

Carbon cycle in the context of urban micro-regeneration: an analysis based on urban pocket parks

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Abstract. Low-carbon urban development is a crucial link in reducing greenhouse gas emissions and achieving the "dual carbon" goals of carbon peaking and carbon neutrality. Most existing studies focus on either carbon emission reduction or carbon sequestration at the macro scale, and fail to systematically analyze the full urban carbon cycle process and its comprehensive benefits from a micro-spatial perspective. Taking urban micro-regeneration as an entry point, this paper adopts literature research and case analysis methods. Based on the binary logic of carbon sources and carbon sinks within the carbon cycle and the "Triple Bottom Line" principle, a "Dual Pathways—Three Dimensions" analytical framework is constructed. Using the micro-regeneration project of Rihui Green Space in Xuhui District, Shanghai, as a case study, this paper analyzes its underlying action mechanisms and conducts a comprehensive benefit evaluation. The study finds that carbon-cycle-oriented urban micro-regeneration can effectively reduce carbon emissions and enhance carbon absorption and fixation throughout the entire life cycle, contributing to environmental protection, economic development, and social equity, thereby promoting sustainable urban development. The analytical framework proposed in this paper can provide a reference for the low-carbon design and benefit evaluation of pocket parks.

Keywords: urban micro-regeneration, urban carbon cycle, pocket park, carbon sink, "Triple Bottom Line" principle

1. Introduction

Global warming has increasingly become a severe challenge confronting human society. The continuous emission of greenhouse gases is a primary driver of this warming [1], particularly in cities, the main spaces for human production and activities. According to 2023 statistics released by UN-Habitat and the International Energy Agency, cities consume two-thirds of the world's total energy and account for more than 70% of global annual carbon emissions [2]. Consequently, promoting urban low-carbon development and facilitating the urban carbon cycle have become critically important.

To date, academic research on urban low-carbon development and carbon cycles has yielded numerous theoretical insights, yet most studies still focus on the macro scale, such as the driving effects of low-carbon city policy pilots, smart city construction, industrial intelligence, and green technology innovation. There is a

noticeable lack of in-depth discussion from a micro-urban perspective [3-6]. Moreover, the majority of these studies concentrate on a single dimension—either promoting urban carbon emission reduction or enhancing urban carbon absorption—without treating the holistic process of promoting the carbon cycle as the targeted outcome of low-carbon urban measures. Analyses of the comprehensive benefits from multiple dimensions are also rare.

Against this practical backdrop and existing research gap, this paper aims to address three core research questions: First, what is the mechanism through which micro-regeneration impacts the carbon cycle? Second, how does the micro-regeneration model differ from the conventional "large-scale demolition and construction" model in terms of carbon cycle benefits? Third, how can the comprehensive benefits of carbon-cycle-oriented urban micro-regeneration be systematically evaluated?

This study systematically reviews global literature on urban carbon cycles and urban micro-regeneration, and analyzes Shanghai Xuhui's Rihui Green Space pocket park as a case. Based on this, a "Dual Pathways—Three Dimensions" analytical framework is adopted (see Figure 1). This framework integrates two analytical pathways within the urban carbon cycle—"reducing carbon sources" and "enhancing carbon sinks"—with three evaluative dimensions under the "Triple Bottom Line" principle: environmental, economic, and social. From a pocket park micro-spatial perspective, the framework fills identified research gaps and delivers a replicable assessment method for low-carbon design of comparable urban micro-renewal schemes. Simultaneously, it demonstrates the low-carbon value of urban micro-regeneration from a carbon cycle perspective, providing scientific support for the formulation and optimization of urban renewal policies.

