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The Role of Ecological Space Structure Optimization in Synergetic Sustainable Development: Evidence from the Guangdong–Hong Kong–Macao Greater Bay Area

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Abstract: Improving carbon sink capacity is critical for meeting energy conservation and emission reduction targets, along with low-carbon development goals. Although many researchers have recognized that urban space can significantly influence the capacity of carbon sinks in urban areas, few studies have quantified the impact of urban landscape patterns, particularly urban green space (UGS) morphology, on carbon sinks. This study quantitatively investigated the impact of UGS morphology on carbon sinks using panel data from nine cities in the Guangdong–Hong Kong–Macao Greater Bay Area (GBA), China, from 2000 to 2017. A series of landscape metrics and land-use data was first selected to quantify the four dimensions of UGS: scale, compactness, type diversity, and shape complexity. Subsequently, the impact of UGS morphology on carbon sinks was estimated using a panel data model. The main findings were as follows. (1) From the carbon sink results, the carbon sink in the GBA was found to be in an evolutionarily stable state, reflecting the relatively limited potential for carbon enhancement in the region. (2) From the landscape metrics results, the AREA_MD was mainly distributed between 0.18 and 0.27. The AI was mainly distributed between 80 and 97, with a concentration at 90. The PAFRAC was mainly distributed between 1.39 and 1.43, with a concentration at 1.41. PR was mainly distributed between 6 and 7. There was a large disparity in the scale of UGS morphology between GBA cities, with an irregular and complex pattern that became more compact over time. (3) From the panel data results, the AI ($p < 0.001$) had a significant positive impact on carbon sinks, while PR ($p < 0.001$) had a significant negative impact. The more compact the UGS morphology, the greater the total carbon sink, and the more complex the UGS morphology, the smaller the total carbon sink. The findings highlighted the importance of urban planning and UGS morphological optimization for increasing carbon sink capacity, as well as providing policy makers and urban planners with theoretical references and guidance for achieving climate goals.

Keywords: green space morphology; carbon sinks; landscape metrics; panel data models; Guangdong–Hong Kong–Macao Greater Bay Area

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1. Introduction

Global warming, defined by increasing temperatures and unique weather patterns [1], has become a serious threat to sustainability [2]. Cities are the centers of human activity, and they will play a major role in climate change as urban populations and energy consumption increase [3]. It is estimated that cities consume more than two-thirds of global energy and produce more than 70% of global carbon dioxide (CO_2) [4]. Researchers have typically considered these issues from the perspective of carbon sources [5], exploring ways to gradually reduce carbon emissions by optimizing the energy and industrial structure and improving the green development approach [6]. Carbon sequestration and storage, focusing on carbon sinks, were a later consideration but have emerged as a highly promising approach for tackling environmental and climate change issues. Urban ecosystems differ significantly from natural ecosystems in terms of their carbon budgets due to their intense human activity [7]. Studying the carbon sinks within urban green space (UGS) is crucial for reaching the goals of carbon neutrality and a carbon emission peak, as well as preserving regional ecosystems and improving the quality of the human environment.

UGS is characterized as "all urban land covered by vegetation of any kind" [8,9]. From a land-cover and land-use perspective, green spaces typically comprise forestland, grassland, agricultural land, wetland, and unused land [10]. The functions of UGS include improving the well-being of residents and bringing various ecological benefits and ecological service values to the city [11], such as reducing the heat island effect [12], reducing noise pollution [13], mitigating waterlogging [14], improving urban ecosystem circulation [15], and meeting citizens leisure, esthetic, and health needs [16]. It is possible to remove atmospheric CO_2 by sequestering it in UGS, which contains the natural elements in urban areas [17]. However, the environmental and climatic change implications of growing urbanization provide a considerable challenge to UGS planning and management [18]. In UGS, the primary means of carbon fixation and oxygen release is through photosynthesis [19]. Natural carbon sinks [20] include the green spaces in primary natural ecosystems, semi-natural ecosystems, and artificial ecosystems, while UGS is the only direct carbon sink within cities.

In recent years, the relationship between UGS and carbon sinks has received increasing attention from researchers. With the development of the multidisciplinary cross-fertilization of ecology, environment, and urban planning, research data and methods have become increasingly diversified. The use of new data and methods to estimate carbon sinks in UGS has become a hot research topic. Potential data sources include net primary productivity (NPP) data [21], geographic information system data [22], biomass regression equations combined with iTree models [23], and terrestrial laser scanning data [24]. Some studies have estimated the carbon storage capacity of green spaces at different scales, such as global, national, provincial, and municipal. Zheng and Chen analyzed the impact of the transference in territorial space composition on carbon storage by focusing on the Fujian Delta urban agglomeration in China, and they found that it was important to improve the regional carbon sink capacity [25]. Sun et al. quantified and mapped the city-wide aboveground carbon storage of UGS in China's capital, Beijing. Their findings indicated that UGSs have the potential to contribute to the mitigation of future climate change if it is planned and designed in accordance with the trajectory of high carbon density [26]. Rachid et al. used the Moroccan city of Nador as an example to evaluate the advantages of urban greening in terms of carbon storage and sequestration. Their study found that a model combining green roofs with urban vegetation can greatly enhance the city's carbon storage capacity [27]. Some studies have also quantified the whole-life biomass of microbial communities in UGS at the meso- and micro-scales. Dahlhausen et al. studied the allometric correlations between stem diameter, tree height, and crown radius in six tree species in six different cities. They also examined the biomass and carbon storage capacity of several urban tree species. More studies of urban tree biomass and carbon storage on a global scale are crucial due to the increasing focus on urban air quality [28]. McHale et al. calculated the carbon storage and NPP of trees and shrubs in six land-use categories in the dry city of Phoenix, AZ, USA. They then compared these findings with native desert ecosystems and other urban and natural systems globally. Their study indicated that shrubs played a large role in total carbon storage and NPP in deserts, and trees functioned as the dominant carbon pool in cities [29].

