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A Multi-Scale Evaluation Model of Sustainable Development Goal 11.7 for Problem-Solving at Different Levels

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Abstract: Sustainable Development Goal 11.7 (SDG 11.7) aims to promote the improvement of urban public spaces. However, the localization process of SDG 11.7 mainly relies on a bottom-up problem-solving approach, which fails to fully encompass the connotation of SDG 11.7. Additionally, existing evaluations primarily focus on a single scale, neglecting the impact of scale issues. These limitations can lead to imbalanced development or misallocation of responsibilities when guiding governments at different levels in promoting the sustainable development of public spaces. Therefore, this article introduces a multi-scale assessment model of SDG 11.7. It employs a top-down problem-solving approach to construct a sustainable development indicator framework, setting appropriate sustainable development indicators for various levels of government based on the connotation of SDG 11.7, and generates city-scale results by integrating three scales: apartment complexes, street blocks, and counties. Testing this model in Xi'an, China, revealed that it adequately captures four key aspects of SDG 11.7—safety, inclusiveness, accessibility, and greenness—through 11 indicators. The evaluation outcomes at the apartment complex, street block, and county levels effectively guide future development directions for various levels of government. Ultimately, the synthesis of these scales reveals the spatial pattern of SDG 11.7 at the city scale and identifies focal areas for development. Overall, this exploratory model demonstrates high accuracy and robustness, providing a comprehensive understanding of the essence of SDG 11.7. It also alleviates challenges posed by scale issues, offering decision support for monitoring SDG 11.7 across different levels of government in Chinese cities and promoting the process of sustainable development.

Keywords: SDG 11.7; top-down problem-solving approach; urban sustainable development indicator framework; multi-scale model; Xi'an city

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1. Introduction

Cities serve as the primary nexus of human activity and play a pivotal role in advancing the United Nations' agenda for sustainable development [1]. Public spaces represent a main facet of implementing sustainable development strategies in cities, intricately linked to the urban environment and residents' well-being [2]. The United Nations Sustainable Development Goal 11.7 (SDG 11.7) particularly emphasizes the assessment of sustainability in urban public spaces, aiming to "provide universal access to safe, inclusive and accessible, green and public spaces, in particular for women and children, older persons and persons with disabilities by 2030" [3].

The connotation of SDG 11.7 mainly encompasses four aspects: safety, inclusiveness, accessibility, and greenness. Within the United Nations' global indicator framework, SDG 11.7.1 and SDG 11.7.2 are two indicators used to monitor SDG 11.7. These indicators have been extensively employed in assessments of SDG 11.7 [4,5]. As research deepens and concerns arise regarding the applicability of the United Nations' SDG indicator framework in cities with different contexts, scholars have begun to focus on the localization of SDG 11.7 indicators. Some studies have established a comprehensive set of indicators, including quality, proximity, and area, to evaluate the sustainability of parks in Denver, USA [6]. There are also studies that have utilized machine learning to extract Google Street View data, allowing for the assessment of accessible greenery for residents [7]. Furthermore, numerous studies have used accessibility indicators to evaluate residents' ability to access public spaces based on different modes of transportation or by distinguishing between different types of parks [8,9]. These efforts reflect the continuous improvement of SDG 11.7 indicators framework from various perspectives.

However, most assessment indicator sets have failed to comprehensively encompass the four key areas that SDG 11.7 aims to address. For instance, while spatial equity is directly involved in United Nations' SDG 11.7 framework, this aspect is not adequately reflected in the UN-SDG 11.7 indicators [10]. Existing research on the construction of the SDG 11.7 indicator framework similarly focuses on public space accessibility or the valuation of ecosystem services, neglecting issues such as inclusivity and safety [11], which results in biased evaluation outcomes. The reason for the inadequacy of sustainable development indicators in fully representing the connotation of SDG 11.7 is that the UN-SDGs framework represents a top-down system, while scholarly efforts to address sustainable development assessments often follow a bottom-up research paradigm, which makes even the UN-SDG 11.7 indicators unable to cover the connotation of SDG 11.7. While a bottom-up research paradigm allows for a more focused resolution of specific issues, the gaps in methods have resulted in an insufficient set of indicators, failing to capture the entire connotation of SDG 11.7 [12]. Neglecting the connotation of SDG 11.7 prevents stakeholders from focusing limited resources on the public space functions that are more important to urban residents, leading to imbalanced development [13]. Therefore, it is urgent to construct a top-down indicator framework to fully reflect the connotation of SDG 11.7.

Furthermore, there is a lack of attention to scale issues in the assessment of SDG 11.7. Scale refers to the spatial and temporal dimensions of the research object or process. In the realm of urban sustainable development, scale is invariably linked to administrative power and thus generally represented by administrative-level [14,15]. Numerous scholars have confirmed the scale-relatedness of sustainability [16]. Taking some SDG 11.7 indicators as examples, public space accessibility and greening rates vary significantly at different administrative levels [17]. However, these differences are related solely to scale rather than to actual objective changes. This highlights the need for research to consider the influence of scale issues on SDG 11.7 monitoring and to conduct multi-scale assessments. Unfortunately, very few studies have focused on the status of SDG 11.7 across different levels of administrative entities. Paying attention to the sustainable development status across different scales is crucial. On the one hand, evaluating SDG 11.7 solely at a singular scale might inadvertently limit considerations of other relevant scales, leading to a "scale trap" [18]. On the other hand, using single scale model for all administrative entities undoubtedly sets sustainable development goals beyond the scope of some governments' authority. These issues are all sources of the misalignment of responsibilities among administrative entities. Therefore, it is necessary to address the issue of responsibility mismatch between administrative entities by developing specific sustainable development indicators and evaluation methods for different levels of government, that is, to conduct multi-scale evaluations of SDG 11.7 at different levels of government [19].

Based on the above, this article constructs a comprehensive multi-scale SDG 11.7 indicator framework through a top-down problem-solving approach, which determines development indicators for apartment complexes, street blocks, and counties and proposes a multi-scale evaluation method to obtain SDG 11.7 results at the urban scale. This article mainly fills the gap of neglecting the connotation of SDG 11.7 and scale issues in related research. To illustrate the applicability of the model, Xi'an city is chosen as the case study area, providing a reference for monitoring SDG 11.7 in other cities in China.

2. Materials and Methods

2.1. Study Area, Data Source, and Processing

This article uses Xi'an city as a case study to validate the appropriateness of the multi-scale assessment model. Xi'an stands out as the sole megacity in northwest China and holds the distinction of being one of the first nine central cities approved by the State Council [20]. In recent years, Xi'an has undergone rapid development. However, this growth has come with challenges, primarily stemming from rapid urbanization and the encroachment upon farmland, resulting in serious environmental concerns. In response to the mounting awareness of sustainable development, the Xi'an government has escalated efforts in environmental stewardship. The "14th Five-Year Plan for Industrial Development of Xi'an" explicitly emphasizes the importance of public space allocation within land planning as a strategic measure to effectively address environmental issues. As such, this case study holds insights and references for other developing cities in China.