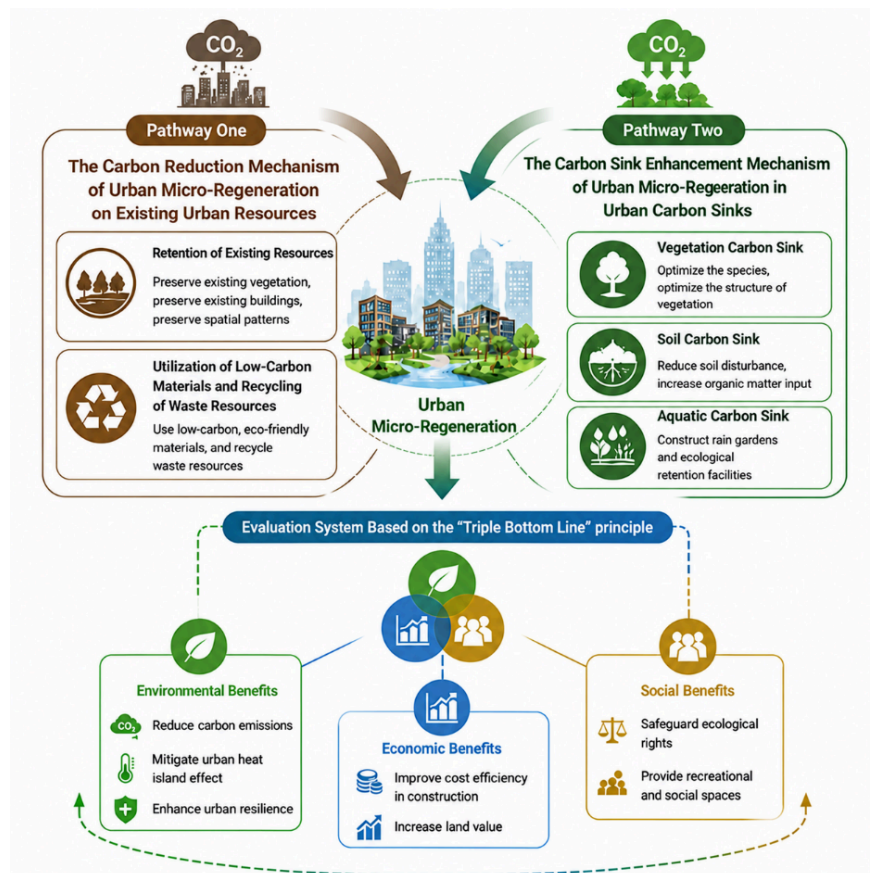


Figure 1. "Dual Pathways—Three Dimensions" analytical framework

2. Conceptualizing urban micro-regeneration and the urban carbon cycle

As China's urbanization enters a phase of stock improvement and the government sets the goals of "carbon peak and carbon neutrality", urban micro-regeneration has gradually gained prominence in recent years. The previous urban renewal model featuring extensive large-scale demolition and construction inherently functions as a major carbon source, generating substantial carbon emissions during both the demolition and new construction phases. This not only leads to resource waste and a short-term spike in carbon emissions but often damages the original urban fabric and layout. In contrast, urban micro-regeneration employs a small-scale, incremental, and low-impact approach to micro-transform spaces such as scattered green patches and idle street corners, thereby supplementing urban functions and improving the living environment.

The urban carbon cycle, in simplified terms, refers to a closed-loop system that covers the emission, absorption, transfer and sequestration of Carbon Dioxide (CO_2) within the urban spatial scope. In urban areas, CO_2 is primarily absorbed and fixed by vegetation, soil, and water bodies—a process also referred to as urban carbon sinks. On this basis, urban carbon sinks can be divided into three major categories. Vegetation carbon sinks: This approach relies on urban three-dimensional greening, making full use of vertical spaces including building walls and rooftops to increase the three-dimensional "green volume" upwards [7, 8]. Soil Carbon Sinks: Using green spaces as carriers, enhancing underground carbon storage by selecting native carbon-fixing vegetation and improving soil quality [9, 10]. Water Body Carbon Sinks: Extending the carbon sink system by restoring aquatic ecosystems and configuring aquatic vegetation [11, 12]. These three types of carbon sinks are interconnected and interact, forming the urban carbon cycle (see Figure 2). Surface vegetation and aquatic plants absorb CO_2 and transfer carbon into the soil and water bodies. Permeable pavements and rain gardens promote the infiltration of carbon, transferring it from water bodies and the ground surface into deeper soil layers, thus achieving long-term carbon sequestration.

