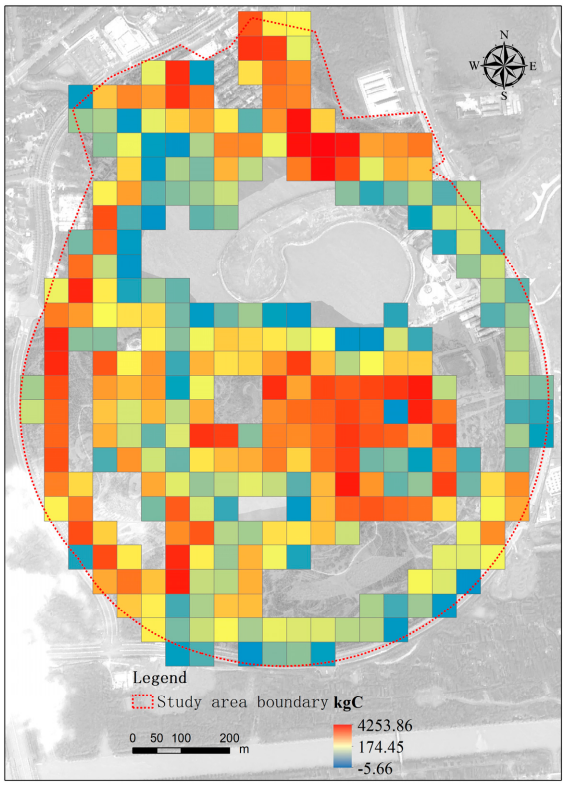


Figure 2. Distribution of carbon stock changes under 50 m × 50 m grids in Shanghai Fish.

After excluding the two grids with the largest and smallest changes in each wetland, sample grids with different values were selected. The ratio of effective grids between Shanghai Fish and Dishui Lake was approximately 5:3. To ensure sufficient sample size,

10 sample grids were selected from Shanghai Fish, numbered S01 to S10 (Figure 4), and six sample grids were selected from Dishui Lake, numbered D11 to D16 (Figure 5), for a total of 16 sample grids.

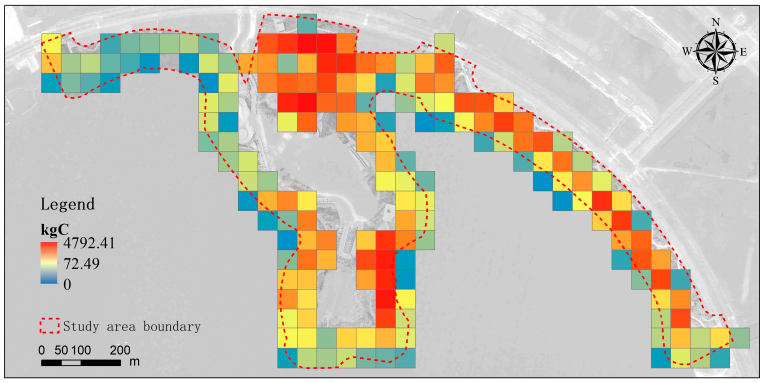


Figure 3. Distribution of carbon stock changes under 50 m × 50 m grids in Dishui Lake.

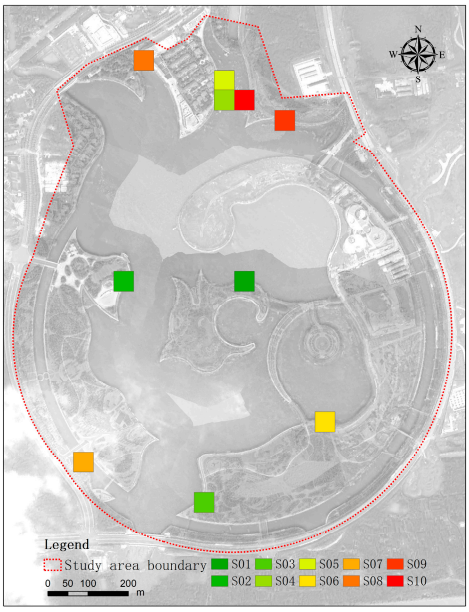


Figure 4. Distribution of sample grids in Shanghai Fish.

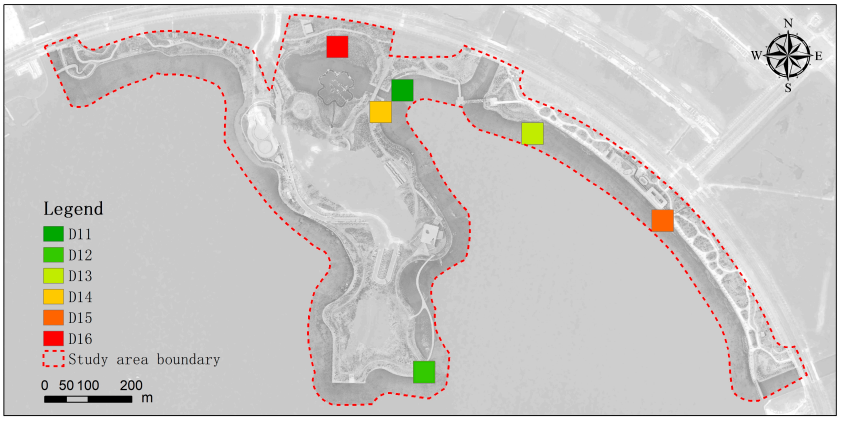


Figure 5. Distribution of sample grids in Dishui Lake.

Using the attribute table tool in ArcMap 10.7 and Excel, the increase in carbon storage quantity for the 16 sample grids, the wetland plant area, and the proportion of plant coverage were organized (Table 1). The grid with the smallest increase in carbon storage was D11, with only 128.09 kgC, and it had the smallest wetland plant area. The grid with the largest increase in carbon storage was D16, with an increase of 3822.56 kgC, and it had the largest wetland plant area.

Table 1. Carbon storage increase and wetland plant area for sample grids.

