Transactions on Environment, Energy and Earth Sciences
ISSN: 2960-1924, eISSN: 2960-2300 | Volume 7
GTREE 2026

Research on the Coordinated Development of Urban Green Infrastructure Construction and Carbon Neutrality

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Abstract. This study systematically explores the intrinsic mechanism and implementation path of the coordinated development of urban green infrastructure (UGI) and carbon neutrality. Based on the four-dimensional analysis framework of input carbon effect synergy institutional guarantee, the contribution characteristics of UGI to carbon neutrality were revealed through remote sensing inversion, model simulation, and multiple case comparisons. Indirect carbon reduction is significantly higher than direct carbon sequestration, becoming the dominant path; In the landscape pattern, compact clustered patches have both carbon fixation and emission reduction advantages, while their shape complexity offsets their carbon fixation gains due to the increase in carbon emissions; The configuration of institutional tools is closely related to carbon performance, and the combination of mandatory greening indicators and incentive policies can enhance synergistic benefits. Research shows that incremental expansion cities should prioritize accumulating carbon fixed scale, while stock optimization cities should focus on spatial pattern adjustment to amplify indirect emission reduction benefits.

Keywords: Urban green infrastructure; Carbon neutrality; Collaborative development; Landscape pattern; Institutional guarantee.

1. Introduction

The current urban carbon neutrality path mostly focuses on "grey" technological means such as energy structure transformation, industrial emission reduction, and transportation electrification [1], with insufficient attention paid to the carbon sink function and synergistic benefits of natural ecosystems. The intensification of urban heat island effect, loss of biodiversity, and frequent rain and flood disasters caused by rapid urbanization have become increasingly prominent, and traditional grey infrastructure is no longer able to meet the diverse needs of urban sustainable development. In this context, urban green infrastructure (UGI), represented by urban parks, green roofs, wetland systems, urban forests and green corridors, as the core component of nature-based solutions, is attracting extensive attention from international academic circles and policy makers [2]. UGI not only provides ecosystem services such as rainwater management, heat island mitigation, and biodiversity conservation, but also has significant potential for carbon sequestration and carbon reduction [3]. It is considered an important bridge connecting urban ecological construction with climate goals.

Most studies consider the carbon sequestration function of UGI as one of its many ecological services, lacking systematic integrated analysis of UGI from the perspective of "carbon neutrality" [4]. In other words, how UGI can be an organic component of urban carbon neutrality strategies, rather than just an incidental ecological supplement, has not been fully elucidated. Existing literature mostly evaluates the carbon benefits of UGI from a single technical perspective, lacking a comprehensive mechanism analysis of UGI's synergistic support for carbon neutrality through multiple pathways such as direct carbon sinks, indirect emission reductions, and substitution effects [5]. At the policy level, the institutional connection between UGI planning and urban carbon neutrality action plans is still unclear, and research on related collaborative governance mechanisms is relatively scarce [6]. The above research gaps indicate an urgent need to construct an analytical framework that integrates UGI types, carbon effect pathways, and policy guarantees to systematically reveal the synergistic development logic of the two.

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Based on this, this study explores the collaborative development mechanism and implementation path between urban UGI construction and carbon neutrality goals.Specifically, this article attempts to answer the following three core questions: (1) Through which mechanisms and pathways does UGI contribute to urban carbon neutrality? (2) What are the differences in the synergistic benefits of different types of UGIs in terms of carbon sequestration and emission reduction? (3) What are the main obstacles and policy support needed to promote the coordinated development of UGI and carbon neutrality? To answer the above questions, this article first constructs a four-dimensional analysis framework of input carbon effect synergy benefit institutional guarantee. Then, representative cities are selected for comparative case analysis, and combined with quantitative estimation, a preliminary quantitative evaluation of the carbon benefits of UGI is conducted.