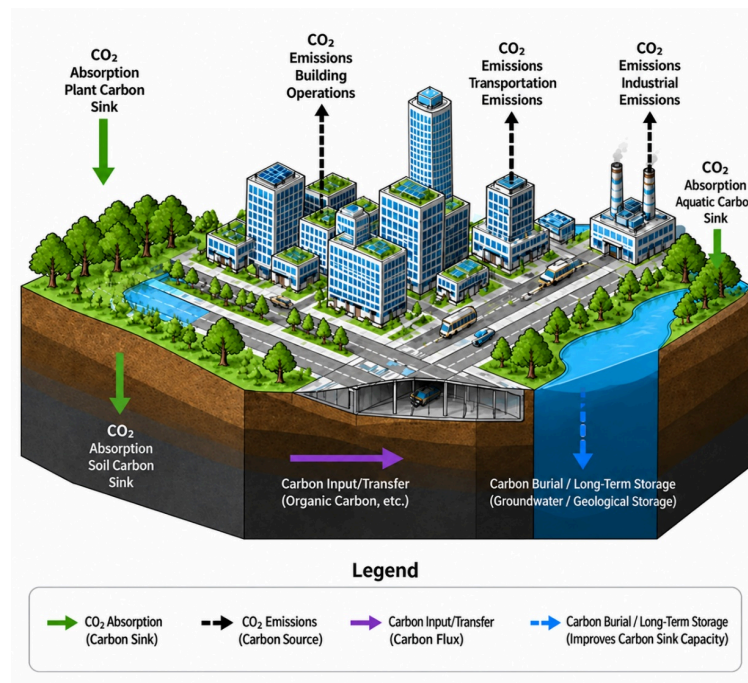


Figure 2. Urban carbon cycle process

3. Mechanisms of urban micro-regeneration acting on the carbon cycle

3.1. Case overview

Pocket parks are typical products of urban micro-regeneration. Often located in densely populated urban areas, they are created through the micro-transformation of small, scattered green spaces into open, green public spaces, harboring significant carbon sink potential. Rihui Green Space in Xuhui District, Shanghai, serves as an exemplary model of such a pocket park.

Situated in the Rihui Community on Xietu Road, Xuhui District, Rihui Green Space covers an area of approximately 6,672 square meters. Constructed on the roof of an underground garage, the site features a flat terrain and is surrounded by densely populated residential blocks with relatively high carbon emission intensity.

Before the micro-renovation, Rihui Green Space was a dated community green space with progressively degraded ecological functions (see Figure 3). The overall environment was dense and enclosed, public spaces were cramped, and supporting service facilities were dilapidated, resulting in a poor landscape appearance. The vegetation structure was homogeneous, the soil was compacted, and some paved areas were disconnected from green belts, disrupting the soil carbon cycle. Despite these shortcomings, the existing vegetation was in good condition, with a large number of trees providing a sound ecological baseline and significant potential for transformation.



Figure 3. Rihui green space before renovation

In 2023, Rihui Green Space was renovated following the micro-regeneration model, becoming the first pocket park in Xuhui District conceived with a low-carbon philosophy. Throughout the whole renovation process, the design team retained 195 mature native arbors, and only removed a tiny proportion of trees that were severely infested by pests, infected by diseases, or posed clear safety risks. In terms of materials, low-carbon-emission landscape materials such as gravel and polymer were prioritized. Permeable pavements and a dedicated rain garden were incorporated into the site to upgrade the on-site rainwater infiltration system and further optimize the local soil conditions and hydrological environment. Ultimately, the space was transformed into a street-corner pocket park blending leisure with nature (see Figure 4).