Serial Number	Grid ID	Carbon Storage Increase (kgC)	Wetland Plant Area (m^2)	Proportion of Wetland Plant Area
1	S01	139.46	151.68	6.07%
2	S02	265.75	176.64	7.07%
3	S03	450.07	248.96	9.96%
4	S04	734.19	470.40	18.82%
5	S05	911.41	556.80	22.27%
6	S06	1010.82	942.72	37.71%
7	S07	1229.35	819.20	32.77%
8	S08	1514.98	1043.84	41.75%
9	S09	2552.05	1170.56	46.82%
10	S10	3062.98	1416.96	56.68%
11	D11	128.09	92.73	3.71%
12	D12	260.06	176.94	7.08%
13	D13	495.99	298.23	11.93%
14	D14	790.53	443.93	17.76%
15	D15	1499.27	667.05	26.68%
16	D16	3822.56	1628.43	65.14%

The main factors contributing to differences in carbon storage increase between grids include wetland plant species diversity, patch area, plant coverage, etc. Larger wetland areas with diverse species compositions tend to exhibit higher carbon sequestration due to more complex ecological interactions, greater plant biomass, and higher rates of photosynthesis. For instance, grids with emergent plants such as Phragmites australis and Typha angustifolia showed significantly higher increases in carbon storage compared to grids dominated by hygrophytes or water surface patches.

3.2. Landscape Pattern Indices Within Different Grids

In this study, grid patches were classified based on community types into four types: emergent plants, hygrophytes, water surface, and other (Figure 6). Hygrophytes include three subcategories: submerged plants, floating plants, and floating-leaved plants.

At both the landscape and type scales, six types of landscape indices were selected to quantify and describe their pattern characteristics in terms of area, aggregation, and shape. These indices include landscape-scale metrics to describe the pattern of mixed patches and type-scale metrics to describe the landscape pattern of the four patch types in the wetlands. The specific calculation results of the landscape pattern indices are provided in Table A1.

The landscape pattern indices, including mainly patch density (PD), edge density (ED), and landscape shape index (LSI), were used to understand the spatial configuration of wetland plant communities. For instance, grids with higher PD values indicate more fragmented patches, which can enhance carbon sequestration by increasing edge effects and promoting diverse microhabitats that support varied plant growth. Similarly, grids with higher LSI values showed more complex patch shapes, which are associated with increased carbon storage due to greater habitat heterogeneity and resource availability.

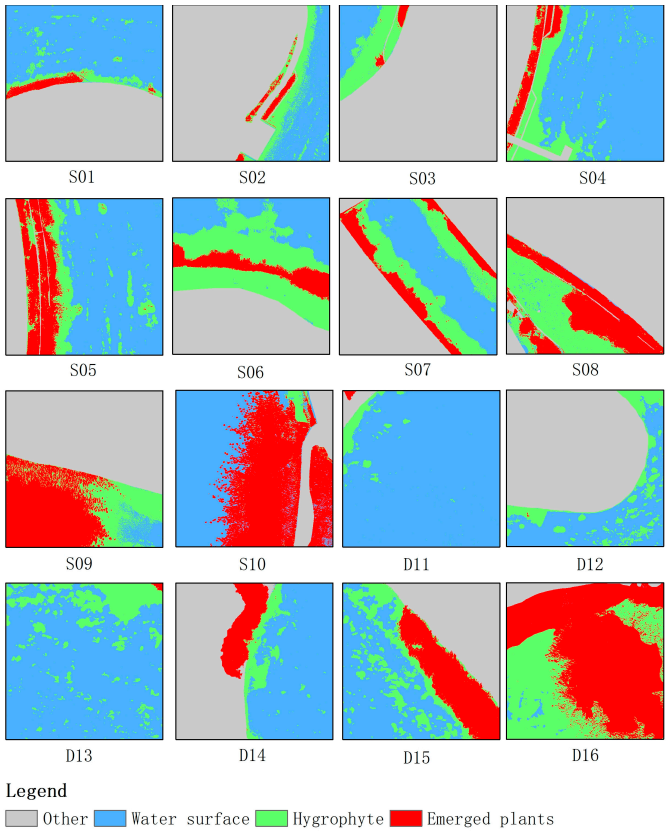


Figure 6. Patch types in sample grids.

3.3. Correlation Between Landscape-Scale Landscape Indices and Wetland Plant Carbon Sequestration

Spearman's Rho correlation analysis was performed on the landscape-scale data using SPSS and Origin, and the correlation between various landscape indices and the increase in carbon storage quantity (ICSQ) was determined within a 95% confidence interval (one-tailed) (Figure 7). The correlation coefficients between PD, ED, LSI, interspersion and juxtaposition index (IJI), and ICSQ were 0.667, 0.686, 0.590, and 0.558, respectively.

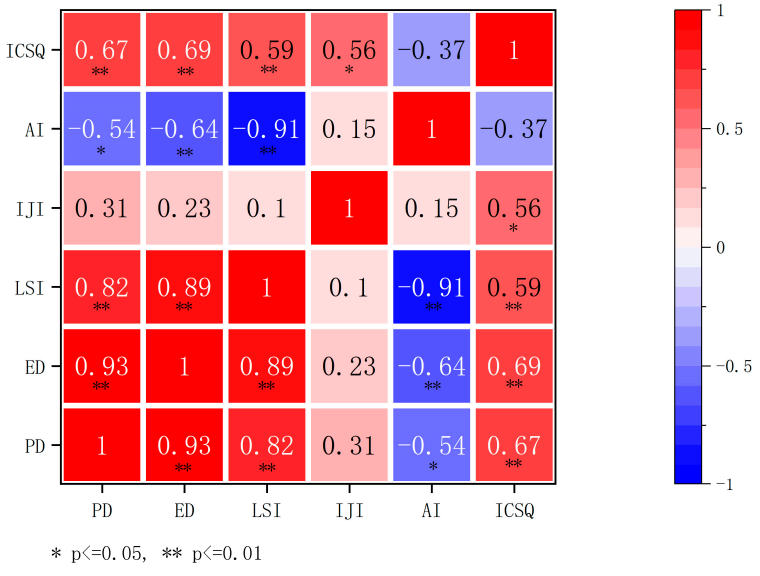


Figure 7. Correlation between landscape-scale landscape indices and ICSQ.

