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Research on the Design and Management of Urban Wetland Park under the Dual-Carbon Background

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ABSTRACT

Under the global context of climate change and the "dual carbon" goals, urban wetland parks serve as significant ecosystem carbon sinks with notable carbon sequestration potential and ecological-economic value in densely populated areas. This paper explores the mechanisms, measurement approaches, design and management strategies for carbon sequestration in urban wetland parks. Through analysis of recent research and cases, the paper proposes practical pathways and development strategies to enhance carbon sequestration capacity. The integration of carbon management into urban wetland park construction requires careful consideration of vegetation species, ecological water level, ecological pattern, ecological zonation and community needs. Meanwhile, current challenges and future researches have been present, this study aims to provide theoretical references and practical guidance for carbon sequestration management and ecological construction in urban wetland parks.

KEYWORDS

Carbon sequestration; Urban wetland park; Design; Management

1 Introduction

The global climate crisis represents one of the most pressing challenges of our time, prompting nations worldwide to establish ambitious carbon reduction targets. In this context, China's "dual-carbon" strategy—aiming to achieve carbon peak before 2030 and carbon neutrality before 2060—has catalyzed comprehensive efforts across all sectors to explore innovative pathways for emissions reduction and carbon sequestration. Urban wetland parks, as integrated ecological spaces within urban environments, have emerged as remarkably efficient natural carbon sinks that simultaneously address multiple sustainability objectives. These ecosystems represent a strategic convergence point between urban development and climate action, offering a promising nature-based solution to the complex challenge of balancing urbanization with environmental stewardship. Although wetlands cover merely 3% of the Earth's surface, they store approximately 20%-30% of the global organic ecosystem carbon, outperforming forests and other terrestrial ecosystems in carbon storage efficiency per unit area [1]. This remarkable capacity stems from the high carbon sequestration rate in wetland soil and the low degradation efficiency of organic matters, allowing carbon to accumulate over centuries. However, rapid urbanization has triggered significant wetland loss globally, with estimates indicating that between one-third and one-half of all wetlands have disappeared over the past two centuries [2]. This loss represents not only the diminishment of a crucial carbon storage resource but also the release of stored carbon when these ecosystems are disturbed, transforming them from carbon sinks to carbon sources. The integration of constructed wetlands into urban environments represents a paradigm shift in urban landscape design. Constructed wetlands are engineered systems that have been designed and constructed to utilize the natural processes involving wetland vegetation, soils, and their associated microbial assemblages to assist in treating wastewater. While they are increasingly recognized for their broader ecological services, particularly their carbon sequestration potential [3]. This paper argues that strategically designed and managed urban wetland parks can contribute significantly to urban carbon neutrality goals while simultaneously delivering co-benefits across biodiversity, public health, education, and community resilience.

2 Carbon Sequestration Mechanisms of Urban Wetland Parks

Urban wetland parks function as effective carbon sinks through complex biological, chemical, and physical processes that capture atmospheric CO_2 and store it in various ecosystem components. The carbon sequestration capacity of these ecosystems stems from the synergistic functioning of several distinct mechanisms that operate across different temporal and spatial scales.

The primary mechanism involves the photosynthetic activity of wetland vegetation, including emergent plants, submerged macrophytes, floating plants, and adjacent woody vegetation. Through photosynthesis, these plants absorb CO_2 from the atmosphere, converting it into organic carbon compounds and deposit them in plant leaves, stems and roots as plant carbon pools. Different vegetation components contribute variably to overall carbon sequestration [4]. This highlights the importance of diverse vegetation structure in maximizing carbon capture throughout the wetland ecosystem. Carbon can also be sequestered in wetland soil carbon pools through a series of food chains of zooplankton, fish, and so on, as well as microbial degradation with bacteria, viruses, and other biological activities [5].

Unlike terrestrial ecosystems where aerobic decomposition rapidly returns carbon to the atmosphere, the anaerobic degradation of organic carbon in the wetland is the main process due to the anoxic and anaerobic environment in the wetlands, and lower decomposition efficiency causes more carbon to be accumulated as carbon sinks, although the CH_4 emission increases [6]. This process results in the formation of substantial soil organic carbon pools that can persist for centuries under stable conditions. Therefore, most of the organic matter in the wetlands is not decomposed but buried in the soil to realize carbon sequestration.