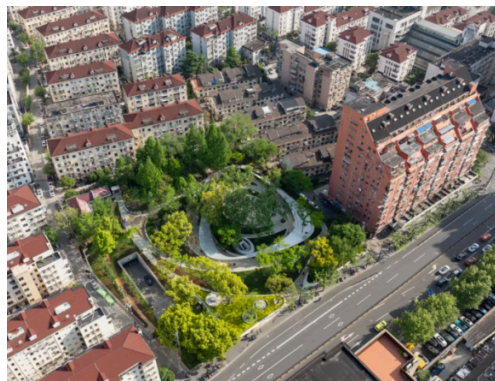


Figure 4. Rihui green space after renovation

3.2. Pathway 1: mechanisms for reducing urban carbon sources through micro-regeneration

"Carbon source reduction" refers to curbing the growth of carbon emissions right at their point of origin. The reducing effect of urban micro-regeneration on carbon sources operates throughout the project's life cycle, primarily achieved through two methods.

First is the preservation and utilization of existing resources. Under the conventional "large-scale demolition and construction" model, existing vegetation and facilities on a site are typically cleared entirely. This generates substantial construction waste and high carbon emissions, and necessitates the subsequent purchase of new building materials or saplings. In contrast, the micro-regeneration model applied to Rihui Green Space largely avoided felling the native trees. Consequently, no carbon emissions were generated from tree transplantation or replanting, the original spatial composition was not disrupted, and energy consumption during construction was saved. Furthermore, only a very small number of trees with potential safety hazards were removed, which substantially mitigated both ecological disturbance and the total carbon emissions throughout the renovation phase.

Second is the replacement of high-carbon materials with low-carbon alternatives and the resourceful utilization of waste. The renovation of Rihui Green Space employed low-carbon materials like previous concrete and timber, deliberately avoiding high-carbon materials such as granite and metals commonly used in past constructions. This effectively constrained the carbon footprint of building materials. Simultaneously, waste generated during the renovation, such as pruned branches and other plant residues, was processed through composting to improve soil and replenish the green space. This converted waste into a resource, avoiding the carbon emissions associated with large-scale waste transportation or landfilling.

3.3. Pathway 2: mechanisms for enhancing urban carbon sinks through micro-regeneration

Enhancing carbon sinks aims to increase the stock of carbon absorption at the end of the cycle. The carbon sink enhancement effect of urban micro-regeneration is primarily achieved through three core carriers: vegetation, soil, and water bodies. The underlying logic is to strengthen carbon sequestration and storage capacity by optimizing the ecosystem structure.

Vegetation Carbon Sink: Utilizing existing and newly added vegetation to improve carbon sequestration. In the carbon cycle, vegetation absorbs and fixes CO_2 through photosynthesis. Part of this is converted into biomass for plant growth, while another part enters the soil as leaf litter and root exudates. By retaining native trees with strong carbon sequestration capacity, such as *Cinnamomum camphora*, *Ginkgo biloba*, and *Sapindus mukorossi*, and arranging shrubs and grasses on the ground surface, a relatively complete and stable vegetation community was established. According to the accounting data (see figure 5), one year after the renovation was

completed, the total annual carbon sequestration of vegetation in Rihui Green Space reached 11,612.58 kg [13]. Crucially, this sequestered carbon is not a one-time gain; it increases year by year as the vegetation grows. Projections estimate 12,802.87 kg after 5 years, 14,083.16 kg after 10 years, and 17,040.62 kg after 20 years, affirming the sustained long-term carbon sink value of the renovated vegetation.

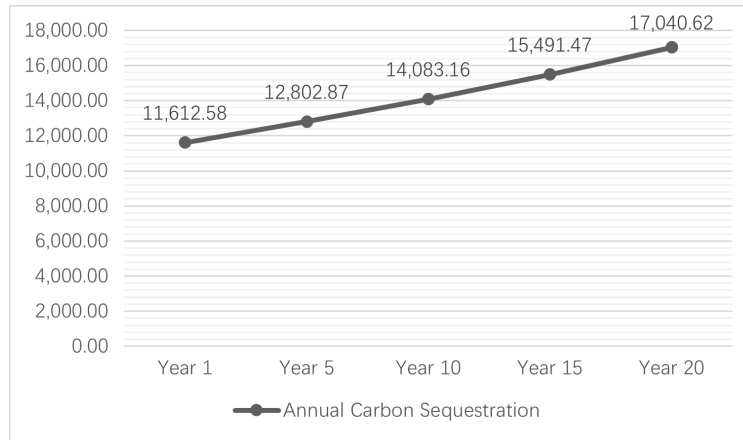


Figure 5. Vegetation carbon sequestration (unit: kg)