The study area (Figure 1), delineated by the urban boundaries, is established using the 2020 land use data of Xi'an and the maps of Xi'an's development zones and segmented management areas released by the Xi'an Civil Affairs Bureau in 2020. This study adopts the United Nations' definition of urban boundaries, which is determined by the degree of urbanization. The specific methodology involves extracting impermeable surfaces from the land use data and delineating the approximate grid range of the main urban areas by comparing it with satellite imagery. Subsequently, the smallest administrative divisions encompassing the main urban areas are chosen as the study area for this research. This approach aims to effectively reduce the fragmentation of the study area caused by directly extracting impermeable surface ranges, thereby mitigating the impact on spatial analysis related to SDG 11.7. Simultaneously, it ensures the integrity of administrative divisions to enhance the accuracy of multi-scale analysis.

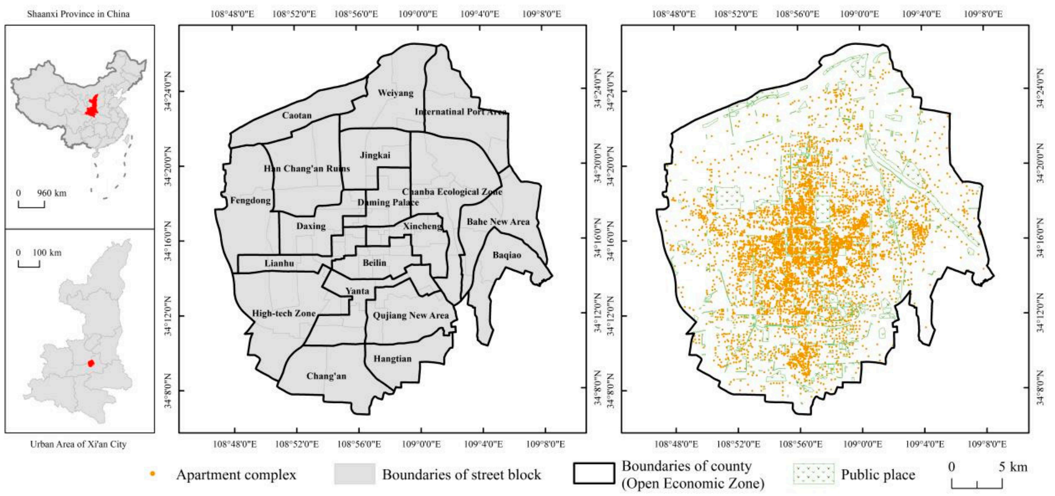

Figure 1. The study area within Xi'an city.

To effectively monitor and report on SDG 11.7, the United Nations defines public space as encompassing all open areas accessible to the public, including open public spaces and streets. Open public spaces are categorized based on their intended function, such as green public areas. The street space category includes streets, boulevards, and similar components. Taking into consideration the specific context within China, we emphasize the importance of public spaces that foster interaction with residents. These spaces should not only offer services like air purification but should also cater to recreational activities and scenic appreciation. Consequently, we exclude certain types of public spaces, such as urban green belts that residents cannot access, and ultimately obtain a total of 642 public spaces. The public space data come from the satellite image data of Xi'an City in 2020 intercepted by the RiverMap application and obtained through visual interpretation and digitization.

This article conducts observations on Xi'an City's satellite images during both winter and summer to enhance the precision of our public space extraction results.

In China, an "apartment complex" refers to a group of buildings constructed by real estate companies for the purpose of housing residents. These complexes are typically managed by neighborhood committees, which function similarly to government entities. Therefore, this article treats "apartment complexes" as political entities and uses residential point data for analysis at this scale. Street block and county (including open economic zone) fall within China's administrative hierarchy as first- and second-level administrative units, and they play essential roles in maintaining the proper functioning of cities. The data used in this article cover the following scales: (1) Apartment Complex Data: A total of 4929 apartment complexes are identified through visual interpretation of 2020 satellite imagery from the RiverMap application. Data on the house prices of apartment complexes are obtained from the Anjuke website (URL: https://xa.anjuke.com, accessed on 10 October 2021). (2) Street Block Data: Maps are sourced from the Bureau of Surveying's standard map service website, and 59 street blocks are extracted through vectorization. (3) County Data: A total of 19 counties and development zones are acquired through vectorization of Xi'an' s development zone and segmented management area maps. (4) Road Network Data: Various types of roads within Xi'an are extracted using the RiverMap application. (5) Grid Data: An ArcGIS 10.1 platform's fishnet tool is employed to partition Xi'an City into 795 grids, each measuring 1 km × 1 km.

2.2. A Top-Down Indicator Framework for Problem-Solving at Different Levels

Guided by the principles of simplicity and ease of calculation, this article refines a set of SDG 11.7 indicators using a top-down problem-solving approach. This comprehensive framework consists of 11 key indicators (Table 1), and it has undergone refinement through four rounds of expert meetings, which can fully reflect the connotation of SDG 11.7.

The connotation of SDG 11.7 includes four aspects: safety, inclusiveness, accessibility, and greenness. This article selects the indicator spatial emergency response capacity (Sa) for the safety connotation of SDG 11.7, indicator resource area per household (Per), dispersibility (NNI), and dominance (Do) to reflect the inclusiveness connotation; indicator proximity (Ne), richness (Ac), NNI, and comprehensive coverage (Co) to reflect the accessibility connotation; and finally, indicator quality (Qa), Ac, Per, diversity (Sh), ecosystem services value (Es), total area (Su), and Co to reflect the greenness connotation. It should be noted that some of the above indicators can reflect multiple aspects of the connotation of SDG 11.7. On the basis of classifying the above indicators through the connotation of SDG 11.7, this article further classifies them based on their applicable scales. The following text introduces the specific classification process and indicators.

As the administrative power gradually extends from the apartment complex scale to the county scale (S1 to S3), we observe that the micro scale (S1) places greater emphasis on access to public spaces. To capture the sustainable development of S1, we employ three indicators: Qa, Ne, and Ac. The indicator Qa is expressed by the area of high-quality public space within a 2 km radius of the apartment complex. It is important to note that the quality of public spaces is calculated based on the weighted area of these spaces. Referring to previous studies, we assign weights of 1.5, 1.2, and 1 to the areas of water bodies, forests, and grasslands within public spaces, respectively. This allows us to calculate the weighted areas of 642 public spaces in Xi'an. We define the top 10% of these weighted areas as high-quality public spaces [21]. Ne is calculated using the shortest distance model, which refers to the time or spatial cost from demand points to public resources. Considering that the time distance is affected by the social and economic levels of different demand points [22], this article uses spatial distance to represent public space proximity. The formula is:

$$Ne_i = Min\left(Cost_{ij}\right) \quad (1)$$

where i is the demand point, j is the public space, $Cost_{ij}$ is the space cost from the i to the public space j, and Ne_i represents the shortest spatial distance from the demand point i to all the public spaces.

The Ac is expressed by the gravity model, which represents the attractiveness of public space of different quality to residential points within its service threshold and the difficulty of residential points to obtain these public spaces [23]. The formula is:

$$Ac_i = \sum_{j \in (d_{ij} \leq d_0)} \frac{S_j f(d_{ij})}{P_i} \tag{2}$$

where i is the demand point, j is the public space point, and Ac_i represents the richness of the public space obtained by demand i. S_j represents the supply capacity of j, which is expressed in the area of public space. P_i is the demand of i, which is expressed by the number of households. d_{ij} is the spatial distance between i and j, and d_0 is the service threshold of j. We divide the public space into four grades based on their quality, accounting for 10%, 20%, 30%, and 40% of the total number and set its service threshold at 2 km, 1.5 km, 1 km, and 0.5 km. $f(d_{ij}) = d_{ij}^{-\beta}$ is the power function considering the issues of spatial friction, which assumes that even within the same spatial limits, residents are more inclined to obtain public space with a closer distance. The value of β is between 1 and 2, and we set it to 1 by referring to the research results of Mao et al. [24]. Since the public space is a polygon, in order to achieve higher accuracy for the public space with a larger area, the OD matrix uses the distance from the demand point to the gate of the public space when calculating Ne and Ac. In the case of fully open public spaces, we segment the space's perimeter at 100 m intervals and calculate the distance from the point of demand to the edge point (Figure 2).