Research on carbon sink management in cities has received extensive attention due to the interplay of two key factors: the demands of urban development and policy directives at the national level. Urban forests, i.e., urban shrubs and trees, are highly regarded by urban environmentalists due to their substantial biomass, which enhances the provision of ecosystem services (ESs) [30]. The urban forest has the greatest carbon storage capacity per unit of land area (carbon density) among the different types of UGS [31]. Management methods include improving urban biodiversity [32], the afforestation of degraded and abandoned land [33], and building a green infrastructure (GI) design framework [34]. Basnou et al. created a practical framework for GI planning on a large scale in the Province of Barcelona. They discovered that it is crucial to prioritize the urban fringes when incorporating both ES and biodiversity indicators into GI planning at the landscape level [35]. In terms of research methods and data, researchers have used the incremental growth estimation method [36], forest inventory method [37], land-use and land-cover data [38], and Sentinel-2 spectral data [39] to assess carbon storage and visualize the spatial and temporal distribution of artificial vegetation. Ali et al. investigated the relationship between carbon sources and sinks by analyzing land-use and land-cover data in the Bangkok metropolitan area, Thailand, showing that the gap between local sources and sinks widened every year [40].

Several researchers have recognized that carbon sequestration and carbon fixation have the potential to combat the problem of global warming. Previous studies have investigated the mechanisms by which land-use change and climate change affect carbon sinks in UGS. These studies have investigated soil carbon storage [41], ecological quality [42], and urban tree species and their growth cycles [43]. Wang et al. applied spatial autocorrelation and econometric models to study how different climatic parameters influence the capacity of carbon sinks on a regional scale, and they found that interannual temperature, evaporation, and relative humidity had beneficial effects on carbon sequestration [44]. The relationships between the sustainable development capacity of UGS, the spatial and temporal heterogeneity of urban ES, and the dynamic development of urban land-use management have also become hot research topics [45,46]. Tate et al. examined the contribution of urban blue-green spaces to the United Nations Sustainable Development Goals and concluded that blue-green spaces are needed to mitigate the adverse environmental impacts of urbanization and to provide equitable access to resources to reduce social and health inequalities [47]. Xu et al. examined the impact of the spatial arrangement of UGS on its ES value using a hedonic pricing model. They concluded that for the optimal realization of ES value, green spaces should cover 2.20%–13.40% of the total urban area [48].

Many previous studies have explored the impacts of carbon sink accounting, carbon sink management, urbanization, climate change, and plant characteristics on carbon sinks. However, relatively few studies have focused on the effects of UGS morphology on carbon sinks. Therefore, this study attempted to validate the impact of UGS morphology on carbon sinks, thereby advancing the theoretical understanding of the relationship between UGS morphology and carbon sinks. The rest of this paper is structured as follows. Section 2 provides a description of the research region and concentrates on data and methods, namely landscape metrics and a panel data model. Section 3 displays the outcomes, including the alterations in carbon sinks, the landscape metrics, and the findings of the panel data regression. Section 4 summarizes the findings. Section 5 shows the theoretical implications and policy recommendations.

2. Methods and Data

2.1. Study Area

The Guangdong–Hong Kong–Macao Greater Bay Area (GBA) is located in the south-central part of Guangdong Province, China. This study selects nine cities located in the GBA, including Guangzhou, Foshan, Zhaoqing, Shenzhen, Dongguan, Huizhou, Zhuhai, Zhongshan, and Jiangmen. The GBA is an important economic zone in the Asia–Pacific region and has been at the forefront of adopting China's reform and opening-up policies. As shown in Figure 1, the nine cities in this study together cover 55,368.7 km^2, which is less than one-third of Guangdong Province's total territory. These cities house 53.35% of the population and provide 79.67% of the total economic production of China's largest economic province. It is one of China's three main urban clusters known for its high population density, strong capacity for innovation, and overall economic strength and is often referred to as the "Pearl of the South China Sea".

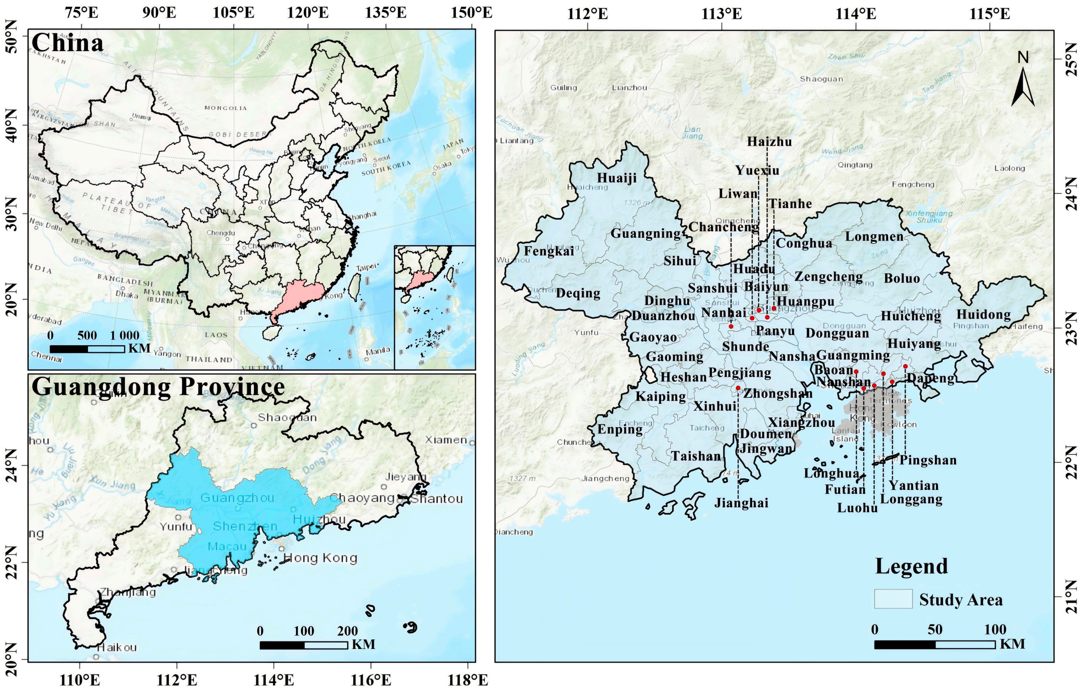

Figure 1. Location of the study area.