2. Analysis framework construction

This study constructs a four-dimensional analysis framework of input carbon effect synergy institutional guarantee (see Figure 1), breaking down the carbon neutrality contribution of UGI into actionable variable chains. The investment dimension focuses on the spatial supply conditions of UGI, including green space coverage, landscape pattern index, vegetation type composition, and maintenance investment. The reason for including this dimension is that the expansion of GI area helps improve carbon balance, but there are differences in the impact of landscape pattern on carbon emissions and carbon fixation: compact clustered patches are conducive to carbon balance, while complex shapes may enhance carbon fixation but increase emissions [7]. Therefore, the input dimension cannot be measured solely by "area" as a single indicator, and pattern and quality variables need to be introduced. The carbon effect dimension distinguishes two parallel paths: direct carbon fixation and indirect carbon reduction. The basis for choosing this "dual path" design is based on empirical findings that indirect emission reductions may far exceed direct carbon sequestration [8]. If the framework only focuses on carbon storage, it will systematically underestimate the climate contribution of UGI. The dimension of synergistic benefits examines the synergistic or trade-off relationship between carbon effects and non carbon benefits such as rainwater management, heat island mitigation, and biodiversity. Adopting a systematic approach can simultaneously evaluate the benefits of mitigation and adaptation, and identify the underlying internal trade-offs in collaboration. The institutional guarantee dimension covers planning policy tools, fiscal incentives, cross departmental coordination mechanisms, and monitoring and evaluation systems, used to explain why similar investments produce differentiated carbon effects in different cities.

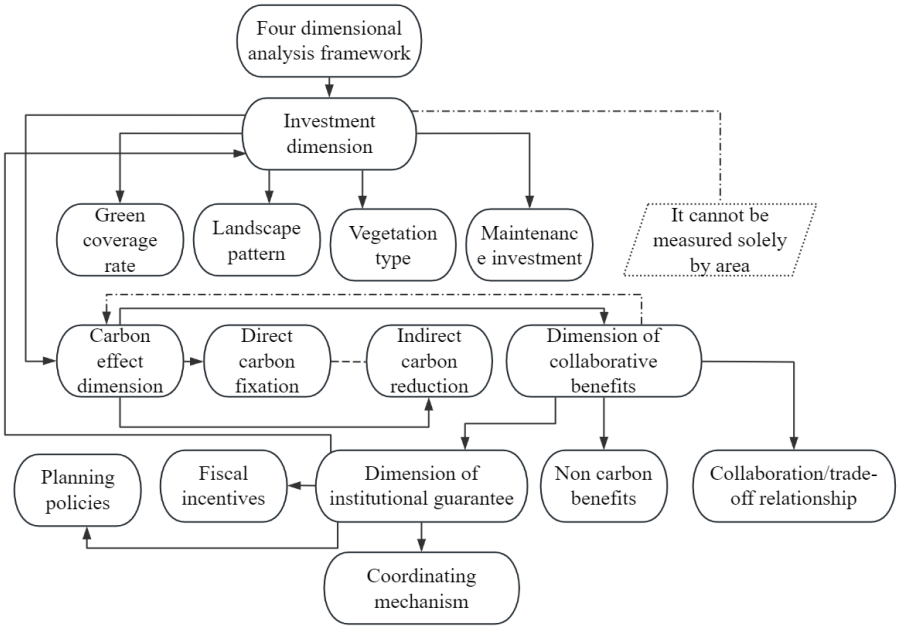


Figure 1. Four dimensional analysis framework of investment carbon effect synergy institutional guarantee.

3. Research methodology

3.1. Quantitative estimation

The Direct Carbon Fixation Strategy uses remote sensing inversion in conjunction with Model Simulation. This includes extracting vegetation indices (NDVI, RVI, SAVI) from multispectral imagery, using LiDAR Data to extract Canopy Structure Parameters, and then building a Hierarchical Regression Model to estimate Above Ground Biomass [9]. At the Plot Scale Validation Level, the i-Tree Eco Model is employed. It accepts input parameters including Breast Height Diameter, Crown Width, and Tree Height; and produces output parameters including Carbon Storage and Annual Carbon Sequestration Rate [10]. The Indirect Carbon Emissions Reduction Estimation Strategy employs a cooling energy-saving carbon reduction transmission chain, based on the regression relationship between UGI Coverage and Surface Temperature; as well as Urban Building Cooling Energy Intensity Data, which are subsequently converted into CO2 emission reductions.