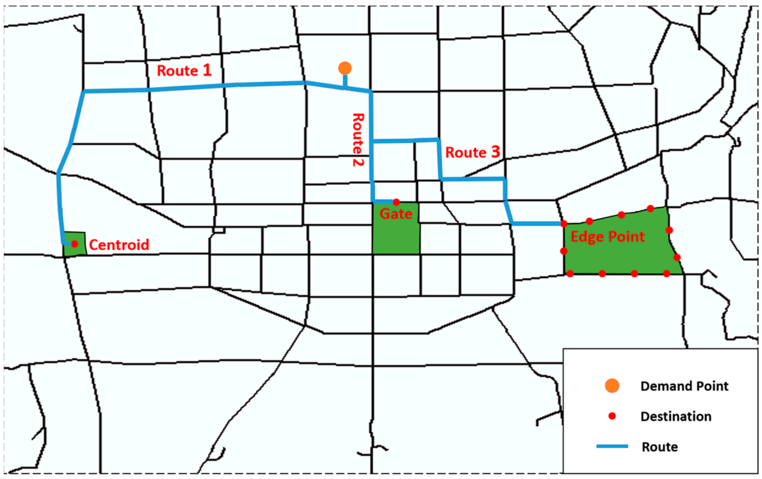

Figure 2. OD distance calculation scheme between apartment complex and public space.

As the most fundamental administrative level in China, S2 possesses specific administrative functions, and it places a heightened emphasis on the allocation of public resources. In this context, we establish four key indicators, namely Per, NNI, Do, and Sa, to comprehensively characterize the sustainable development of public spaces at the street block scale.

Per is expressed as the ratio of the total area of public space to the number of households within the administrative scope of the street block. NNI is used to describe the spatial distribution of public space and is analyzed by the Nearest Neighbor Index method [25]. The calculation method can be summarized as follows:

$$NNI = \frac{\overline{r_1}}{\overline{r_e}} = \frac{\overline{r_1}}{\frac{1}{2\sqrt{m/S}}} \tag{3}$$

where $\overline{r_1}$ represents the average actual nearest distance and $\overline{r_e}$ represents the theoretical nearest distance. m is the number of entrances and boundary points of the public space in the study area, and S is the area of the study area. When $NNI < 1$, it indicates that the public space is distributed in a concentrated manner, when $NNI = 1$, it indicates random distribution, and when $NNI > 1$, it indicates even distribution.

The indicator Do gauges the balance of services offered by public space resources within the region, specifically examining whether services like tourism and recreation are primarily controlled by one or a few significant public spaces. The calculation method is outlined below [26]:

$$Do = 1 - \sum_{k=1}^{n} P_k^2 \tag{4}$$

where n is the number of public spaces in the study area, P_k is the ratio of the area of public space k to the total area of public spaces in the area.

Given the limited occurrence of criminal incidents, such as robberies, in China, this article uses the spatial emergency response capacity of public space to expand the security connotation of SDG 11.7. Sa represents the ability of public spaces to facilitate the evacuation of people and mitigate disasters during emergencies, such as earthquakes. To assess this emergency capacity, the proportion of the population within the public space service threshold in comparison to the entire city's population is taken as the emergency capacity of the public space. The sum of the emergency capacities of all public spaces within the street block's boundaries is then computed to derive the Sa indicator.

At the county scale, we believe that greater emphasis should be placed on the overall quantity of public resources, owing to the substantial administrative influence wielded by counties. Consequently, we have established four indicators, with indicator *Sh* representing the diversity of various public space types within the region. In this study, we employ the Shannon diversity index to calculate *Sh* [27]. The calculation method is as follows:

$$Sh = -\sum_{t=1}^{T} H_t \ln H_t \tag{5}$$

where T represents the number of types of public spaces in the area. H_t represents the proportion of the area of the t-th type public space to the total area of the public space in the region.

The indicator Es signifies the ecosystem service value provided by public spaces within each county, considering four key aspects: environmental purification, climate regulation, temperature control, and tourism and leisure. The unit of measurement for Es is denominated in RMB (Chinese Yuan). For precise calculation, we reference the urban landscape ecosystem service evaluation index framework developed by Li and Zhou [28].

The Su indicator quantifies the total area of public spaces within the county, while Co reflects the extent of public space coverage throughout the county. In this article, we utilize the mean of both coverage and service coverage to establish a comprehensive coverage assessment. Coverage, in this context, denotes the ratio of public space area to the entire region's area, whereas service coverage refers to the proportion of the area that public spaces can effectively serve within their service thresholds in relation to the entire region. The calculation of service coverage involves overlapping analysis and the merging of overlapping areas.

Table 1. A top-down SDG 11.7 indicator framework.

Scale	Indicator	Description	Unit	SDG 11.7 Connotation				Notes [2]	References
				Safety	Inclusiveness	Accessibility	Greenness		
Apartment complex(S1)	Quality	Total area of available high-quality public space	m^2				√	Qa (+)	[6]
	Proximity	Proximity of the apartment complex to the public space	m			√		Ne (-)	[6]
	Richness	The richness of apartment complex's access to public space	m^2/per			√	√	Ac (+)	[29]
Street block(S2)	Resource area per household	Area of public space per household	m^2		√		√	Per (+)	[16]
	Dispersibility	Degree of dispersion of public space	/		√	√		NNI (+)	[25]
	Dominance	Advantage degree of public space area	/		√			Do (+)	[26]
	Spatial emergency response capacity	Emergency response capability of public space in streets in case of disasters	/	√				Sa (+)	[30]
	Equity [1]	Social equity of public space services	%		√			Eq (+)	[31]
County(S3)	Diversity	Diversity of public space	/				√	Sh (+)	[27]
	Ecosystem services value	Ecosystem service value of public space	yuan				√	Es (+)	[28]
	Total area	Total area of public space	m^2				√	Su (+)	[15]
	Comprehensive coverage	Overall coverage of public space within county	%			√	√	Co (+)	[32]

[1] This indicator is a supplementary indicator to supplement the social equity connotation of SDG 11.7. [2] The content in parentheses indicates that the indicators belong to positive or negative indicators.

2.3. Multi-Scale Evaluation Method for Urban SDG 11.7 Monitoring

After constructing a top-down SDG 11.7 indicator framework, this article further proposes a multi-scale evaluation method for urban SDG11.7 monitoring. To ensure comparability across various indicators, it is essential to establish boundaries for each indicator and normalize their values to a standardized range from 0 to 100.0 indicates the poorest performance, while 100 indicates the highest level of achievement. We utilize the term performance or score to characterize the degree of sustainable development, as opposed to solely focusing on indicator values, given the presence of certain negative indicators. Our approach draws from the methodology used to determine upper and lower bounds for data (decision tree method), as outlined in the 2018 SDG Index and Dashboard Report. This method effectively mitigates the potential impact of skewed data by mitigating the influence of extreme values on the data distribution, thereby enhancing the accuracy of standardized results [33].