The study area was chosen mainly because the GBA is a vibrant world-class urban agglomeration with large urban research value. As an international center for science, technology, and innovation, the GBA faces the challenge of creating a quality living environment while addressing various environmental issues [49]. Since the reform and opening-up policies were initiated in 1978, the region has been one of the fastest-expanding and largest metropolitan districts in China, with significant changes in its UGS. Several studies have identified GDP and population as the two key anthropogenic determinants of CO_2 emissions. The resulting high energy consumption in the GBA presents a significant challenge to its sustainability. Studying how the morphology of UGS in the GBA affects carbon sinks is crucial for policy makers and urban planners in their efforts to reduce CO_2 emissions and combat climate change by supporting environmentally friendly urban development.

2.2. Landscape Metrics

Landscape metrics are often employed in landscape ecology studies to evaluate landscape patterns at three different levels: patch, class, and landscape [50]. These metrics are often used to measure urban morphology, with a focus on size, shape complexity, and compactness [51,52]. They can also provide important information about landscape structure, function, and dynamics, as well as help gain a deeper understanding of the impact of landscapes on ecological space structure, biodiversity, and ecosystem services. Four landscape metrics were selected for this study, taking into account their significance in landscape ecology, the availability of research data, the characteristics of the study area, and their relevance to the research questions. As shown in Table 1, the form of urban green space was quantitatively measured in terms of scale, compactness, type diversity, and shape complexity.

Table 1. Metrics used to describe UGS morphology.

Class	Indicators	Equation	Description
Scale	AREA_MD (Median patch area)	$\mathrm{AREA\_MD} = \mathrm{X}_{50\%}$	$\mathrm{X}_{50\%}$ = the midpoint of the rank order distribution of patch metric values based on all patches in the landscape.
Compactness	AI (Aggregation index)	$\mathrm{AI} = [\frac{\mathrm{g}_{\mathrm{ii}}}{\max \rightarrow \mathrm{g}_{\mathrm{ii}}}](100)$	g_{ii} = number of like adjacencies (joins) between pixels of patch type (class) i based on the single-count method. $\max \rightarrow \mathrm{g}_{\mathrm{ii}}$ = maximum number of like adjacencies (joins) between pixels of patch type (class) i based on the single-count method.
Shape complexity	PAFRAC (Perimeter-area fractal dimension)	$PAFRAC = \frac{\overline{\left[n_i \sum_{j=1}^{n}\left(lnp_{ij} \cdot lna_{ij}\right)\right] - \left[\left(\sum_{j=1}^{n} lnp_{ij}\right)\left(\sum_{j=1}^{n} lna_{ij}\right)\right]}^{2}}{\left(n_i \sum_{j=1}^{n} lnp_{ij}^{2}\right) - \left(\sum_{j=1}^{n} lnp_{ij}\right)^{2}}$	a_{ij} = area (m^2) of patch ij. p_{ij} = perimeter (m) of patch ij. n_{i} = number of patches in the landscape of patch type (class) i.
Diversity of types	PR (Patch richness)	$\mathrm{PR} = \mathrm{m}$	m = number of patch types (classes) present in the landscape, excluding the landscape border if present.

Table 2 compares the advantages, limitations, and common research scenarios of the four landscape metrics. The median patch area (AREA_MD) can be used to measure the size of patches within a landscape. It is calculated by determining the value of the patch metric for patches that fall in the middle of the rank order distribution of patch metric values across the entire landscape. It functions as a metric for the standard dimensions of patches within the landscape. The AREA_MD is an important landscape structure indicator, which reflects the distribution characteristics of patch area in the landscape, which is of great significance for analyzing landscape heterogeneity and biodiversity. The aggregation index (AI) is used to examine the connectivity between patches of each landscape type. It is of great significance for understanding the ecological function of the landscape and species migration. The Al increases as the terrain becomes more aggregated and reaches 100 when the landscape is a single patch. Although the CLUMPY can also reflect aggregation and dispersion, its value range is −1–1, which may not be as intuitive as the AI value range of 0–100. AI provides a quantitative measure that can more accurately assess the connectivity of patches in the landscape. Moreover, a high AI value directly indicates a high degree of aggregation, which is more convenient for the interpretation and application of the research. The patch richness (PR) is defined as the total number of distinct patch types found inside a landscape boundary. The PR is considered the most intuitive indicator of landscape composition and, together with spatial heterogeneity, is a key indicator of landscape components, influencing many ecological processes. A positive correlation between PR and species abundance has been previously reported. A suitable PR is especially important for organisms whose survival requires multiple habitats. The perimeter–area fractal dimension (PAFRAC) represents the shape complexity over a range of spatial scales of patch sizes, with values between 1 and 2. The PAFRAC can reflect the tortuosity and complexity of landscape boundaries and is of great significance for understanding the structure and function of landscapes. The PAFRAC approaches 1 for simple geometries with basic perimeters and approaches 2 for geometries with intricate perimeters. Although the FRAC can also describe the shape characteristics of the landscape, PAFRAC focuses more on the complexity of the patch shape and has more obvious advantages in capturing the irregularities of patch shape at different scales and assessing the degree of human interference.

Table 2. Comparison between four landscape metrics.