The positive correlation between these landscape indices and ICSQ suggests that greater landscape fragmentation, more complex patch shapes, and a more even distribution of patches contribute to increased carbon sequestration. This can be explained by the fact that fragmented patches often create more edge environments, which can enhance plant growth and biomass accumulation. Additionally, complex patch shapes provide diverse microhabitats that support higher plant productivity, contributing to greater carbon sequestration.

3.4. Correlation Between Type-Scale Landscape Indices and Wetland Plant Carbon Sequestration

Spearman's Rho correlation analysis was performed on the type-scale data using SPSS and Origin, and the correlations between various patch-type landscape indices and ICSQ were determined within a 95% confidence interval (two-tailed) (Figure 8).

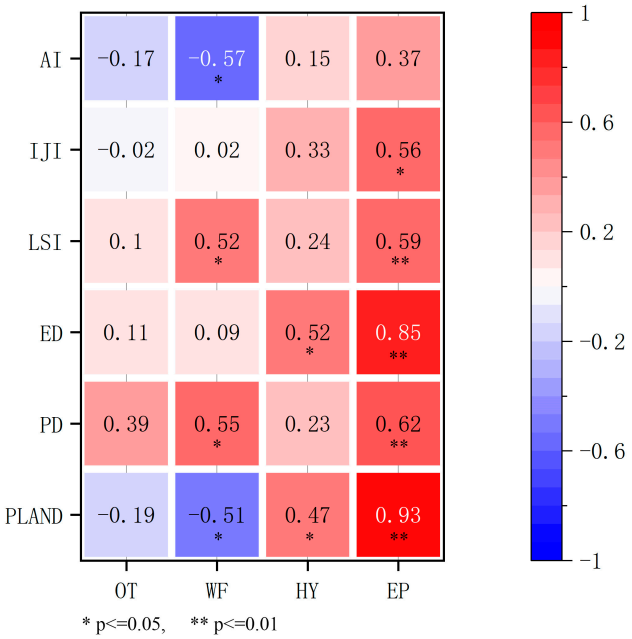


Figure 8. Correlation between type-scale landscape indices and ICSQ.

For emergent plant patches, the PLAND, PD, ED, LSI, and IJI indices were all positively correlated with ICSQ, indicating that as the total area of emergent plant patches increased, their fragmentation, shape complexity, and distribution uniformity also increased, leading to a more significant increase in carbon storage. Emergent plants, such as *Phragmites australis* and *Typha angustifolia*, are known for their high biomass and carbon sequestration potential, which explains their significant contribution to ICSQ. In contrast, the landscape indices for 'Other' patches were not significantly correlated with ICSQ, suggesting that these patches had little effect on carbon storage.

4. Discussion

4.1. Analysis of the Relationship Between Selected Landscape Pattern Indices and the ICSQ

Landscape pattern indices are the most commonly used quantitative research methods in landscape ecology for describing changes in landscape patterns. Studies have shown that landscape patterns significantly impact vegetation carbon sequestration [27–29]. Among the indices discussed in Figures 7 and 8, the area index (patch area proportion, PLAND) is a key indicator for determining the dominant landscape elements in a landscape [12,28]. The aggregation index PD represents the ratio of the number of patches to the area, with larger PD values indicating greater spatial heterogeneity and higher fragmentation [30,31]. The interspersion and IJI reflect the degree of mixing between different landscape types; lower values indicate that patches are adjacent to only a few other types, while higher values indicate a more even distribution of patches [27,30,32]. The aggregation index (AI)

reflects the connectivity of patches, with lower values indicating greater dispersion [27,33]. The shape index LSI is the total length of all patch boundaries (in meters) divided by the square root of the landscape area (in square meters) multiplied by a normalization constant for a square; larger values indicate more complex patch shapes [34,35]. ED represents the total length of all edges for type i patches; larger values indicate more complex shapes [34]. Selecting the right landscape indices is essential for linking ecological processes with landscape structures and conducting effective ecological research [29].

As shown in Figure 7, PD, ED, LSI, and IJI are significantly positively correlated with ICSQ, indicating that the degree of fragmentation, shape complexity, and distribution uniformity of landscape patches are positively correlated with ICSQ. The correlation coefficient suggests that AI is not significantly correlated with ICSQ, meaning that the connectivity between landscape patches has little impact on carbon storage. Except for IJI, the other four indices are correlated, with PD, ED, and LSI being positively correlated, while these indices have a negative correlation with AI.

Figure 8 shows that the six landscape indices for the 'Other' (OT) patches are not significantly correlated with ICSQ (p-value greater than 0.05), indicating that OT patches have little effect on ICSQ. For the water surface (WF) patches, multiple indices, including PLAND, PD, LSI, and AI, show significant correlations with ICSQ, with PLAND and AI being negatively correlated while PD and LSI are positively correlated, meaning that as the proportion of water surface decreases and the water surface becomes more dispersed, the increase in carbon storage becomes greater. On the other hand, the PD and LSI indices for WF patches are positively correlated with ICSQ, indicating that the more fragmented and complex the water surface patches are, the greater the increase in carbon storage.

For hygrophyte (HY) patches, only the PLAND and ED indices show a significant positive correlation with ICSQ, meaning that the larger the total area and the more complex the shape of the hygrophyte patches, the higher the corresponding carbon storage. The majority of indices for emergent plant (EP) patches show a highly significant correlation with ICSQ (p-value less than 0.01), with the landscape pattern of EP patches having the greatest impact on ICSQ. The PLAND, PD, ED, LSI, and IJI indices for EP patches are all positively correlated with ICSQ, indicating that as the total area of EP patches increases, their fragmentation, shape complexity, and distribution uniformity also increase, leading to a more significant increase in carbon storage.

In comparison to similar studies, Rogerson et al. [11] found that urban artificial wetlands could support multiple sustainability dimensions beyond just carbon sequestration. Zhang et al. [8] highlighted that urbanization reduces wetland areas and weakens carbon sequestration capacity, similar to our findings on the effects of fragmentation. Additionally, Wang et al. [9] demonstrated that changes in plant community structure affect carbon sequestration, consistent with our observations regarding emergent plants. These comparisons underline the broader applicability of our findings across different geographical and urban contexts, supporting the robustness of our results.