The upper bounds of the indicators are determined with reference to the five-step decision tree method. If the conditions of the previous steps are met, the subsequent steps will not be carried out. (1) First, we use relevant absolute quantitative thresholds for the indicator framework, such as "absolute equality" to determine the boundary. (2) Secondly, we use the principle of "leaving no one behind" to determine the upper bounds of indicators related to coverage of public space. (3) We set the upper bounds of other indicators as the average of the top five performance indicators.

The determination of the lower bounds of indicators is similar to the upper bounds. (1) For indicators with clear absolute quantitative threshold meaning or completely contrary to the principle of "leaving no one behind", such as "absolute inequality" and "zero coverage", we use its worst possible performance to define the lower bounds. (2) For other indicators, the lower bound is defined as the value closest to the bottom 2.5% of the performance ranking of sustainable development indicators.

Following the establishment of upper and lower bounds for the indicators, we proceed to standardize their values, resulting in the final performance of the SDG indicators:

$$X = \frac{x - x_l}{x_u - x_l} \times 100 \quad (6)$$

where X represents the standardized score, i.e., standardized sustainable development performance; x represents the original value of the indicator; and x_u and x_l represent the upper and lower bounds of the indicator, respectively. The standardized score is set to 100 when the indicator value is greater than the upper bound and is set to 0 when the indicator value is less than the lower bound.

For the performance of SDG 11.7 at the apartment complex, street block, and county scales, this study calculates the weighted average of the performance of the indicators associated with each scale. Due to the complexity of hierarchical scales, multi-scale things in geography are interrelated and affected at different scales. Scale integration can span the interaction among scales to provide an overall assessment of the research area on a broader, more macroscopic level. Hence, building on the research findings of Wu et al. [34] and Yigitcanlar et al. [35], this article introduces a scale integration scheme (Figure 3). This scheme transfers the sustainability performance scores of S1, S2, and S3 to 1 km × 1 km grids, enabling city-scale analysis and allowing decision-makers to plan public spaces at the urban scale (S4). It is worth noting that, after experimenting with various grid sizes, this article has found that the one-kilometer grid effectively reflects the city's performance of SDG 11.7.

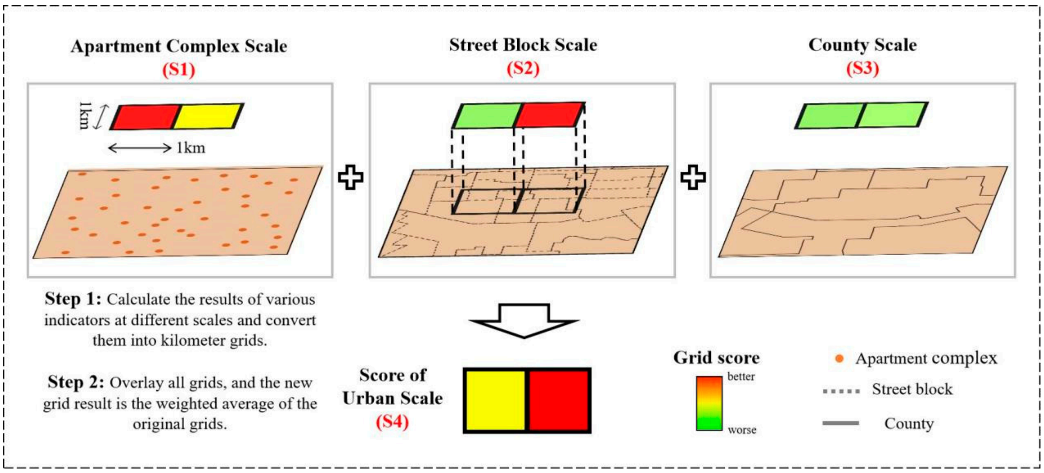

Figure 3. Scale integration scheme for multi-scale assessment.

To transform the points representing apartment complexes into a grid format, we employ interpolation to assign scores from a range of sustainable development indicators to

100 × 100 m resolution grids. By applying an overlapping analysis with the one-kilometer grid, we compute the average scores within each kilometer grid, resulting in the spatial distribution of each sustainable development indicator.

At both the street block and county scales, this article employs the area weighting method to superimpose the administrative boundaries onto the one-kilometer grid. There are two approaches for evaluating and analyzing sustainable development on a city scale (S4): (1) The first method involves directly calculating a weighted average of the one-kilometer grid data for the 11 indicators. (2) The second method entails first determining sustainability scores for the three different scales and subsequently averaging these three scale scores. It is worth noting that when the scores of the three scales are averaged, the impact of certain indicators can be either amplified or diminished due to the varying number of indicators at different scales. To mitigate this issue, we opt for the first scheme to transition between scales, ultimately generating the spatial pattern of SDG 11.7 at the S4 scale. The workflow of this study is shown in Figure 4.

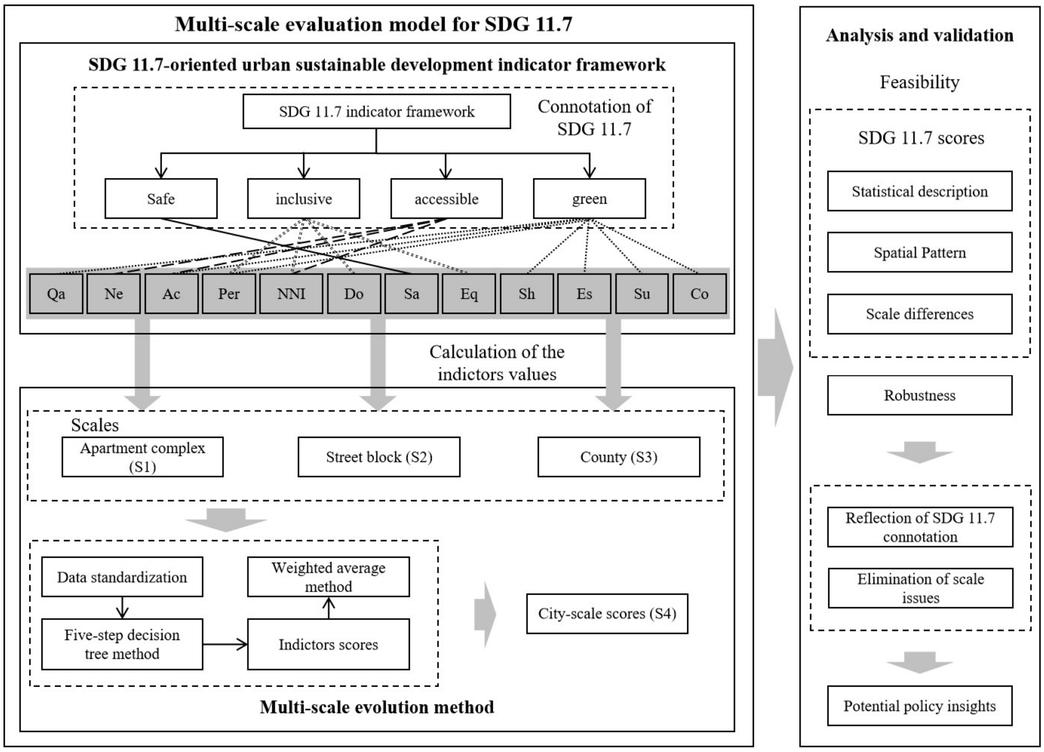

Figure 4. Workflow of this study.