Indicators	Advantage	Limitation	Common Research Scenarios
AREA_MD	This metric provides a central trend in patch size in the landscape and is an important indicator of landscape heterogeneity. It helps to understand the typical size of patches in the landscape and is important for analysing landscape structure and function.	This metric may not fully capture the variability in patch size in the landscape, as it only provides a mean value. AREA_MD may not be sufficient to fully describe the structure of the landscape when patches of significant size variation are present in the landscape.	Suitable for land use planning, ecological restoration assessment, etc.
AI	This metric measures the degree of aggregation of landscape elements and is important for understanding species distribution patterns and landscape connectivity. High aggregation may indicate a strong tendency for spatial aggregation in the landscape, which is critical for conserving biodiversity and maintaining ecological processes.	This metric may be affected by the shape and size distribution of patches, and therefore may need to be interpreted with caution in different landscape types. In addition, AI may not be able to capture all types of spatial patterns, especially those that are non-aggregated in spatial distribution.	Suitable for shape optimization of ecological reserves, urban green space planning, etc.
PAFRAC	This metric is an indicator of the complexity of the shape of a patch, which measures the edge effect of the patch by considering the relationship between the perimeter and area of the patch. PAFRAC is very useful for assessing the edge effect and shape heterogeneity of patches in a landscape.	The calculation of this metric may be complex and require high data processing capabilities. In addition, PAFRAC is sensitive to changes in the scale of the patch, and interpretation may need to be adjusted for landscapes at different scales.	Suitable for landscape fragmentation analysis, ecological restoration monitoring, etc.
PR	This metric is a measure of landscape diversity that reflects the richness of different patch types in the landscape. PR is important for assessing the biodiversity and ecological complexity of a landscape because it provides important information about the diversity of the landscape composition.	This metric may be affected by the sample size and the number of patch types, so it may need to be interpreted differently in different landscapes. In addition, PR may not capture the complexity of interactions between patches in the landscape, such as connectivity and functional links between patches.	Suitable for urban expansion monitoring, ecological risk assessment, etc.

2.3. Panel Data Models

Panel data analysis, a form of regression analysis, can be used for the examination of data from multiple individuals over multiple periods [53]. Panel data combine cross-sectional and time-series dimensions, providing panel data models with benefits over traditional statistical models that rely only on cross-sectional or time-series data. Panel data models usually feature more data points than cross-sectional models, leading to more degrees of freedom and lower collinearity among the explanatory variables, which may enhance the estimate efficiency. Before completing parameter estimates in panel data modeling, many pre-tests must be conducted, such as the multicollinearity test and Hausman test. Panel data modeling typically utilizes two principal estimators: random-effects and fixed-effects estimators. The appropriateness of each strategy is often assessed using a Hausman test [54]. The random-effects model includes unobservable and time-invariant elements for each observation unit inside the disturbances, supposing no correlation with the regressors, which is the null hypothesis in the Hausman test. When this test rejects the null hypothesis, the random-effects estimator exhibits superior efficiency relative to the fixed-effects estimator. As an alternative, one ought to use the fixed-effects estimator. This study examined how the morphology of UGS has impacted the carbon sink capacity. The panel data modeling approach was deemed an effective technique for this investigation and was used during the period of 2000–2017. The model was specified as follows:

$$ln(CS)_{it} = \alpha_0 + \alpha_1 In\text{AREA\_MD}_{it} + \alpha_2 InPAFRAC_{it} + \alpha_3 In\text{AI}_{it} + \alpha_4 In\text{PR}_{it} + \varepsilon_{it}$$

where $(CS)_{it}$ is the carbon sinks. $InAREA\_MD_{it}$, $InPAFRAC_{it}$, $InAI_{it}$, and $InPR_{it}$ denote the landscape metrics. α represents the coefficient to be estimated, which is the coefficient of the impact of the independent variable on the dependent variables. ε_{it} is an error term.

2.4. Data Sources

The land-use data used in this study were obtained from the Resource and Environment Science Data Centre of the Chinese Academy of Sciences (http://www.resdc.cn (accessed on 25 March 2024)). Carbon sink data were obtained from the Carbon Emission Accounts and Datasets for emerging economies (CEADs) of Tsinghua University (https://www.ceads.net (accessed on 25 March 2024)).

3. Results

3.1. Evolution of Carbon Sinks, 2000–2017

Based on the results of the carbon sink data, a map of the time-series changes in the carbon sinks of the nine cities from 2000 to 2017 was constructed to further analyze the spatial differentiation characteristics of the carbon sink capacity. As shown in Figure 2, there was little overall change in the carbon sink capacity from 2000 to 2017, and the data remained largely stable. This reflects the relatively small potential for carbon sequestration in the study area and the relatively limited scope for the further upgrading of ecological space. Guangdong Province, where the study area is located, has the reputation of being "the first province in China to reforest barren mountains". According to incomplete statistics, over 5 billion trees have been planted in the region over the past 40 years. Based on the "Green Guangdong" campaign, the GBA region has established China's first national forest city cluster.

The regional distribution of total carbon sink capacity exhibited elevated levels in the northwest, southwest, and eastern areas, while demonstrating decreased levels in the center region. High values were mainly found in Huaji County and Fengkai County in Zhaoqing City in the northwest; Taishan City, a county-level city under Jiangmen City in the southwest; and Huidong County in Huizhou City in the east. The total carbon sink capacity of all three regions remained relatively high from 2000 to 2017. In high-value areas, there was a high total urban carbon sink capacity over the study period, reflecting these regions' ability to absorb and store CO_2 and their high-quality natural environment. The minimal values were mostly seen in the Huangpu, Haizhu, Yuexiu, and Liwan Districts in Guangzhou City, the center region of the research area; Chancheng District in Foshan City; and Jianghai District in Jiangmen City. The Futian and Luohu Districts in Shenzhen in the southeast were the areas with the lowest total carbon sink capacities over the calendar year. The areas with the next lowest values included Tianhe District of Guangzhou City, Shunde District of Foshan City, and Pengjiang District of Jiangmen City in the center, as well as Duazhou District of Zhaoqing City in the west. In the low-value areas, there was a low total urban carbon sink capacity over the study period, reflecting these regions' relatively poor ability to absorb and store CO_2 and their relatively low-quality natural environment. Tianhe and Haizhu Districts in Guangzhou, Chancheng District in Foshan, and Futian District in Shenzhen surrounded the low-value and sub-low-value regions, all of which had high levels of economic development. Land types with a high carbon sink capacity were mainly composed of forestland, unused land, low-cover grassland, and other land-use types with low carbon sink coefficients. Recent fast urbanization has led to a loss in the carbon sink capacity and ecological quality of low-value regions due to the ongoing expansion of building land, alongside deforestation and the reduction in grassland cover.