4.2. Optimization Strategies for Artificial Wetlands

Plant-based carbon sequestration is the foundation and core of the carbon sink function in wetlands. The most direct method for enhancing carbon sequestration and increasing carbon storage is to expand plant communities [7,36]. Different plant species and configuration principles are key factors affecting the carbon source and sink dynamics in various types of wetlands [7,37,38].

4.2.1. Plant Selection Principles for Wetlands

To enhance the carbon sequestration capacity, plant selection should consider the following aspects: First, priority should be given to plants with strong carbon sequestration abilities, such as *Cyperus alternifolius*, *Arundo donax*, *Nelumbo* sp., *Phragmites australis*, and *Typha latifolia*. These species are large, long-lived, and fast-growing, which enhances the wetland's carbon sink function, as they can store more carbon throughout their life cycles,

significantly boosting the carbon sink function of wetlands. Second, plants with developed root systems significantly impact soil carbon content. Species with high root-to-shoot ratios, such as *Nelumbo* sp., *Acorus tatarinowii*, *Phragmites australis*, *Acorus calamus*, and *Typha latifolia*, secrete organic matter into the soil, aiding in long-term carbon sequestration under anaerobic conditions [39]. Overall, emergent plants tend to have a higher root-to-shoot ratio than other types of plants. Lastly, plant biodiversity (e.g., plant richness, plant abundance, and taxonomic distinctness) is also crucial. Diverse plant communities are more resilient and adaptable to environmental changes and can significantly enhance the carbon sequestration capacity of wetlands [40,41]. Therefore, increasing wetland plant variety can thus promote long-term carbon sequestration of artificial wetlands.

4.2.2. Configuration Principles

Plant configuration should take the following aspects into account: First, there is a significant positive correlation between wetland vegetation coverage and carbon storage. Expanding the area of wetland plantings can effectively improve the quality of the wetland environment, maintain ecological balance, and enhance the carbon sequestration capacity of plants. Second, studies have shown that emergent plants, such as high-carbon sequestration species, have the most significant correlation between their landscape patterns and ICSQ. Increasing the proportion of emergent plants in wetland plantings can make a significant contribution to the carbon storage of artificial wetlands. Third, optimizing the structure of wetland vegetation by promoting diverse and multi-layered plant configurations can improve the uniformity of patch distribution. This layout not only enhances the uniform distribution of landscape patches but also promotes biological activity in the soil food web, which stores carbon long-term in the soil, thereby maximizing the carbon storage potential of wetlands [12]. Finally, controlling planting density is crucial for optimizing plant growth conditions. Excessively high planting density can lead to increased shading and competition for light, reducing photosynthesis efficiency and negatively impacting carbon storage [42,43].

4.2.3. Limitations and Future Research Directions

This study has certain limitations. The analysis is limited by the scale of the study area and the availability of detailed remote sensing data, which might introduce uncertainties in estimating carbon density. The study findings indicate a significant positive correlation between wetland fragmentation and carbon sequestration capacity, which contrasts with some beliefs that higher fragmentation weakens carbon sequestration [12]. This discrepancy can be attributed to the following reasons:

(1) Differences in study scale

The impact of wetland fragmentation on carbon sequestration may be scale-dependent:

At larger scales (e.g., city or regional scales), wetland fragmentation is typically accompanied by reduced wetland area and connectivity, which weakens overall carbon sequestration capacity.

At smaller scales (e.g., local grids or sample plots), this study shows that fragmentation may enhance spatial heterogeneity and plant diversity, leading to increased carbon sequestration.

(2) Effects of patch characteristics and plant types

Fragmentation may alter edge effects in wetlands:

Edge areas are often more exposed to sunlight, water, and nutrients, which can enhance plant growth and carbon accumulation.

In the study area (Shanghai Fish and Dishui Lake), most wetland plants are artificially introduced and selected to adapt to edge environments. Plants such as *Phragmites australis* and *Typha angustifolia* may accumulate higher biomass in edge areas, contributing to higher carbon sequestration.

Future research should focus on expanding the study to include other types of wetland ecosystems and utilizing higher-resolution data to improve accuracy. Additionally, explor-

ing the use of advanced modeling techniques to simulate plant growth dynamics under various management scenarios could provide deeper insights into optimization strategies.

4.3. Application of Different Optimization Models in the Two Artificial Wetlands

4.3.1. Optimization Model Design

Based on previous findings on the correlation between landscape indices and wetland plant carbon sequestration, it was concluded that more fragmented wetland plant patches, complex shapes, and even distributions increase carbon storage. The following section uses these conclusions to design optimization models for high carbon sequestration capacity in wetland plants. The design of plants in urban artificial wetlands includes horizontal and vertical spatial design. The horizontal space is divided into three types—wetland islands, water body edges, and open water areas—corresponding to point, linear, and planar spaces [44]. The vertical space is divided into four levels based on plant growth habits: water depth of 0–10 cm, dominated by emergent plants; water depth of 5–50 cm, emergent plants + floating-leaved plants; water depth of 20–150 cm, floating-leaved plants + submerged plants; and water depth of 20–300 cm, submerged plants. Based on the traditional wetland plant model, this study proposes three optimization models, which share common features: expanding the planting area within limited space, increasing plant diversity, and enhancing the mix of different types of wetland plants.

The point model (Figure A1) is characterized by the use of natural gentle slopes at the edges of islands, which promotes the growth of emergent plants and maximizes the utilization of wetland space, increasing vegetation coverage and biodiversity. The linear model (Figure A2) features a stepped water entry design that promotes plant community diversity. Multi-level platforms facilitate the combination of emergent plants, floating-leaved plants, and other types, optimizing the wetland ecosystem. The planar model (Figure A3) is suitable for open water areas in artificial wetlands. By adding ecological floating island facilities to plant emergent plants with strong carbon sequestration capacity and combining with underwater topography, a composite plant community is constructed. By selecting different optimization models, the carbon sequestration capacity of these areas can be maximized.