3.2. Comparative case

Select several cities with differences in climate conditions, urbanization stages, and UGI strategies, and use structured comparative analysis [11]. The comparative dimensions include differences in the composition of UGI types, differences in carbon benefit structures, and differences in collaborative/trade-off modes. The data sources include remote sensing products, urban green space census data, energy statistical yearbooks, and policy texts.

3.3. Institutional analysis

Conduct content analysis and coding of UGI related policy documents at the selected city and national levels through institutional analysis. The coding framework refers to the classification of UGI policy tools in existing research, distinguishing between consistency and descriptive modes, covering the entire cycle of planning, construction, control, and monitoring [12]. By encoding and calculating the allocation ratio between mandatory and incentive tools in each city, and comparing it with the aforementioned carbon benefit estimation results, identify the correlation pattern between institutional allocation and carbon performance.

4. Research finds

4.1. The overall scale and structural characteristics of UGI carbon benefits

The study initially showed the overall size and the direct/indirect two-tiered structure of carbon benefits provided by urban green infrastructure through remote sensing estimates and quantitative analysis. It is estimated that blue-green infrastructure within the Greater Bay Area generated a total carbon offset of 1.5 x 10^8 t C/yr in 2019, which includes direct carbon sequestration of 3.5 x 10^7 t C/yr and indirect carbon emission reductions of 11.0 x 10^7 t C/yr. In relation to the region's total CO2 emissions of 1.1 x 10^8 t for 2019, direct carbon sequestration offset 32.0% of the CO2 emissions, whereas the contribution of indirect carbon reduction amounted to 49.9% (Table 1).

Table 1. Structural decomposition of UGI carbon offset capacity in the Greater Bay Area (2019).

Carbon benefit type	Estimated quantity (t · C/yr)	Proportion of total carbon offset	Offset rate for carbon emissions
Direct carbon fixation	3.5×10^7	23.3%	32.0%
Indirect carbon reduction	11.0×10^7	73.3%	49.9%
Total	1.5×10^8	100%	—

This structural feature has been further validated at a finer spatial scale. A study using Xi'an as a case study shows that the average annual carbon neutrality capacity of urban green spaces from 2000 to 2020 was 1.44 $kg \cdot C \cdot m^{-2} \cdot yr^{-1}$, with an average indirect carbon reduction of 1.16 $kg \cdot C \cdot m^{-2} \cdot yr^{-1}$ and direct carbon fixation of only 0.27 $kg \cdot C \cdot m^{-2} \cdot yr^{-1}$, which is about 4.3 times that of the latter. The daily scale estimation of Chengdu urban parks also shows a similar pattern, with a direct carbon fixation intensity of 73.0 t·C and an indirect emission reduction intensity of 2671.3 t·C. The comprehensive carbon savings amount to 2744.3 t·C, which can offset 9.8% of the daily carbon emissions in the study area. The above multi-scale evidence consistently indicates that if only carbon stocks are used to account for the climate contribution of UGI, it will systematically underestimate its true carbon benefits and indirectly reduce carbon emissions, which is the dominant path for UGI's carbon neutrality function.

4.2. Differentiated patterns of carbon benefits between cities

Comparative case analysis reveals significant differences in the total and structural carbon benefits of UGI between cities. Within the Greater Bay Area of Guangdong, Hong Kong, and Macau, the combined carbon sequestration and water-saving carbon reduction of Shenzhen, Guangzhou, Hong Kong, and Dongguan account for 88.7% and 82.0% of the regional total, respectively, demonstrating a highly spatially clustered carbon benefit. This agglomeration is not solely caused by differences in UGI area, but is closely related to differences in urban development stages. The longitudinal analysis of Xi'an shows that the direct carbon fixation capacity has increased from negative values in 2000-2005 to 1.97 $kg \cdot C \cdot m^{-2} \cdot yr^{-1}$ in 2015-2020, mainly driven by the stage of urban development; Indirect carbon reduction is more influenced by spatial characteristics, and the temporal trend is relatively stable. This means that cities at different stages of urbanization should focus on improving their UGI carbon efficiency. Incremental expansion cities should prioritize the accumulation of carbon sequestration capacity, while stock optimization cities should focus on amplifying indirect emission reduction benefits through spatial pattern adjustments.