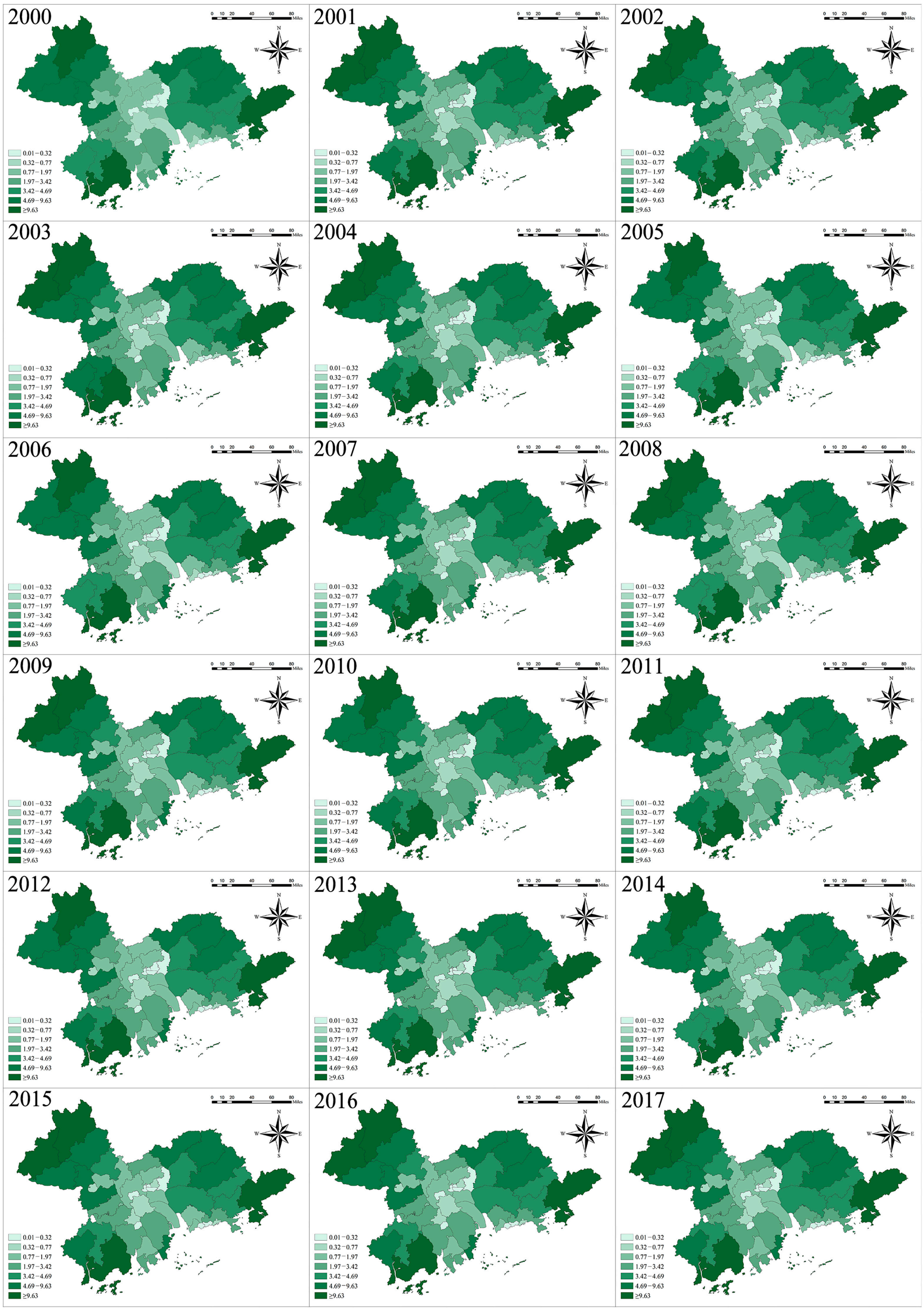

Figure 2. Changes in the carbon sinks over the study period.

3.2. Estimation Results of the Landscape Metrics, 2000–2017

From 2000 to 2017, with the acceleration of urbanization, the UGS morphology of the nine cities in the GBA underwent significant changes. AREA_MD, AI, PAFRAC, and PR are presented as a series of boxplots. In Figure 3, each box represents the statistical results of a set of landscape metrics. The x-axis represents four different types of landscape metrics, and the y-axis represents the statistically derived values used to quantify the landscape pattern of USG. In the boxplot, the values on the y-axis show the distribution of each landscape metric, including statistical information, such as the median, quartiles, and outliers. The bottom and top of each boxplot represent the 25th and 75th percentiles, respectively. As shown in Figure 3, the AREA_MD mainly ranged from 0.18 to 0.27. The wider box for the AREA_MD indicates that these data were more spread out. The AI mainly ranged between 80 and 97 and was concentrated at 90. The PAFRAC mainly ranged between 1.39 and 1.43 and was concentrated at 1.41. The PR mainly ranged from 6 to 7.