A specific area in the Shanghai Fish artificial wetland was selected for detailed optimization design. The current plant species in this area are limited, consisting of a mixed community of two emergent plant species, one floating-leaved plant species, and three submerged plant species. The planting area proportion is relatively low, accounting for only 11.3%, and the plant configuration is relatively simple (Figure 9). Based on the previous research results, the optimized plant design for this area is shown in Figure 10.

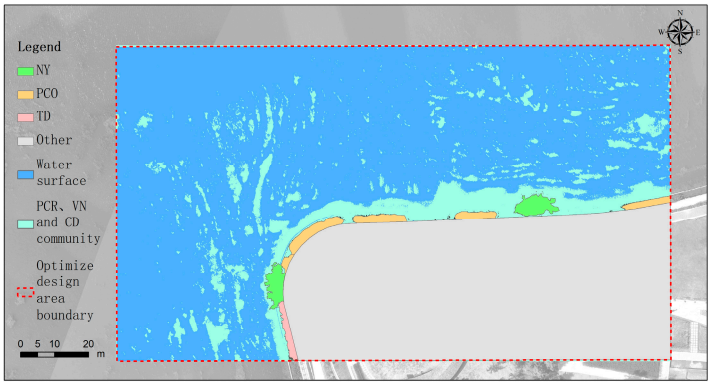


Figure 9. Current vegetation distribution in the optimized design area.

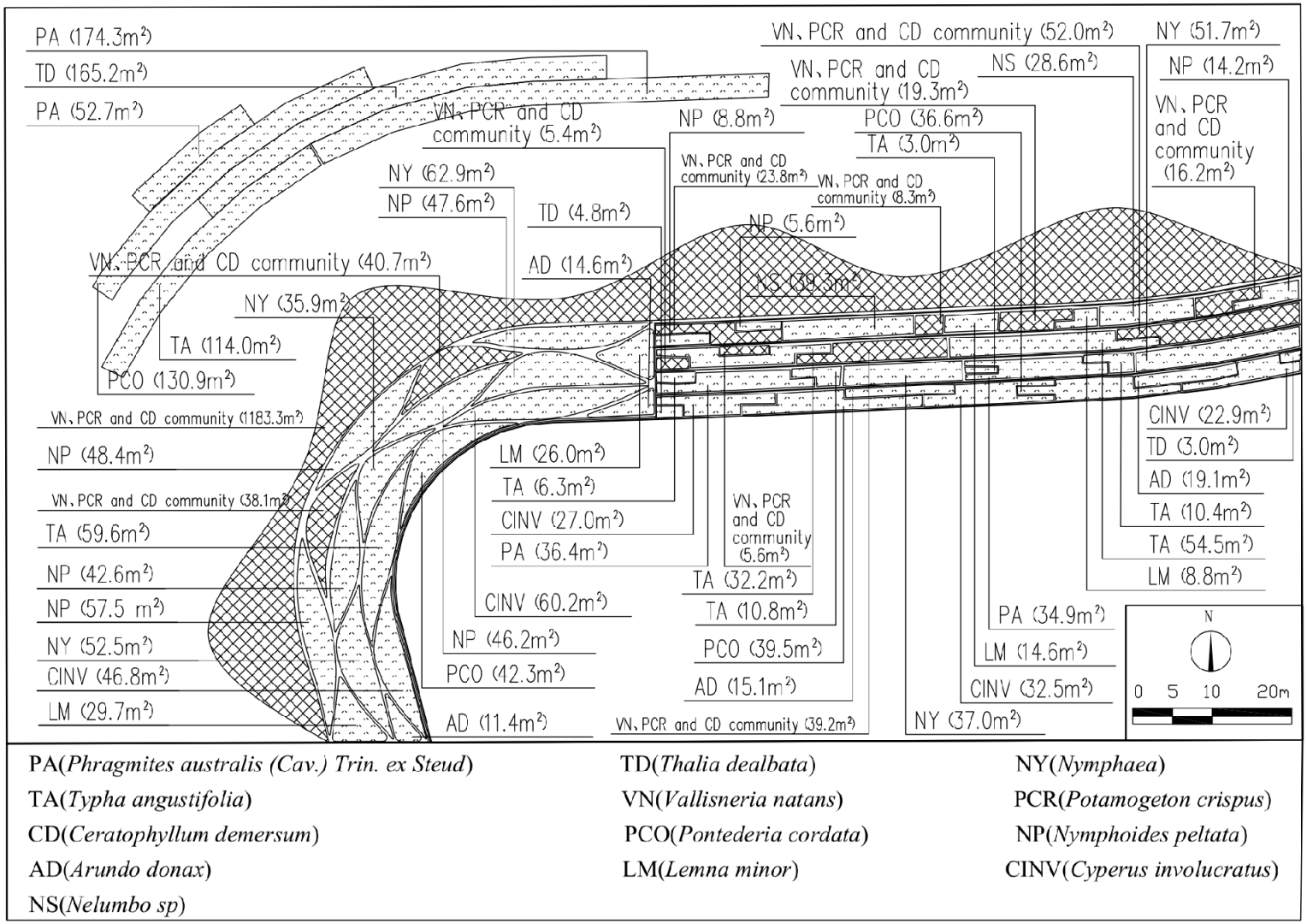


Figure 10. Planting design for the optimized area.

4.3.2. Carbon Storage After Optimization in the Two Wetlands

After optimization, the ecological benefits of the optimized design area increased significantly (Table 2). The number of wetland plant species increased from 6 to 13, a 1.2-fold increase. The proportion of wetland vegetation area in the region increased to 22%, with the planting area expanding from 1710.1 m^2 to 3351.3 m^2, a 96% increase. Carbon storage increased from 4157.1 kg to 10,988.3 kg, a 1.6-fold increase. The shoreline length is 146 m, with a carbon storage of 75.26 kg per meter of shoreline.

Table 2. Wetland vegetation area and carbon storage before and after optimization.