Soil Carbon Sink: Enhancing the soil's carbon sink capacity for longer-term carbon storage. The project minimized human disturbance and adopted naturalistic planting methods, such as composting leaf litter back into the soil. This practice increased soil organic matter content and, correspondingly, enhanced soil carbon storage, bringing the project's total soil carbon sequestration to 6,630 kg [14]. With the establishment of an ecologically robust, multi-layered vegetation community, natural symbiotic mechanisms reduce the need for human management, thereby preventing damage to the soil carbon pool from anthropogenic operations. This allows carbon to be preserved for longer periods, yielding more pronounced overall carbon sink effects.

Water Body Carbon Sink: Using permeable pavements and rain gardens to enhance water conservation. The park's pedestrian pathways adopt a crushed stone sub-base paired with sand-based imitation-stone permeable bricks, achieving a 33% lower carbon emission level than that of traditional stone paving materials [14]. The plaza areas featured high-strength, cast-in-place, artistic permeable flooring, significantly improved in water permeability. During rainfall, rainwater infiltrates through the paving materials into the ground, recharging groundwater. Beyond its stormwater regulation function, the moist soil and aquatic vegetation it supports also contribute to carbon sequestration.

3.4. "Three Dimensions": an evaluation system based on the "Triple Bottom Line" principle

The "Triple Bottom Line" (TBL) principle serves as a foundational framework for sustainable development, encompassing three dimensions: environmental protection, economic prosperity, and social equity. It serves as a primary theoretical analysis model for measuring sustainability, and is widely applied across socio-economic fields [15]. Introducing the TBL principle into the benefit evaluation of urban micro-regeneration projects can transcend the limitations of a purely ecological assessment, providing a more comprehensive measure of a project's holistic value. This paper applies this framework to evaluate the comprehensive benefits of the Rihui Green Space micro-regeneration project (see Figure 6).



Figure 6. Evaluation of the "Triple Bottom Line" principle

The Environmental Protection dimension of the TBL framework centers on net carbon reduction and carbon sink enhancement throughout the entire life cycle of the micro-regeneration project, with a specific focus on evaluating the time horizon required to reach the carbon balance point between carbon emissions and sequestration. This gauges the carbon cycle efficiency and climate benefits. The Rihui Green Space project achieved a "win-win" for both ecological and climate benefits across its life cycle. According to calculations (see figure 7) [13], after the project's completion, the gap between the green space's cumulative carbon sink and cumulative carbon emissions gradually narrowed. A balance state was reached around the eighth year, after which the cumulative carbon sink surpassed cumulative emissions, with the gap continuing to widen. By the 20th year—the end of the project's assessed life cycle—total carbon sequestration reached 286,531.99 kg, exceeding total carbon emissions of 220,767.67 kg by 65,764.32 kg. This verified carbon-positive outcome provides tangible support for the low-carbon transformation of urban spaces and the broader advancement of low-carbon cities. Additionally, the combined effect of newly added permeable pavement and vegetation systems helps regulate the regional microclimate and lower ambient temperatures, which is beneficial for mitigating the urban heat island effect and enhancing urban climate resilience [16, 17].