The hydrological regulation of wetlands represents another crucial mechanism influencing carbon sequestration. As mentioned above, the anaerobic environment with high water levels slows down the decomposition of wetland plants and increases soil carbon content. But the low water level may lead to a more aerobic environment, increasing CO_2 concentrations and probably decreases CH_4 concentrations while reduces soil organic carbon storage [7]. The interconnection between urban wetland parks and water management infrastructure creates opportunities for coordinated operation that maximizes carbon sequestration while fulfilling other ecosystem services.

Furthermore, the ecological succession processes within urban wetland parks influence long-term carbon sequestration dynamics. Therefore, wetland vegetation type and vegetation richness directly influence carbon sequestration [8]. The increase in species richness strengthens the ecological stability of wetlands, which improves continuous plant productivity, as well as the diversity and activity of microbial communities in the soil.

3 Methodology for Assessing Carbon Sequestration

3.1 Field Measurement Techniques

Accurate assessment of carbon sequestration in urban wetland parks requires multi-faceted methodological approaches that capture both spatial heterogeneity and temporal variability. Field-based measurements remain essential for ground-truthing and validating other assessment methods. The most precise in-situ approach involves direct quantification of CO_2 and CH_4 fluxes across wetland compartments using chamber-based measurements and eddy covariance techniques [9].These direct measurements capture real-time gas exchange processes but are limited in spatial coverage and resource-intensive to maintain. Biomass sampling provides complementary data on carbon stored in vegetation. This involves destructive harvesting of representative quadrats to determine aboveground and belowground biomass, coupled with elemental analysis to calculate carbon content. For woody vegetation, allometric equations are used to estimate biomass non-destructively based on diameter, height, and other morphological characteristics [10].

3.2 Modeling and Remote Sensing Approaches

To overcome the spatial limitations of field measurements, some computational models and remote sensing technologies were be relied on increasingly. Process-based models like the SUSI peatland simulator represent one approach, incorporating mechanisms of dissolved organic carbon formation, transport, and biodegradation to predict carbon dynamics under different management scenarios [11]. While these models can elucidate the processes that play a role in carbon dynamics, they require extensive mechanistic parameterization to accurately represent the interactions in various ecosystems.

Data-driven models offer a complementary approach, leveraging available datasets, artificial intelligence and machine learning to identify patterns in complex environmental datasets for large-scale applications. By integrating vertically-resolved atmospheric, subsurface, and spectral reflectance information from readily available sources, these AI models identify key drivers of wetland CO_2 and CH_4 emissions, and enables regional upscaling [12].

Remote sensing technologies as a mainstream method for estimating aboveground biomass, provide critical data for model parameterization and validation. Spectral reflectance data can be correlated with field measurements to develop inversion models for wetland plant carbon density [13]. This approach enables comprehensive assessment of vegetation distribution characteristics and carbon density variations across entire wetland parks, even the global scale.

Table 1 Comparison of Carbon Sequestration Assessment Methods

Method	Spatial Scale	Temporal Resolution	Key Advantages	Key Limitations
Chamber Measurements	Plot-scale ($\leqslant$1 m^2)	Hours to days	High precision for point measurements	Limited spatial representation
Eddy Covariance	Ecosystem-scale ($\approx$1 km^2)	Continuous	Direct measurement of net ecosystem exchange	High equipment cost and complexity
Biomass Sampling	Plot-scale	Seasonal to annual	Direct measurement of carbon stocks	Destructive
Process-Based Models	Local to regional	Daily to decadal	Mechanistic understanding	scenario testing
AI/Machine Learning	Local to regional	Daily to annual	Pattern recognition	handling complex datasets
Remote Sensing	Local to global	Days to years	Comprehensive spatial coverage	Indirect measurements requiring validation

4 Design and Management Strategies for Carbon-Optimized Wetland Parks

Strategic design and management are fundamental to maximizing the carbon sequestration functionality of urban wetland parks while ensuring their integration into urban systems. Deliberate design interventions can significantly enhance carbon storage capacity while providing multiple ecological and social co-benefits.

4.1 Ecological Zonation Planning

Effective zoning within urban wetland parks creates distinct ecological functions that contribute differently to carbon sequestration. Research suggests integrating forest patches, open water zones, marsh areas, and transitional upland buffers to create a diverse habitat mosaic that maximizes carbon capture. Topographic diversity creates microhabitats that support varied hydrological regimes and plant communities, increasing overall ecosystem resilience and carbon storage potential [14].

Meanwhile, recovering farmland from freshwater wetlands is also a strategy for wetland creation.