Serial Number	Wetland Plant	Area (m^2)		Carbon Storage (kgC)	
		Before Optimization	After Optimization	Before Optimization	After Optimization
1	*Vallisneria*, *Potamogeton crispus*, and *Ceratophyllum demersum* community	1432.2	1432.7	3177.6	3178.8
2	*Pontederia cordata*	142.2	249.3	640.5	752.9
3	*Thalia dealbata*	31.8	173	138.8	393.4
4	*Nymphaea*	103.9	239.9	200.1	462
5	*Cyperus involucratus*	0	189.3	0	2928.8
6	*Arundo donax*	0	60.2	0	554.6
7	*Nelumbo* sp.	0	67.9	0	572.3
8	*Phragmites australis* (Cav.) Trin. ex Steud	0	298.2	0	1208.7
9	*Typha angustifolia*	0	290.9	0	927.3
10	*Lemna minor*	0	79.1	0	0.4
11	*Nymphoides peltata*	0	270.8	0	9.3
	Total Amount	1710.1	3351.3	4157.1	10,988.3

In the Shanghai Fish wetland study area, the length of shoreline that meets the optimization criteria is approximately 7.75 km. After optimization, the carbon storage is estimated to be around 583.27 tons, a 2.6-fold increase compared to the current carbon storage of 162.23 tons. In the Dishui Lake wetland study area, the length of shoreline that meets the optimization criteria is approximately 4.07 km. After optimization, the carbon storage is estimated to be around 306.31 tons, a 3.5-fold increase compared to the current carbon storage of 67.5 tons.

4.4. Practical Recommendations

For urban planners and policymakers, our study provides practical recommendations for enhancing the carbon sequestration function of artificial wetlands. First, increasing the planting area and prioritizing species with high carbon sequestration abilities can significantly boost carbon storage. Second, optimizing wetland vegetation configuration to include emergent, submerged, and floating-leaved plants can enhance ecosystem resilience and maximize carbon storage. Lastly, maintaining appropriate planting densities is crucial to avoiding overcrowding, which can negatively impact plant growth and carbon sequestration capacity.

5. Conclusions

This study explored the carbon sequestration capacity and spatial patterns of two major urban artificial wetlands in Shanghai—Shanghai Fish and Dishui Lake. The analysis involved field sampling, remote sensing data processing, and landscape pattern analysis, focusing on changes in carbon density and spatial distribution between 2018 and 2023. Based on these findings, optimization strategies were proposed to improve carbon sequestration performance in artificial wetlands.

The results indicate significant spatial variability in carbon storage changes across both wetlands. In Shanghai Fish, carbon storage varied from a decrease of 5.66 kg to an

increase of 4.25 tons, while Dishui Lake displayed changes ranging from an increase of 2.25 kg to 4.25 tons. The differences in grid-level carbon storage are strongly associated with factors such as landscape fragmentation, patch complexity, and plant distribution.

The correlation analysis of landscape pattern indices showed that metrics like patch density, edge density, and landscape shape index had a positive impact on the carbon sequestration increase in wetland plants. Specifically, emergent plant patches such as *Phragmites australis* and *Typha angustifolia* demonstrated a significant relationship with increased carbon storage, emphasizing the importance of both area expansion and spatial complexity for carbon sequestration.

Three optimization models—point, linear, and planar—were proposed to enhance the carbon sequestration potential of urban wetlands. Each model aims to maximize carbon storage by diversifying plant species, optimizing vegetation configurations, and increasing the uniformity and complexity of landscape patches. The application of these models is projected to lead to significant increases in carbon storage, with Shanghai Fish potentially achieving a 2.6-fold increase and Dishui Lake reaching a 3.5-fold increase in carbon storage after optimization.

These findings provide important insights into enhancing carbon sequestration in urban wetlands through thoughtful design and management. The strategies proposed can serve as a practical guide for optimizing wetland ecosystems to support urban carbon neutrality initiatives, offering a pathway for Shanghai and similar cities to achieve their carbon reduction goals.

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Appendix A

Table A1. Landscape-scale landscape pattern indices.

GID	PD	ED	LSI	IJI	AI	ICSQ
S01	341,874.00	4793.26	6.93	48.65	99.10	139.46
S02	1,070,551.68	10,653.24	14.18	45.50	97.92	265.75
S03	166,513.65	2115.38	3.62	65.13	99.62	450.07
S04	541,198.39	7470.25	10.24	61.29	98.57	734.19
S05	613,902.78	8955.87	12.08	61.97	98.28	911.41
S06	254,465.36	4952.39	7.13	59.63	99.08	1010.82
S07	661,565.25	6602.59	9.17	57.99	98.75	1229.35
S08	679,663.49	7095.62	9.78	78.52	98.64	1514.98
S09	921,875.30	10,826.58	14.39	47.24	97.90	2552.05
S10	1,599,496.53	13,178.61	17.30	64.93	97.42	3062.98
D11	194,113.33	2422.57	4.06	42.49	99.48	128.09
D12	206,611.57	5019.40	7.35	33.62	98.90	260.06
D13	267,540.50	6335.79	9.01	15.94	98.58	495.99
D14	197,808.28	3555.87	5.50	60.28	99.26	790.53
D15	352,614.77	7833.39	10.90	48.86	98.28	1499.27
D16	582,339.98	9278.84	12.74	35.12	97.93	3822.56

Table A2. Type-scale landscape pattern indices.