3. Results

3.1. Multi Scale Monitoring of SDG 11.7 in Xi'an City

To obtain the spatiotemporal distribution of SDG 11.7 in Xi'an, we first calculate benchmarks for various sustainable development indicators (Table 2).

The evaluation results for Xi'an's progress in achieving SDG 11.7 are depicted in Figure 5. At the S1 scale, areas exhibiting higher levels of sustainable development are predominantly situated in proximity to Daming Palace, which is close to the urban center. This outcome underscores that the compact urban core area facilitates the residents' accessibility to public spaces in these locales. At the S2 scale, the regions boasting high scores in sustainable development are primarily concentrated within the heart of the High-tech Zone, Qujiang New Area, Hangtian, and Chanba Ecological Area. Evidently, these newer urban districts excel in the equitable distribution of public resources compared to the urban center, a conclusion that holds true at the S3 scale as well. Notably, the high-scoring areas for sustainable development at the S3 scale form a belt-shaped core, highlighting the adequate quantity of public spaces in these regions.

Table 2. Sustainable development indicators benchmarks.

Scale	Indicator	Upper Bound	Lower Bound	Units
S1	Quality	7,303,097	0	m^2
	Proximity	300	2515	m
	Richness	13,616.76	0	m^2/per
S2	Resource area per household	179	0	m^2
	Dispersibility	9.30	0	/
	Dominance	0.95	0	/
	Spatial emergency response capacity	0.32	0	/
S3	Diversity	1.53	0	/
	Ecosystem services value	6,191,608	0	yuan
	Total area	9,351,280	0	m^2
	Comprehensive coverage	57.57	0	%

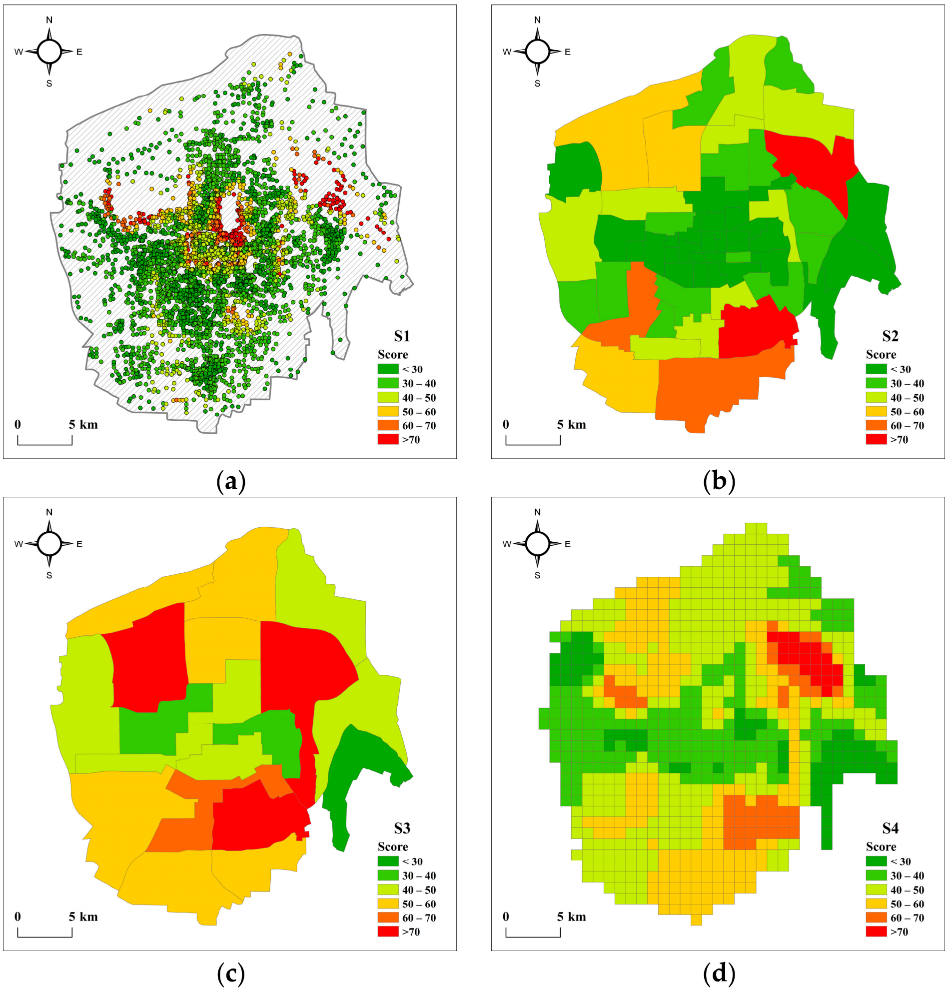

Figure 5. Multi-scale spatial pattern of SDG 11.7 level in Xi'an. (**a**) S1 scale performance; (**b**) S2 scale performance; (**c**) S3 scale performance; (**d**) S4 scale performance.

The spatial pattern of SDG 11.7 observed at the S4 scale confirms the significant impact of rapid urbanization on sustainable development in the study area. Owing to the scarcity of land resources in the central urban region, public resources are primarily channeled into the new urban area, culminating in an "anti-core-edge" structure. The central urban area may exhibit superior performance in certain indicators due to historical factors (indicators of S1, for example), but in the broader context, the new urban area predominantly drives the city's sustainable development. It is important to note that although the overall performance of SDG 11.7 in newly developed urban areas is relatively good, there are low-value cores at both the eastern and western ends of the city. This is primarily due to the eastern part of Xi'an being a mountainous region, while the western area, having been developed later, remains in a rural–urban dual structure, resulting in inadequate levels of SDG 11.7.

As illustrated in Figure 6, the average scores for various sustainable development indicators are depicted. On the whole, SDG 11.7 in Xi'an is at a medium level, with ample room for enhancement. Among all the indicators, Ne and Co indicators demonstrate commendable performance, whereas Ac falls short. Given the relatively low sustainable development level of the new area at the S1 scale, urban managers should pay more attention to the acquisition of public space in future planning to enhance the performance of SDG 11.7.

Moreover, the spatiotemporal pattern of SDG 11.7 in this article differs significantly from those of other similar studies. Huang et al.'s assessment of public space accessibility in Xi'an reveals a spatial pattern of sustainability that decreases outward from the core of public spaces [36], while the results of this study do not support that conclusion. This discrepancy is particularly evident in the northwestern regions of Xi'an, where only a few areas near public spaces show relatively good levels of SDG 11.7. The reason for this divergence lies in the fact that the indicators used in other studies typically rely solely on accessibility to reflect certain aspects of SDG 11.7, while these studies are conducted at a single scale. The above further validates the necessity of constructing a multi-scale assessment model for SDG 11.7.