4.2 Plant Species Selection and Configuration

The strategic selection and arrangement of plant communities significantly influences carbon sequestration efficiency. Native species with high biomass productivity and deep root systems enhance both aboveground and belowground carbon storage. Emergent macrophytes like Phragmites australis and Arundo donax demonstrate particularly high carbon storage capacities in urban artificial wetlands, while floating plants exhibit relatively weaker carbon storage capability [15]. This suggests that managing for biodiversity and structural complexity can enhance carbon storage capacity over time. Furthermore, implementing successional planting strategies that account for temporal changes in plant communities can optimize long-term carbon sequestration.

4.3 Hydrological Design and Management

Hydrological engineering represents another critical design consideration for optimizing carbon sequestration. Water level management directly influences both carbon capture rates through plant productivity and carbon storage stability through decomposition regulation. Design strategies that create variable hydrologic zones—including permanently flooded, seasonally flooded, and intermittently flooded areas—support diverse plant communities with complementary carbon sequestration patterns. The rise in the water level leads to the shift of environment from aerobic to anaerobic, reducing the decomposition rate of organic matter. Ensuring consistent water quality and quantity through engineered solutions is essential for maintaining the anaerobic conditions that inhibit carbon release from soils.

The SUSI peatland simulator has demonstrated that relatively modest adjustments to water management can significantly impact carbon balance, with reduced ditch cleaning depth (by 0.3 m) decreasing annual dissolved organic carbon export by 5-19% across different European countries [11]. These management changes simultaneously enhanced site annual carbon sink by 32-409 kg ha^{-1}, highlighting the importance of hydrological optimization..

4.4 Community Integration and Multifunctional Design

Perhaps most critically for urban contexts, successful wetland park design incorporates community needs and multifunctional spaces that integrate carbon sequestration with other ecosystem services. Potential co-benefits include health and wellbeing, biodiversity, education, food security, behavioral changes, and social care. This integrated approach must be adopted, engaging stakeholders from the project outset to define and facilitate collaboration towards shared outcomes for society, community, and environment.

Table 2 Design Strategies for Enhancing Carbon Sequestration in Urban Wetland Parks

Design Strategy	Carbon Sequestration Benefit	Implementation Approach
Zonation Planning	Diversifies carbon pool types and sequestration mechanisms	Delineate specific areas for forest vegetation, seedling cultivation, and wetland ecosystems
Native Species Selection	Enhances biomass productivity and ecosystem stability	Prioritize deep-rooted perennial species with high biomass production
Hydrological Regulation	Maintains anaerobic conditions for soil carbon storage	Create water level control structures and variable depth zones
Successional Planting	Optimizes long-term carbon storage capacity	Combine early and late successional species in layered planting design
Community Integration	Secures long-term maintenance and carbon function preservation	Incorporate educational, recreational, and cultural functions within ecological zones

5 Challenges and Future Directions

Despite the significant potential of urban wetland parks in contributing to dual-carbon goals, several substantial challenges must be addressed to optimize their implementation and effectiveness. These challenges span technical, methodological, governance, and socio-economic dimensions.

Wetlands play a pivotal role in carbon sequestration but emit methane—a potent greenhouse gas—under anaerobic conditions [12]. Therefore, integrating CO_2 and CH_4 emissions is critical to assess the net climate benefits of wetland conservation and restoration initiatives.

Vegetation is the main pathway for carbon sequestration in wetland systems. The response of vegetation type, density, and configuration to wetland carbon sequestration is relatively vague. Further research is needed to build an inventory of efficient carbon sequestration species and plant configuration modes for effective wetland conservation and restoration while improving the carbon sequestration capacity of wetlands. Innovations and mechanisms of carbon sequestration processes of vegetation are equally needed for further research.

To standard measurement methodologies across diverse wetland types and urban contexts remains an ongoing challenge. The development of standardized carbon accounting protocols specific to urban wetland parks would facilitate more consistent measurement and reporting across different sites. Additionally, more research is needed on the social dimensions of urban wetland carbon management, including public perceptions, governance models, and financing mechanisms that support long-term carbon sequestration.

6 Conclusion

Urban wetland parks represent a powerful nature-based solution for advancing urban carbon neutrality goals while simultaneously addressing multiple urban sustainability challenges. This research has demonstrated that strategically planned, designed, and managed wetland parks can contribute significantly to carbon sequestration through multiple mechanisms. As cities worldwide accelerate efforts to combat climate change, urban wetland parks offer a multifunctional approach that contributes to carbon goals while simultaneously enhancing biodiversity, climate resilience, public health, and community wellbeing. The practice for synergy of carbon sequestration and ecological restoration should be more carried out. Through continued innovation and collaboration across disciplines and sectors, urban wetland parks can become cornerstone elements of carbon-smart urban development strategies worldwide.

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