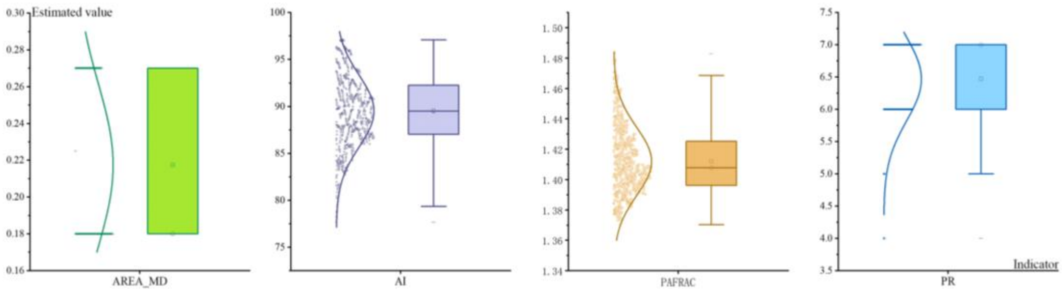

Figure 3. The results of landscape metrics.

Based on the results shown in the boxplots, a basic picture of UGS morphology in the GBA could be constructed. The AREA_MD typically reflects the average or characteristic patch size within a landscape at a specific scale. During 2000–2017, the patch area data distribution of UGS morphology was relatively discrete, and the differences between the data were relatively large. This suggests large differences in the scale of UGS between cities. In terms of compactness, the AI increases with the degree of aggregation of the landscape, with smaller values when the landscape is more discrete. The landscape pattern became more compact during 2000–2017, while the UGS morphology continued to integrate and expand with other regions, resulting in more continuous urban patches. In terms of shape complexity, the closer the value of the PAFRAC is to 1, the more regular the patch shapes are, indicating a greater degree of human disturbance. During 2000–2017, the UGS morphology was disturbed by urban construction activities and an increasingly irregular and complex pattern developed. In terms of type diversity, the PR is also used to indicate the degree of anthropogenic disturbance. The greater the PR, the greater the patch-type richness and the greater the landscape fragmentation. During 2000–2017, the typological diversity of UGS morphology increased and the naturalness of the landscape decreased, which was not conducive to the formation of stable ecological communities.

3.3. Estimation Results of the Panel Data Models During 2000–2017

3.3.1. The Pre-Test Results

As shown in Table 3, the VIF test (values < 10) shows that there is no serious multiple collinearity among the four selected landscape metrics. The panel data model may then be approximated. Hausman tests were conducted to determine appropriate regression types for the model, among which were random-effects and fixed-effects models. If the test rejects the assumption of the random-effects model (i.e., there is endogeneity), it indicates that the fixed-effects model is a more appropriate model [55]. The assumption and potential limitation of the fixed-effects model are that the model may be affected by non-linear models, especially when the assumption of normal distribution is violated, which may lead to significant deviations. The model's p values in Table 4 were below the crucial values at a 5% significance level, leading to the rejection of the null hypothesis that random variation could sufficiently account for the observations. Therefore, the model was established based on fixed effects.

Table 3. Multicollinearity diagnostic of landscape metrics.

Indicators	AREA_MD	AI	PR	PAFRAC
VIF	3.125	4.126	1.943	3.462

Table 4. The Hausman test results.

Chi-sq Statistic	*p* Values	Type of Regression Model
70.08	0.0000 ***	Fixed effects

*** $p < 0.01$.

3.3.2. The Estimation Result of the Panel Data Model

Table 5 shows the parameter estimation results, enabling the impact of UGS morphology on carbon sink capacity to be determined. The indicators AREA_MD and PAFRAC did not have a significant impact on carbon sink capacity. The scale and shape complexity of UGS morphology had a limited ability to influence carbon sink capacity. Despite the variations in scale and shape complexity, the influence of both factors on carbon sink capacity was considered negligible. The AI exerted a significant positive effect on carbon sink capacity, while PR exerted a significant negative effect on carbon sink capacity, which was consistent with expectations.

Table 5. Estimation results for the panel model.

Explanatory Variables	Data
In AREA_MD	0.0297724 (0.021972)
In AI	1.505478 *** (0.3258745)
In PR	−0.1542419 *** (0.056161)
In PAFRAC	−0.1073701 (0.6063399)
Constant	−5.981958 *** (1.567506)
F test	F(46, 796) = 4679.75 $p = 0.000$ ***
Area FE	YES

*** $p < 0.01$.

As mentioned previously, the AI is a measure of compactness that represents the connectivity between patches. Generally, a higher AI value corresponds to a more compact UGS morphology. The model's estimate findings indicate that a more compact UGS morphology leads to an increased overall carbon sink, signifying a greater carbon sink capability. This was because compactness reflects the aggregation of UGS. The compact UGS morphology emphasizes the concentrated distribution and clustering of green space into patches. The reality manifested itself in continuous, scaled urban ecological patches. The higher the connectivity and the more closely linked the ecological network, the more likely it would be to increase carbon sequestration, which would ultimately lead to an increase in the total carbon sink. Previous studies have shown that urbanization produced two patterns of development in urban space. The first is urban sprawl, which can lead to haphazard development. The second is internal, smart growth, i.e., intensive urban growth. National experiences in urban development have shown that urban compactness is significantly more efficient in terms of resource use than urban sprawl. Compact UGS includes ecological patches, such as nature reserves, country parks, city parks, and urban water bodies. It also includes various types of green corridors.

Since 2000, the GBA has been attempting to build a world-class forested city cluster, with a commitment to creating highly connected ecological corridors and high-quality natural parks. The protection and connectivity of mountains and green eco-open spaces have been promoted within and between cities, and a complete urban green eco-network has been actively created. As a city with a strong carbon sink capacity, Zhaoqing in the northwestern GBA makes full use of the established greenways, forest parks, wetland parks, and geological parks to construct green corridors. This has enhanced the urban landscape and greening level and greatly improved the quality of the natural environment. Overall, UGS in the GBA, as an important form of public open space in the urban environment, is dominated by public green areas. These spaces have gradually developed into a large-scale ecosystem that is intensive, compact, and functionally diversified, ultimately taking the form of a green complex. Thus, developing a compact UGS morphology is vital for boosting the carbon sink potential of the GBA.