4.3. The differentiated impact of landscape pattern on carbon efficiency

The carbon benefit of urban green infrastructure (UGI) is dependent upon both the total number of green areas and the way in which those green areas are organized. Random Forest and Ridge Regression based on a panel dataset containing information for 31 Chinese cities over 21 years (from 2001-2021) indicate that landscape pattern indices have statistically significant effects on carbon emissions and carbon sequestration.

Table 2. The correlation direction between landscape pattern index and carbon benefits

Landscape pattern index	Symbolic meaning	Fixed with carbon	Regarding carbon emissions	Net effect
Plaque density (PD)	Fragmentation degree	Negative correlation	Positive correlation	Disadvantage
Percent of Like Adjacencies (PLADJ)	Degree of aggregation	Positive correlation	Negative correlation	Advantageous
Landscape Shape Index (LSI)	Shape complexity	Positive correlation	Positive correlation	Bidirectional

The landscape aggregation represented by PD and PLADJ is positively correlated with carbon emission reduction and carbon fixation enhancement; The shape complexity represented by LSI and area weighted average fractal dimension can enhance carbon fixation, but it is also positively correlated with an increase in carbon emissions [13]. The policy implication of this "shape paradox" is that compact and clustered UGI patch configurations are superior to dispersed and complex configurations in terms of carbon balance. The carbon fixed gain of shape complexity may be offset by the carbon emission increment it causes, and maximizing landscape heterogeneity should not be an unconditional principle for carbon optimization in planning practice. In addition, the expansion of

water landscape area has unexpected negative effects on carbon fixation, indicating that the carbon benefits of blue-green infrastructure do not increase monotonically with scale [14].

4.4. Quantitative evidence and trade-off identification of collaborative benefits

The realization of UGI carbon benefits is not an isolated process, but is nested within the collaborative and balancing relationships of multiple ecosystem services. Bayesian network analysis based on the blue-green space of Xi'an city shows a strong synergistic relationship between carbon sequestration services and habitat quality, with a correlation coefficient of 0.78; There is a clear trade-off between natural accessibility and rainwater mitigation and cooling services, with correlation coefficients of -0.65 and -0.58, respectively. This discovery indicates that the planning objectives of UGI cannot simply pursue the superposition of multiple benefits, but require conscious prioritization and spatial configuration among service clusters.

In 10 Italian cities, simulating tree canopy coverage can provide an estimate of what the economic value of synergistic benefits is. With a 30% or more tree canopy coverage, there was a reduction in average heatwave-related deaths of 36%. Additionally, the average dollar value of new ecosystem service benefits per city was estimated at $10 million and included several categories such as reduced rainwater runoff, decreased air pollution, and increased carbon storage; The annual value of services generated by these 10 cities increased from $47.7 million (in the base case) to $132.8 million [15]. These results demonstrate that while the carbon benefits of UGI exist within a larger ecosystem service value system, if UGI projects are designed to maximize only carbon benefits, they will miss out on the potential for composite returns through multi-service collaboration, which can result in even larger returns than those associated with only carbon benefits.

4.5. The correlation model between institutional configuration and carbon performance

There is a recognizable correlation between the types and allocation ratios of policy tools and UGI carbon performance. The evaluation of China's "National Garden City" policy shows that during its 30-year implementation, the policy expanded urban green spaces by approximately 12645 km², synergistically enhanced the city's carbon sequestration capacity by approximately 34662 Tg C, and simultaneously improved the level of biodiversity [16]. The core feature of this policy is the use of mandatory green coverage indicators as constraints, supplemented by periodic assessment and evaluation, which is a typical configuration of consistency policy tools.

5. Conclusion

At the level of benefit structure, the carbon neutrality contribution of UGI is dominated by indirect carbon reduction, while direct carbon fixation only occupies a secondary position. The current carbon accounting system's systematic neglect of the former constitutes a major blind spot; At the spatial configuration level, a compact and clustered landscape pattern is beneficial for both carbon fixation and carbon reduction, while the carbon effect of shape complexity has inherent contradictions that need to be carefully balanced in planning; At the governance level, the realization of UGI carbon benefits highly relies on institutional integration and cross departmental coordination. Simply increasing green space area or improving green coverage indicators is not enough to ensure sustained improvement in carbon performance.

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