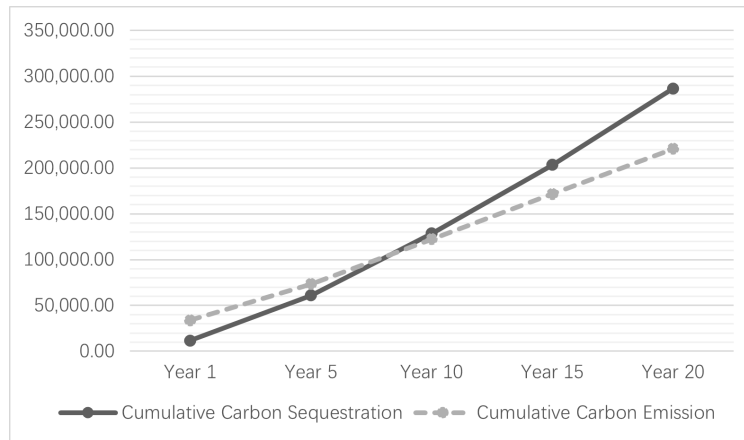


Figure 7. Life cycle carbon sequestration and emission comparison (unit: kg)

The Economic Development bottom line dimension focuses on the economic benefits generated by the micro-regeneration model, including cost savings and long-term value creation. This project not only achieves significantly lower upfront construction costs but also delivers sustained high long-term economic returns, forming a virtuous cycle that supports the goals of sustainable urban development. During construction, the micro-regeneration model preserved the site's original vegetation and layout, reducing costs associated with demolition and the procurement of new plants. It promoted resource recycling and supported the development of industries related to low-carbon materials. In the long run, reliance on the vegetation community to maintain soil health reduced recurring costs for labor and nutritional inputs. After completion, the upgraded Rihui Green Space attracted new residents to the surrounding area, revitalized the community atmosphere, and stimulated consumption. Furthermore, the improved environmental quality of the green space drives a noticeable uplift in surrounding property values, attracts incremental commercial investment in the neighborhood, and ultimately generates significant positive economic externalities derived from the appreciation of local environmental assets [18].

The Social Equity bottom line dimension emphasizes the social benefits generated by micro-regeneration, relating to citizens' rights, health security, and need fulfillment. The micro-regeneration of Rihui Green Space embodies the principle of broadly shared ecological well-being [19]. The pocket park guarantees the ecological rights and public space rights of nearby residents. Within its service radius, it provides a safe and healthy environment for groups of all ages—for instance, through clean air, water, and soil within the green space—meeting the residents' environmental needs. Simultaneously, it offers a free space for recreation and social interaction, satisfying the residents' spiritual and cultural needs.

4. Conclusion

This paper draws the following conclusions:

First, the Rihui Green Space renovation case demonstrates that under the urban micro-regeneration model, targeted measures, including preserving on-site existing resources, adopting low-carbon building materials, and implementing on-site waste recycling can significantly reduce the carbon emissions generated during both the construction phase and long-term building operation processes.

Second, compared to the conventional "large-scale demolition and construction" model of urban renewal, a carbon-cycle-oriented urban micro-regeneration project starts at a granular level. Through a prudent intervention in the existing built environment, it systematically acts upon both the carbon sink and carbon

source ends of the urban carbon cycle. While reducing emissions and enhancing sinks, it also minimizes destruction to the original environment and built structures. This represents a promising model for low-carbon urban development that fosters urban sustainability.

Third, the "Three Dimensions" of environment, economy, and society, grounded in the Triple Bottom Line principle, can comprehensively evaluate the benefits brought by carbon-cycle-oriented urban micro-regeneration. A systematic evaluation should not only consider carbon balance and heat island effects under the environmental dimension, but also incorporate cost reduction and value enhancement under the economic dimension, alongside the protection of ecological rights and the provision of public space under the social dimension.

This study has certain limitations, and future research could be deepened in several directions. First, a large-sample multi-case comparative study can be carried out to horizontally compare the carbon sequestration and comprehensive benefit performance of more pocket park projects with different scales, types and site conditions, so as to establish a more robust and generalizable empirical database. Second, finer quantification of multiple carbon sink types should be pursued by strengthening the long-term monitoring of soil and water body carbon sinks and exploring accurate carbon accounting methods for them. Third, a standardized micro-regeneration evaluation indicator system should be developed. Based on further case studies, a standardized low-carbon micro-regeneration evaluation index system covering dimensions such as carbon sources, carbon sinks, and comprehensive benefits could be constructed, providing a unified tool for project assessment and policy formulation.

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