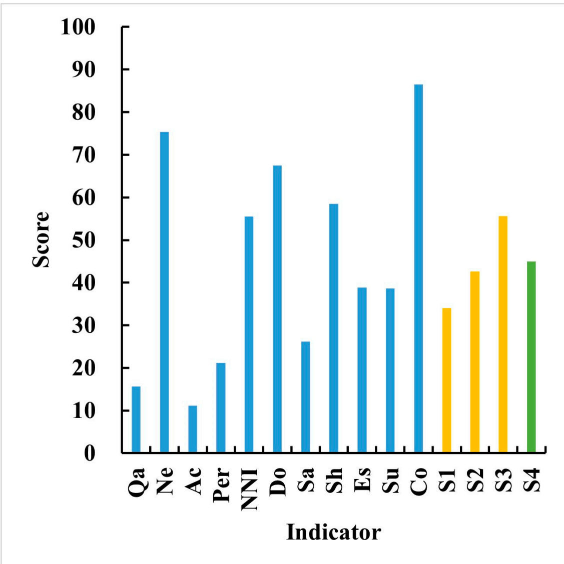

Figure 6. Performance of sustainable development indicators and different scales. To facilitate differentiation, the blue bars in the bar chart represent the individual indicators, the yellow bars represent the three scales of apartment complex, street block, and county, and the green bar represent the final results at the city scale. The same applies to the following figures.

3.2. Validation of the Model Robustness

The robustness of the model encompasses both uncertainty and sensitivity. We observe that a smaller number of indicators at each scale magnifies the influence of individual indicators on the outcomes during the analysis. When only a single indicator is used, the SDGs result becomes solely dependent on that particular indicator. To investigate the uncertainty arising from the variation in the number of SDG indicators, this study conducts an uncertainty analysis. Across the three distinct scales, the study explores various combinations of all sustainable development indicators within each scale. The outcomes yield a distribution of sustainable development performance, as depicted in Figure 7.

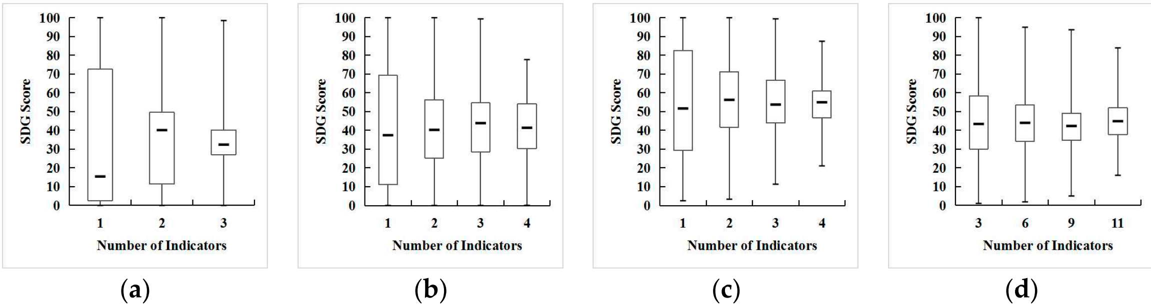

Figure 7. Uncertainty analysis for sustainable development performance. (**a**) S1; (**b**) S2; (**c**) S3; (**d**) S4.

The study observes that as the number of indicators increases, the uncertainty associated with the SDG results decreases, and the range of the overall sustainable development score tends to narrow. This trend is especially pronounced when examining the coefficient of variation (CV) of the indicators, as depicted in Figure 8. The coefficient of variation is notably high for individual indicators, while the CV for S4, which integrates all indicators, remains at a lower level.

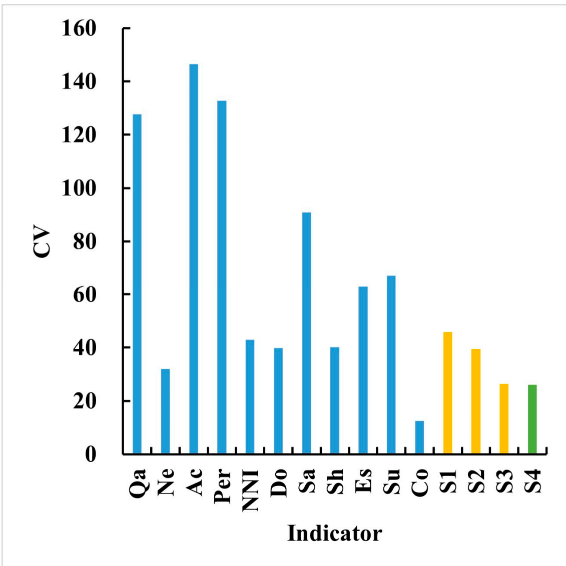

Figure 8. CV of SDG performance.

Furthermore, this article conducts a sensitivity analysis to assess how variations in individual indicator performance impact the assessment of sustainable development. This involves increasing and decreasing the value of each SDG indicator by 10%, followed by a recalibration of the sustainable development level to determine the sensitivity index, as depicted in Figure 9. Notably, the results reveal that alterations in a single indicator have a relatively minor impact on the overall outcomes, with the overall range staying within a 2% margin. In summary, the multi-scale sustainable development evaluation model outlined in this article exhibits a high degree of robustness.

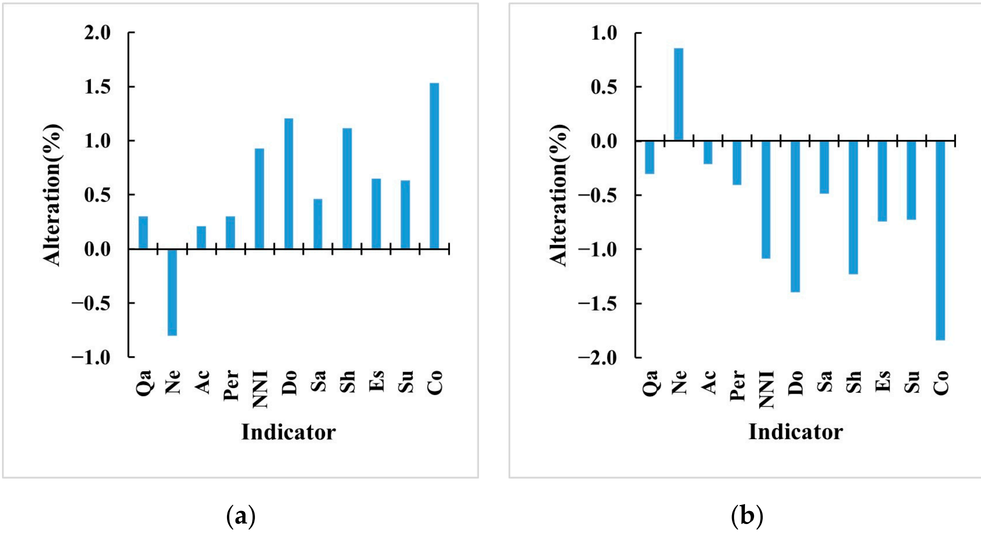

Figure 9. Sensitivity analysis of SDG performance. (**a**) Indicator's origin value increased by 10%. (**b**) Indicator's origin value decreased by 10%.

The robustness analysis of the model establishes the reliability of the framework developed in this study. It should be noted that the SDG11.7 framework, which includes multiple indicators, effectively reduces evaluation errors caused by a single indicator [33]. In addition, the calculation of indicators mainly relies on GIS spatial analysis, which greatly reduces the costs associated with data acquisition and computation [9]. The results of the spatial pattern of this case are consistent with Peng et al. [37], as they demonstrate the changing trend of urban sustainability from the core to the periphery. Overall, this evaluation model is both efficient and accurate.

4. Discussion

4.1. The Embodiment of Connotation of SDG 11.7 in the Indicator Framework

The advantage of a top-down problem-solving approach lies in its early consideration of the connotation of SDG 11.7 when establishing the indicator framework. Some previous comprehensive assessments of sustainable development goals have adopted similar approaches [17]. However, due to data limitations, some indicators are overlooked in early research, which also results in an incomplete reflection of the connotation of sustainable development goals.