TYPE	GID	PLAND	PD	ED	LSI	IJI	AI	ICSQ
Other	S01	47.04	1225.35	373.00	1.55	94.44	99.94	139.46
	S02	68.82	1633.81	1257.21	3.03	67.73	99.80	265.75
	S03	81.67	408.12	501.50	1.62	72.65	99.94	450.07
	S04	12.99	1225.35	1278.78	5.16	56.60	99.06	734.19
	S05	20.11	3676.06	1175.85	4.43	85.52	99.38	911.41
	S06	35.16	2042.26	587.84	2.56	79.67	99.79	1010.82
	S07	42.36	408.12	758.78	2.87	90.51	99.77	1229.35
	S08	58.34	12,253.55	1454.25	3.49	97.50	99.74	1514.98
	S09	52.95	1633.81	378.88	1.56	70.74	99.94	2552.05
	S10	10.76	2042.26	654.50	3.77	64.90	99.32	3062.98
	D11	2.72	1171.71	531.26	7.05	95.19	96.64	128.09
	D12	62.14	390.57	838.30	2.50	63.07	99.83	260.06
	D13	0.18	1562.28	382.50	22.84	31.53	51.02	495.99
	D14	39.90	9773.14	830.44	2.85	90.38	99.73	790.53
	D15	28.77	3518.33	666.79	2.85	95.00	99.69	1499.27
	D16	5.99	781.14	622.35	6.23	65.70	98.05	3822.56
Water	S01	44.82	67,394.52	3470.70	6.98	16.27	99.28	139.46
	S02	19.43	204,225.81	8331.92	23.42	13.93	95.88	265.75
	S03	7.62	102,438.54	1437.89	6.88	39.86	98.27	450.07
	S04	65.26	62,493.10	4112.45	6.94	6.67	99.40	734.19
	S05	55.83	26,957.81	3625.74	6.55	12.51	99.40	911.41
	S06	21.98	91,084.71	2785.15	7.59	28.51	98.86	1010.82
	S07	27.46	271,809.04	3954.21	9.37	11.11	98.71	1229.35
	S08	1.24	412,536.13	2929.74	32.52	63.07	76.83	1514.98
	S09	3.96	253,240.00	4707.00	29.48	1.93	88.38	2552.05
	S10	41.97	672,719.81	9619.69	18.76	64.89	97.78	3062.98
	D11	92.63	19,137.93	2142.47	3.33	33.05	99.78	128.09
	D12	26.49	45,306.13	4560.01	11.22	27.48	98.19	260.06
	D13	79.47	32,026.75	6255.84	9.10	19.26	99.17	495.99
	D14	43.30	54,729.56	2566.47	5.31	25.90	99.40	790.53
	D15	34.86	58,247.89	5670.44	12.44	12.06	98.23	1499.27
	D16	1.00	70,302.61	883.04	11.19	29.94	90.61	3822.56
Hygrophyte	S01	5.82	219,338.52	4576.29	23.54	62.87	92.42	139.46
	S02	9.60	819,762.39	10,288.41	41.10	61.20	89.50	265.75
	S03	9.73	33,057.86	1874.42	7.54	80.75	98.30	450.07
	S04	15.62	387,620.58	7202.47	22.95	87.34	95.50	734.19
	S05	11.27	452,155.94	8343.03	30.81	80.93	92.80	911.41
	S06	33.62	128,662.26	4654.06	10.03	79.34	98.74	1010.82
	S07	20.34	324,456.74	6138.97	16.91	73.17	97.14	1229.35
	S08	20.65	175,634.19	5793.15	15.93	82.30	97.34	1514.98
	S09	14.72	607,776.00	10,649.31	34.70	70.12	92.88	2552.05
	S10	2.60	829,565.23	5540.56	42.70	63.69	78.96	3062.98
	D11	4.19	171,460.26	2056.59	12.69	26.09	94.77	128.09
	D12	11.35	159,352.59	4610.31	17.53	31.72	95.52	260.06
	D13	19.92	233,560.91	5994.61	17.62	7.27	96.61	495.99
	D14	7.71	114,150.24	2885.12	13.13	53.65	96.01	790.53
	D15	17.39	265,047.46	7496.03	22.94	63.55	95.20	1499.27
	D16	33.35	157,399.74	8851.42	19.61	39.90	97.06	3822.56
Emerged Plants	S01	2.33	53,915.61	1166.54	9.44	19.83	95.49	139.46
	S02	2.15	44,929.68	1428.93	12.05	17.78	93.87	265.75
	S03	0.99	30,609.13	416.94	5.17	13.87	96.58	450.07
	S04	6.14	89,859.36	2346.80	11.86	27.48	96.44	734.19
	S05	12.79	131,112.97	4767.12	16.56	30.61	96.47	911.41
	S06	9.24	32,676.13	1877.73	7.78	8.37	98.19	1010.82
	S07	9.83	64,891.35	2353.23	9.33	38.89	97.85	1229.35
	S08	19.78	79,239.61	4014.10	11.27	63.09	98.13	1514.98
	S09	28.37	59,225.48	5917.97	13.99	12.14	98.02	2552.05
	S10	44.68	95,169.23	10,542.46	19.93	63.16	97.71	3062.98
	D11	0.47	2343.42	114.80	2.25	7.34	98.30	128.09
	D12	0.02	1562.28	30.18	3.00	0.00	84.62	260.06
	D13	0.43	390.57	38.63	1.35	2.70	99.51	495.99
	D14	9.08	19,155.35	829.72	3.48	62.57	99.25	790.53
	D15	18.97	25,801.08	1833.50	5.41	28.20	99.08	1499.27
	D16	59.67	353,856.49	8200.86	13.59	20.75	98.52	3822.56