The PR is a measure of type diversity, which represents the complexity of patch types and landscape components. Overall, the higher the PR value, the more patch types are present within UGS and the higher the degree of human interference. The clearer the landscape differentiation, the higher the landscape fragmentation. Therefore, the estimation results of the model could be interpreted as the more complex the UGS morphology, the smaller the total carbon sink, i.e., lower carbon sink capacity. This is due to the development of a fragmented and complex UGS pattern, which places the ecological level and carbon sink capacity of cities at risk. There are two main types of cases. In the first, as urbanization continues to advance and cities continue to expand outwards, a large amount of natural ecological space becomes built-up, leading to the compression of UGS. Many original grasslands and woodlands have been developed into residential, commercial, and industrial areas, resulting in the fracturing and fragmentation of urban ecosystems. High-intensity urban construction activities imply excessive human intervention. The complexity of UGS patch types increases, resulting in a destabilization of the internal structure of UGS and a reduction in carbon sink capacity. In the second case, the role of UGS is valued by all sectors, but economic development without considering the environmental and social aspects and flawed approaches to environmental management hinder the scientific deployment of UGS. Complex patch types often mean a rough approach to plant configuration. The carbon sink capacity of UGS is directly limited by the size of the green area, plant type, community structure, vertical hierarchy, plant age, specification, green volume per unit area, and canopy density. The more complex the plant community level, the better the carbon sequestration effect, and the higher the plant community density, the stronger the carbon sink function.

Following the implementation of reform and opening-up policies, the GBA has progressively evolved into one of the most densely inhabited urban regions in China, characterized by the highest degree of urbanization and the greatest intensity of development and building in the nation. This has resulted in problems, such as the non-intensive use of resources, uncoordinated land-use patterns, and insufficient capacity for ecological space management. According to data released by the Shenzhen Planning, Land, and Development Research Centre, the intensity of land development in a number of GBA cities is close to or exceeds the internationally recognized warning threshold of 30%. In summary, it is important to control the development of UGS fragmentation and to follow a pathway of natural development, while scientifically configuring plant communities with strong carbon sequestration benefits to improve the carbon sink capacity of the GBA.

4. Conclusions

This study quantitatively investigated the impact of UGS morphology on carbon sinks using panel data from nine cities in the GBA from 2000 to 2017. A series of landscape metrics (AREA_MD, AI, PR, and PAFRAC) were selected. Landscape metrics and land-use data were used to quantify the four dimensions of UGS morphology: scale, compactness, type diversity, and shape complexity. Subsequently, the impact of UGS morphology on carbon sinks was estimated using a panel data model. The findings were as follows. (1) In terms of carbon sinks, the total carbon sink capacity did not change substantially over the study period and the data remained basically stable. This reflects the relatively small potential for carbon sinks and the relatively limited scope for further upgrading the ecological level. The spatial pattern of carbon sink capacity had the general characteristics of high in the northwestern, southwestern, and eastern regions, and low in the central region. Regions with a higher level of economic development had low total carbon sinks, and the carbon sink capacity needed to be upgraded. (2) In terms of the landscape metrics, there was a large disparity in the scale of UGS between cities. From 2000 to 2017, the UGS morphology adopted a more irregular and complex pattern, and the spatial morphology became more compact. The diversity of UGS morphology increased over the study period, while the naturalness of the landscape decreased, with a trend of fragmentation and complexity. (3) In terms of the panel data model, the AI exerted a significant positive effect on carbon sink capacity, while the PR exerted a significant negative effect on carbon sink capacity. The estimation results of the model could be interpreted as a more compact UGS morphology resulting in a greater total carbon sink capacity. The more complex the UGS morphology, the smaller the total carbon sink capacity. The findings highlighted the importance of urban planning and UGS morphological optimization for increasing carbon sink capacity, as well as providing policy makers and urban planners with theoretical references and guidance for achieving climate goals.

5. Implications

5.1. Theoretical Implications

This study offers significant theoretical insights into the impact of UGS morphology on carbon sink and extends the discourse on eco-city construction and sustainable urban development. The research emphasizes the key role of UGS as a direct carbon sink, which is crucial for maintaining the carbon–oxygen balance and ecological stability. The findings reveal that the morphological characteristics and spatial layout of UGS substantially influence the carbon sink capacity, underscoring the importance of urban planning and green space design in achieving carbon-neutrality goals. In regions with a relatively limited carbon sink potential, attention to the compactness of UGS is particularly critical. Concurrently, the fragmented development of UGS should be appropriately managed, and plant communities with robust carbon sequestration capabilities should be scientifically configured in accordance with natural developmental patterns. These insights offer distinct advantages for further enhancing carbon sink capabilities. Urban planners and policymakers should consider not only the multifaceted values of UGS beyond esthetics and recreation but also prioritize its role in mitigating climate change and achieving global sustainable development goals.

5.2. Practical and Policy Recommendations

In urban planning, UGS, as the only land use carrying the function of a carbon sink, has a critical role in the future green development of cities and the attainment of carbon neutrality. To address the effects of climate change, the GBA government must comprehensively grasp the function of planning instruments in optimizing the configuration of UGS and augment the carbon sink potential of urban areas by scientifically structuring UGS morphology. The following are suggestions for urban planning measures to enhance the carbon sink capacity of GBA green spaces.