In response to the connotation of SDG 11.7, this study establishes a total of 11 indicators that encapsulate various aspects of SDG 11.7. "Safety", represented by the Sa indicator, is previously described using crime rate data [38]. However, to overcome the limitations of statistical data, this article devises an index computed through spatial analysis methods. "Inclusiveness" is portrayed by the Per, NNI, Do, and Eq indicators, drawing inspiration from human geography indicators related to the allocation of public resources. These indicators reflect inclusiveness from different perspectives. For example, the indicator Per primarily reflects inclusiveness by assessing whether the configuration of public spaces meets the needs of all residents, while the indicators Do, NNI, and Eq, reflect inclusiveness by evaluating the spatial equity of public space distribution and its ability to cover vulnerable groups.

"Accessibility" is manifested through Ne, Ac, and NNI, with the core Ac indicator assessing residents' capacity to access public spaces after considering competition. The aforementioned indicators have been widely used in studies involving resources such as healthcare and green spaces [22], but they only reflect a portion of the connotation of SDG 11.7. This is also the reason why this study integrated indicators from different sources to reflect the entire connotation of SDG 11.7. "Greenness" is reflected by Qa, Ac, Per, Sh, and Es, drawing primarily from definitions of relevant indicators in landscape ecology to characterize a city's sustainable development level [27]. It should be noted that indicators related to landscape ecology are rarely used in the study of SDG11.7, resulting in a lack of relevant research reflecting its "greenness" connotation. The improvements presented in this article provide a reference for future research.

In view of the inclusion connotation of SDG 11.7, that is, the issue of equity, this study only reflects the meaning of spatial equity but does not provide relevant indicators of social equity [39]. This exclusion is due to the unavailability of comprehensive socio-economic data for residents in China. To ensure the model's applicability, the SDG 11.7 indicator framework does not include indicators related to social equity.

However, the robustness analysis has shown that introducing elements that reflect some aspects of social equity within the constraints of available data can enhance the accuracy of the assessment without unduly affecting the overall results. Therefore, we have employed apartment complex house prices as a proxy for certain socio-economic characteristics of residents. Through correlation analysis between house prices and SDG performance, the study has identified a substantial positive correlation between the level of sustainable development and residents' economic strength. This finding is further substantiated by both Mood's Median and the Jonckheere–Terpstra test. Mood's Median test reveals significant variations in sustainable development levels among regions with differing economic strengths, while the Jonckheere–Terpstra test confirms that sustainable development levels rise concomitant with increased economic strength. Hence, it is justifiable for us to introduce an indicator Eq (Table 1) that partially encapsulates the connotation of social equity and make revisions to the outcomes of the multi-scale evaluation model of SDG 11.7 so as to verify the hypothesis stated earlier.

This study defines residents of apartment complexes in the lowest 10% of housing prices as low-income groups. Subsequently, service thresholds (2 km, 1.5 km, 1 km, and 0.5 km) based on public space quality are used to create buffers and to count the number of low-income individuals within these buffers. Finally, the equity indicator Eq is calculated as the ratio of the number of low-income individuals with access to public space resources to the total number of low-income individuals. Notably, areas exhibiting higher equity levels in Xi'an are predominantly concentrated in the central urban area and the Qujiang New Area (Figure 10). The introduction of this equity indicator significantly reduces uncertainty at the street block scale as well. Broadly speaking, this additional indicator has a minor impact on the overall spatial pattern of sustainable development at the S4 scale. The most notable changes occur within the High-tech Zone and the Chanba Ecological Zone. Upon introducing the Eq indicator, the sustainable development performance of the old urban area in the High-tech Zone decreases, while the performance of the newly developed area in the High-tech Zone improves. Conversely, the performance of the old urban area in the Chanba Ecological Zone improves, while the performance of the newly developed area declines. Given the slower development pace of the old urban area, these results suggest that without considering the connotation of social equity, there may be a risk of underestimating the determination of economically driven urban new areas to achieve SDGs and overestimating the focus of ecologically oriented urban new areas on social equity.

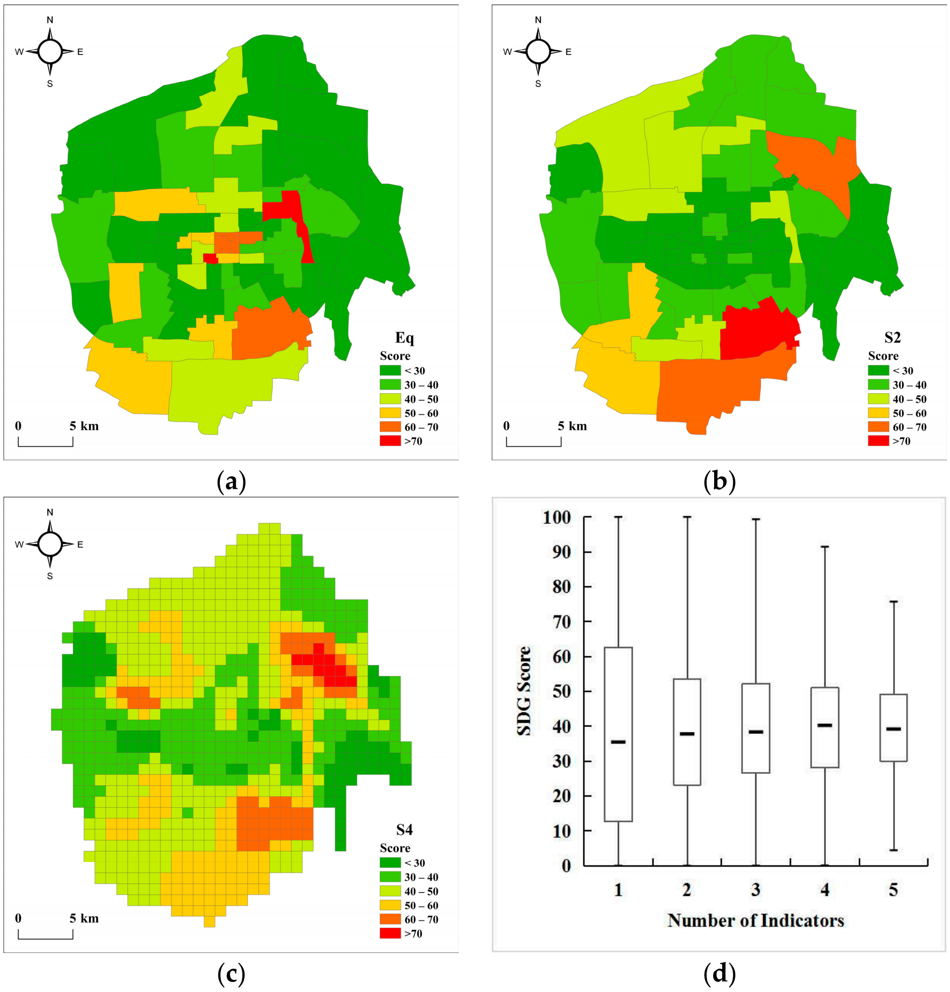

Figure 10. Revised spatial pattern of SDG 11.7 status of Xi'an. (**a**) Result of indicator Eq. (**b**) Revised S2 performance. (**c**) Revised S4 performance. (**d**) Uncertainty after the addition of the indicator Eq.