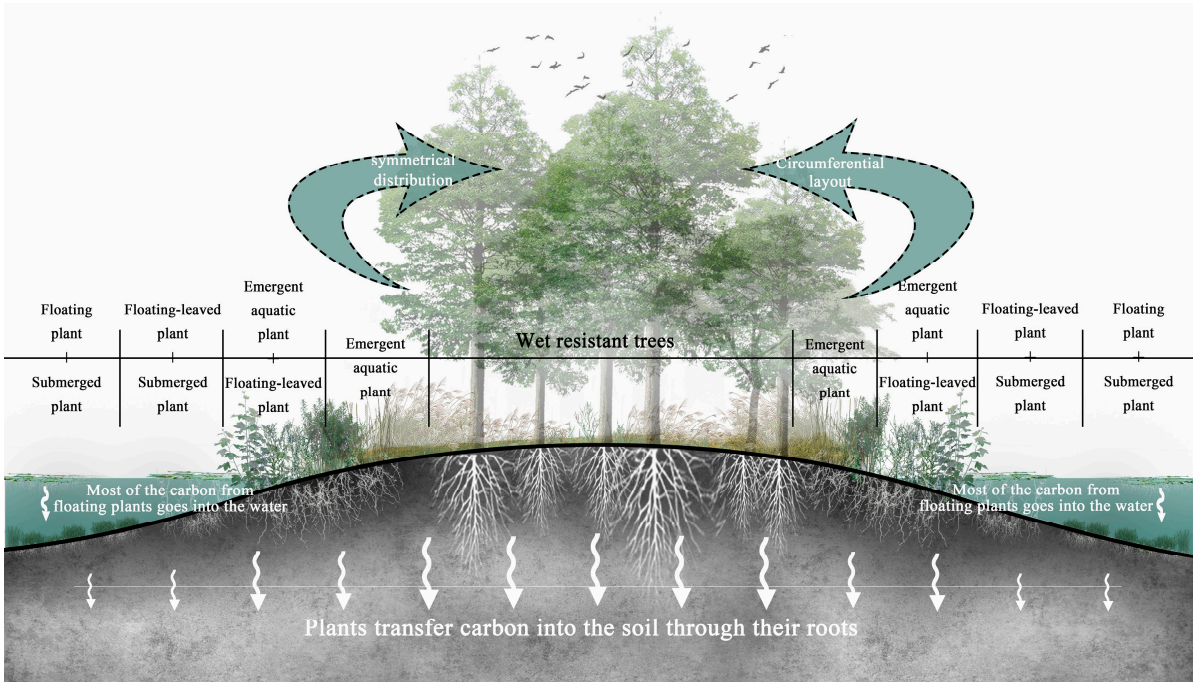


Figure A1. Point-based carbon sequestration model of artificial wetland plants. (Source: Drawn by the Authors).

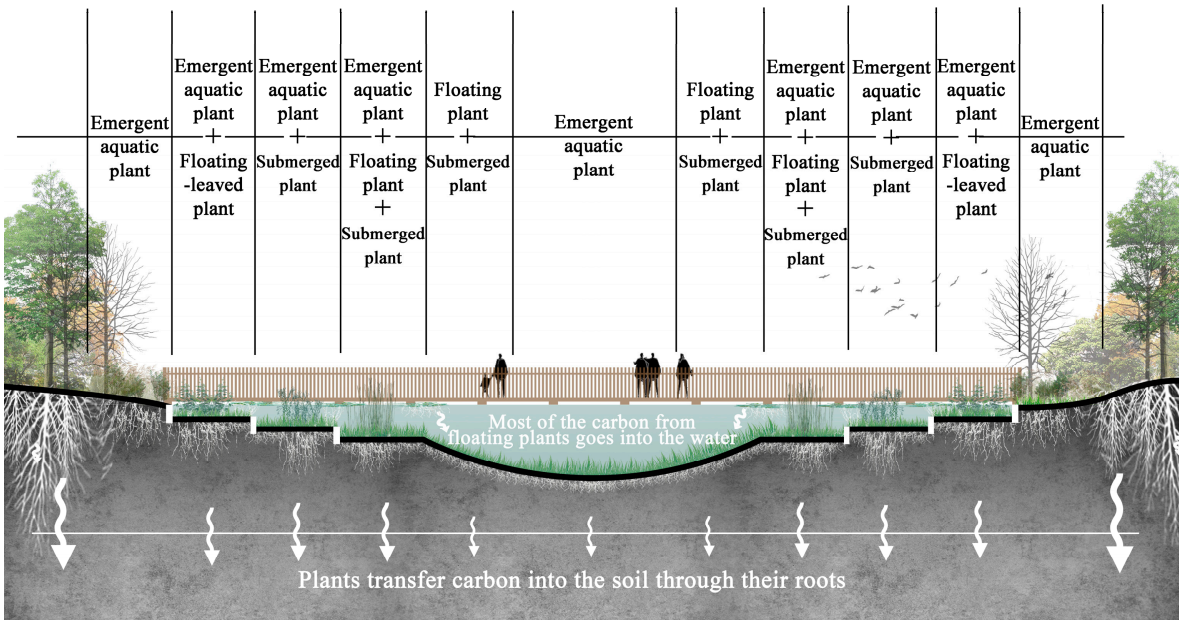


Figure A2. Line-based carbon sequestration model of artificial wetland plants. (Source: Drawn by the Authors).

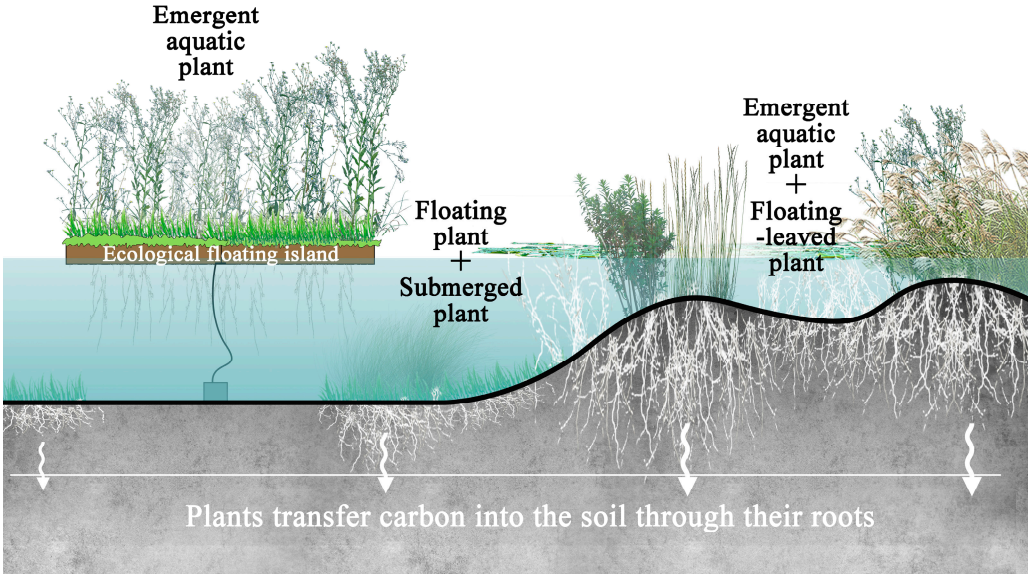


Figure A3. Planar-based carbon sequestration model of artificial wetland plants. (Source: Drawn by the Authors).

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