First, in terms of scale, this study showed that the scale of UGS in the GBA has only a limited potential to influence carbon sink capacity. However, past studies have shown that an increase in the area of UGS and green covering may effectively boost the overall urban carbon sink capacity. Therefore, in addition to focusing on increasing the extent of UGS, more emphasis should be placed on improving the quality of UGS. It is important to build a connected and solid urban green ecological network based on the ecological background. By promoting green ecological patterns, establishing forests as carbon sinks, creating nested UGS systems, scientifically repurposing built-up land, and other spatial response measures, the quality of UGS in the GBA could be improved, and the total carbon sink capacity of the regional ecosystem could be increased. To promote the balance between population, resources, and the environment, the red line for urban ecological protection should be strictly adhered to. This would also ensure the unity of economic, social, and ecological benefits. It is also necessary to follow the planning concepts of low-carbon cities, resilient cities, and garden cities to build a UGS network that is integrated with nature. Multi-tiered ecological corridors and landscape ecological nodes must be established to develop urban ecological barriers and enhance the city's overall ecological quality. A comprehensive understanding of the interplay between natural resource conservation and urban growth is essential for the best allocation of natural resources, enhancement in carbon capture efficiency, and improvement in urban environmental quality.

Second, in terms of compactness, the development of a compact and intensive UGS morphology and the improvement in the connectivity of urban green patches will help increase the total carbon sink. UGSs in high-density cities are often "isolated", as evidenced by their weak ecological connectivity, homogeneous landscape structures, and fragmented landscapes. For example, the "green corridor movement" in the United States uses the connectivity of corridors to link natural ecosystems on the periphery of cities, thus ensuring the greatest possible natural landscape value of UGS. It is, therefore, important to focus on the wholeness and connectivity of UGS. Urban green patches are coordinated to ensure the systemic wholeness of UGS. Through the rational layout of large-scale forests, grasslands, unused land, and other ecological patches, and by relying on urban architectural space, agricultural production space, and rural settlement space, a large urban green complex will be formed. The effective connection and mutual supplementation of urban green resources will be realized, and the wholeness and functionality of the UGS of the whole region will be guaranteed. Additionally, the construction of ecological corridors should be prioritized to ensure the systematic connectivity of UGS. The construction of ecological corridors between cities in the GBA and between cities and villages should also be strengthened by linking major forest parks, nature reserves, scenic spots, country parks, and waterfront parks. Efforts should be made to build green ecological barriers, green corridors, and large-scale green networks to form a "continuous, complete, systematic, and tangible" UGS pattern.

Third, in terms of the diversity of types, the UGS morphology in the GBA displayed a trend of complexity and fragmentation. Optimizing the internal structure of UGS, improving the fine management of UGS, and developing an efficient UGS morphology will help increase the total carbon sink capacity. Some scholars have used Tokyo as an example and found that the richness of shrubs and evergreen trees has a positive impact on bird diversity. The variation in plant structure is one cause for this pattern. Amidst the challenges posed by urbanization, it is imperative to preserve and effectively manage small green spaces [56]. Therefore, it is necessary to optimize the configuration of urban plant communities and the scientific layout of UGS with a large carbon sink capacity. According to the results of previous studies, in terms of plant configuration characteristics, the type, age, size, and community structure of plants have different degrees of influence on their carbon sequestration capacity. The carbon sink capacity of different types of plants varies greatly. The carbon sequestration capacity of trees surpasses that of shrubs, herbs, and lianas; broad-leaved forests exhibit a greater capacity than coniferous forests; deciduous trees outperform evergreens; certain native plants exceed exotics in capacity; and young to middle-aged plants possess a greater capacity than mature plants. Increasing the overall green volume and establishing plant communities with strong carbon sequestration abilities can significantly enhance the carbon sink capacity of UGS. It is necessary to establish a carbon sink database of common local urban plants to effectively quantify the dynamics of carbon sinks in UGS and to monitor and forecast carbon and oxygen balances. This is a key step to support the construction of UGS. When selecting individual plants, it is necessary to combine the carbon storage measurements of individual plants, plant tree species with a moderately high carbon sink capacity, and use more native plants to reduce the carbon emissions generated by the maintenance process. The local natural community structure needs to be combined with the desired landscape visual effect to match the individual plants to form a plant community with a large number of plants with a high carbon sink capacity, rich species diversity, and an overall strong carbon sequestration capacity.

Fourth, in terms of shape complexity, the shape of UGS patches in the GBA had a limited influence on carbon sink capacity, but there is still a need for urban planning managers to consider shape complexity. Excessive or frequent anthropogenic disturbances will affect the system stability and biodiversity of UGS, thus affecting the carbon sink capacity. It is, therefore, important to ensure that UGS remains as natural as possible, and excessive, unnecessary, and non-scientific human intervention is reduced. This will safeguard the ecological stability, sustainability, and inclusiveness of UGS. In urban planning, it is important to retain and introduce new UGS in its natural state. It is possible and beneficial to establish relatively large areas of forested UGS and important ecological corridors, retain a certain proportion of minimally disturbed or wilderness-managed natural belts, and cultivate long-term, stable, and aging UGS. This will create a source of biodiversity and leave a historical ecological legacy for the city. Through the near-naturalization of urban artificial forests, the naturalness of UGS will be enhanced, and the originality and integrity of the UGS will be actively realized. Certain research, using Hong Kong as a case study, indicates that forest restoration is an effective strategy for alleviating climate change, reinstating ecological services, and safeguarding biodiversity. They assert that it is essential to integrate the natural regeneration and active restoration of forests into the planning framework for urban green space restoration [57]. At the same time, the quality of UGS in areas accessible to the public will be enhanced, providing more opportunities for the public to get closer to nature.

Optimizing UGS morphology has significant value and offers the potential for enhancing the carbon sink capacity of urban areas. There were some limitations to this study, and further in-depth research will be required in the future. UGS includes a variety of land types, such as woodland, grassland, farmland, wetland, and unused land. The impacts of these different land types on carbon sinks may be spatially heterogeneous. It is expected that more comprehensive conclusions could be drawn if the different land types within UGS are further subdivided in future studies.

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