4.2. Weakening the Impact of Scale-Related Issues to Promote Governance Capacity at All Levels of Government

In the context of urban sustainable development, the absence of a multi-scale perspective might introduce bias into the assessment process [40]. Some studies have demonstrated differences in sustainable development assessment outcomes between multi-scale and single-scale approaches [35]. Consequently, some studies have highlighted the significance and complexity of selecting the optimal scale [41]. The model introduced in this article establishes development goals based on different scales, aiming to reduce the impact of scale issues as much as possible, thereby achieving a more precise simulation of the SDG 11.7 patterns and guiding policy implementation.

Currently, two scale-related issues warrant discussion: the modifiable areal unit problem (MAUP) and ecological fallacy [42,43]. The MAUP comprises scale effects and zoning problem—where scale effects refer to variations in statistical results caused by aggregating data into smaller or larger geographical units, while zoning problems signify result variations due to different partitioning schemes at a given scale. The ecological fallacy refers to biases or even completely contradictory outcomes when conclusions drawn at a specific scale are extrapolated to other scales [44].

The scale effect has a significant impact on the results of this study. When the scale gradually shrinks, some statistical indicators undergo dramatic shifts; that is, the negative externality is aggravated [45] when one of two adjacent spatial units achieves a high score in sustainable development due to the presence of public spaces, while the other languishes at a very low level of sustainable development due to a lack of such spaces. Although this scale effect is inevitable, we must point out that the sustainable development of local region cannot be disregarded even if the public space of its adjacent areas is sufficient. This discovery contradicts the notion that smaller scales yield more precise indicators. Although spatial indicators may enhance accuracy at the micro-level, the statistical indicators become less stable due to intensified edge effects. Given that edge effects cannot be entirely resolved or mitigated, our recourse is to exercise greater caution in indicator selection. This means reflecting the essence of SDGs through the simplification of indicators and the reduction of indicator redundancy.

The zoning problem is primarily evident at the county scale. Owing to the variations in the shapes and sizes of administrative divisions, certain areas with low sustainable development scores at the micro-level are influenced by their neighboring regions within the same county, resulting in what can be termed the "illusion of prosperity." Consequently, total quantity-based indicators may not accurately portray the sustainability of these areas. In recognition of the administrative unity within the county, we have made efforts to employ indicators that underscore the principle of equality to mitigate this impact. For instance, this article incorporates the use of indicators Es and Su to represent the SDG 11.7 level at the S3 scale. Additionally, we utilize the coverage indicator Co to alleviate the influence of zoning effects. Nonetheless, some scholars argue that data integration in statistical issues related to ecological fallacy might mask the needs of the most marginalized and vulnerable groups, as they merely reflect an overall improvement at the macro-level [10].

Overall, this article solves the problem of administrative responsibility misalignment caused by the mismatch between scale and development goals from a multi-scale perspective. However, it is crucial to acknowledge that the inherent scale-related disparities in assessment outcomes cannot be entirely eliminated. We strive to minimize these effects by employing the mentioned methodology and carefully selecting appropriate indicators to enhance the overall accuracy of the results.

4.3. Contributions and Limitations

SDG 11.7 is currently a focal point in urban sustainability assessments, with numerous studies analyzing the spatiotemporal evolution of SDG 11.7 patterns across different regions. However, the neglect of SDG 11.7′s connotation and scale issues in these studies is concerning. This article addresses these gaps, with key contributions, including (1) the development of a top-down sustainable development indicator framework that reflects the four aspects of SDG 11.7; (2) the establishment of a multi-scale assessment method for SDG 11.7 by setting development goals for different levels of administrative entities; and (3) the validation of the indicator framework and assessment method using Xi'an as a case study. Together, these elements constitute the uniqueness of this article.

Although the model constructed in this paper is set against the backdrop of Chinese cities, it has potential relevance for urban planning and sustainability assessments in other countries or regions. First, the connotation of SDG 11.7 is collectively agreed upon by UN member states, confirming the recognition of its four aspects—safety, inclusiveness, accessibility, and greenness—by most countries. Second, when establishing development goals for different administrative levels, this article emphasizes the progressive relationship between government levels and their development priorities (access, allocation, and overall quantity of public spaces), which is consistent with the administrative logic of most countries. Although different cities may have variations in the reasonable scale for selecting allocation and total quantity indicators, the use of indicators that reflect access issues at the micro-scale has been extensively validated. Of course, the indicator framework constructed in this article to assist governments at different levels in addressing issues of access, allocation, and total quantity of public spaces may face localization challenges. However, the indicators, such as accessibility and greening rates, developed in this article have been widely used in SDG 11.7 research across various regions, thereby providing guidance for policy formulation by governments at corresponding levels in those areas.

Inevitably, this study is not without its limitations. Firstly, data acquisition heavily relies on visual interpretation, especially the digitization of residential areas and public spaces, which is a time-consuming process. With the advancements in machine learning, some scholars have successfully employed algorithms to recognize and extract spatial features [46]. It is anticipated that in the future, urban sustainable development assessment can be accomplished entirely by computer-based methods. Secondly, the SDG 11.7 indicator framework exhibits shortcomings in adequately reflecting the connotation of social equity, necessitating supplementation with statistical data. Thirdly, while the article highlights that the choice of the number of indicators and fluctuations in indicator scores contribute to result uncertainty and sensitivity, it does not provide a specific number of indicators or sensitivity thresholds that could significantly reduce these biases. Future research could involve applying this model to other cities and conducting comparative analyses to determine more appropriate numbers of indicators and sensitivity thresholds, thereby further optimizing the indicator framework. Lastly, concerning the types of public spaces, this article does not encompass agricultural landscapes such as cultivated land on the outskirts of urban areas within the assessment. However, some studies have underscored that these agricultural landscapes contribute to ecological protection for cities and offer recreational and scenic services to urban residents, particularly those residing at the urban periphery [47]. This omission may lead to an underestimation of the sustainable development level in urban fringe areas.

5. Conclusions and Outlook

This article proposes a multi-scale assessment model for SDG 11.7 using a top-down problem-solving approach. The model integrates 11 indicators across three scales to comprehensively reflect the connotation of SDG 11.7, which includes safety, inclusiveness, accessibility, and greenness. By setting development goals for different levels of government and fully capturing the connotation of SDG 11.7, this study primarily fills the gap of neglecting the connotation of SDG 11.7 and scale issues in related research. In testing the model in Xi'an city, the model accurately assesses the sustainable development level of public spaces at the scales of apartment complex, street block, and county. Through scale transformation, we obtain the spatial pattern of SDG 11.7 at the urban level and identify areas requiring focused attention. Additionally, the model demonstrates strong robustness.

We believe that this model can be applied to monitor SDG 11.7 in other cities. First, by reflecting the connotation of SDG 11.7, the government can identify which aspects of public space need improvement rather than engaging in blind development. Second, by setting reasonable development goals for different levels of administrative entities, the model clarifies governmental responsibilities, significantly enhancing management efficiency. Finally, by providing the spatial pattern of SDG 11.7, managers can identify areas requiring focused attention. These advantages can help administrative entities effectively formulate policies and actions that balance environmental and development issues, thereby addressing the development imbalances and responsibility misalignments among various levels of government in promoting the sustainable development of public spaces. Future research can continue to improve the model's ability to reflect social equity connotations, such as by utilizing big data to develop spatial indicators instead of relying solely on statistical data, further enhancing the model's applicability and extending it to sustainability assessments of different social resources like housing, healthcare, and transportation.

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