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No Child Left on the Sidelines: Fostering Equality in Outdoor Activity Environments in Beijing Metropolitan Area

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Abstract

In rapidly urbanizing metropolitan areas, children increasingly face risks to their physical and mental health, largely due to constrained access to suitable outdoor spaces that support regular physical activity. The uneven distribution and varying quality of these urban outdoor environments further intensify such risks by limiting children's opportunities for safe, stimulating, and health-promoting activities. However, the existing research often lacks a systematic framework to quantify these spatial inequities across multiple dimensions. This study aims to fill this gap by constructing a robust analytical framework for evaluating outdoor environmental quality. It quantifies spatial distribution and determinants of these inequalities. The framework is structured around four core dimensions: Safety, Facility Variety, Fun, and Greenness. Taking Beijing as a case study, data from 1598 primary and secondary schools were analyzed. The Gini coefficient and Moran's I were used to evaluate the equality and spatial clustering of environmental indicators, while the Geographically Weighted Regression model explored how Spatial Construction, Social Development, and Economic Level shape environmental quality. The results reveal the following findings: (1) the quality of children's outdoor physical activity environments in Beijing is notably unequal, especially regarding Greenness and Fun; (2) these disparities correspond closely to the city's "core–periphery" metropolitan structure; and (3) the relationships between metropolitan-level factors and environmental quality exhibit strong spatial heterogeneity. This study provides a comprehensive framework for evaluating and visualizing inequalities in children's outdoor environments, offering empirical support for inclusive and health-oriented urban governance.

Keywords: children's outdoor physical activity environments; environmental equality; metropolization; child-friendly cities

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1. Introduction

Physical activity is globally recognized as a fundamental determinant of children's mental and physical health [1–3]. However, many school-aged children are experiencing a decline in these areas, largely attributable to insufficient physical activity [4–6]. These issues are particularly evident in metropolitan areas where environmental quality has declined because of urban expansion and the lack of public recreational spaces [7–9]. Against this backdrop, outdoor physical activity is increasingly recognized as a critical determinant of children's health and well-being [1,2], positioning the creation of supportive and equal outdoor environments as a key priority in urban planning.

The quality of the built environment fundamentally affects children's outdoor physical activity access [10–12], with factors like traffic safety [13,14], facility diversity [3], and access to natural environment [15–17] being critical features of children's outdoor environments. However, the ongoing process of metropolitan development poses significant challenges to the quality of children's outdoor activities [18]. A metropolitan area is generally defined as a large urban system composed of one or more central cities and its surrounding suburban and peri-urban areas [19]. While promoting economic growth, this rapid expansion often leads to a deterioration in the built environment, characterized by overloaded infrastructure, service mismatches, and ecological degradation [20], all of which adversely affect children's outdoor physical activity quality.

Improving the equality of children's outdoor physical activity environments is a pressing concern [21,22]. However, such challenges are especially severe in monocentric metropolitan areas, where the central city serves as the functional core and forms a nested "core–periphery" network [23,24]. This spatial structure ultimately gives rise to a significant development gap [25]. These spatial disparities exacerbate economic and social inequalities [26–28] in residents' quality of life. Given that children's daily activities are highly reliant on their immediate environment [29–31], these planning deficits are likely to result in substantial spatial inequalities in outdoor physical activity environment quality across different zones within the metropolitan area.

Few studies have examined how the spatial inequality triggered by metropolization impacts the equality of children's outdoor physical activity environments. To this end, this study focuses on Beijing, a representative international metropolis with substantial disparities in educational and outdoor environmental services across its metropolitan area [4,32]. This study aims to explore the following question: to what extent does metropolization affect children's access to high-quality outdoor physical activity environments? We further break it down into three steps, which correspond to the following key questions:

(1) What indicators can be used to proxy the quality of children's outdoor physical activity environments?
(2) To what extent does the quality of children's outdoor physical activity environments differ spatially across different parts within the metropolitan area?
(3) What is the spatial relationship between the level of metropolitan development and the quality of children's outdoor physical activity environments?

This study aims to develop a multidimensional framework that captures children's specific needs to evaluate the quality of outdoor activity environments. Building on this framework, it assesses the spatial distribution of environmental quality to reveal inequalities across the metropolitan area. Furthermore, it explores the spatially heterogeneous relationships between metropolitan development and children's outdoor activity environments.

This study approaches the issue from the perspective of children's outdoor physical activity environments in metropolitan areas, emphasizing the promotion of equality across different urban zones. Beyond the specific case of Beijing, this study underscores a critical transition in urban equality: from ensuring basic "quantity" to addressing the structural stratification of "quality". The findings provide a scientific basis for policy making and offer practical pathways for promoting the shared health and well-being of the next generation.

The remainder of this paper is organized as follows: Section 2 presents the conceptual framework and details the establishment of the evaluation system; Section 3 describes the methodology and data; Sections 4 and 5 present the results and analysis; and Section 6 provides the discussion and conclusions.

2. Conceptual Framework

2.1. Background

2.1.1. High Environmental Demands of Children's Outdoor Physical Activities

Outdoor physical activities fundamentally improve children's strength, endurance, and motor skills [33,34] while simultaneously providing psychological benefits [35]. Because children's activities are inherently characterized by spontaneity, high frequency, playfulness, and adventurousness [36,37], they are extremely sensitive to environmental quality and depend on well-equipped facilities [38,39]. For school-aged children, engagement occurs across three distinct but interconnected physical domains: on-campus environments, the built environments surrounding campuses, and natural ecological environments outside school [40,41]. While each domain serves a different function, children's fundamental needs for high-quality activity spaces remain constant across all of them.

Within on-campus environments, the richness and playfulness of sports facilities are crucial. Sufficient open spaces (playgrounds, sports fields) and flexible equipment (such as movable furniture) are necessary to accommodate activity needs [3]. Low building density and high greenery promote both activity frequency and social interaction [42,43].

In the built environments surrounding campuses, children's activities primarily occur along commuting routes [44], making path safety paramount. Safer conditions are achieved through traffic control strategies (lower road network density, reduced traffic) and pedestrian infrastructure (sidewalks, crossings, traffic signals), which jointly reduce collision risk and boost safety perceptions [13,14,45,46]. The diversity of street environments (node design, color schemes, facility provision, and child-oriented commercial functions) provides spaces for spontaneous and playful activities, effectively enhancing children's willingness to participate [14,47].

Natural ecological environments outside school constitute a vital component of child-friendly cities. Access to natural spaces plays a critical role in child daily well-being and physical and psychological development [16], and academic performance [48]. Critically, playful features like adventure playgrounds attract children more effectively than traditional sports facilities [15,17]. In addition to these features, the walkability of green spaces significantly facilitates children's participation in park-based activities [49].

Consequently, the environmental demands of children's physical activities are multidimensional, transcending basic availability of space. Although the physical forms of on-campus, surrounding built, and natural ecological environments differ, children's fundamental needs for high-quality settings remain consistent across all three domains.

2.1.2. Impacts of Metropolization on Children's Outdoor Physical Activity Environments and the Challenges of Spatial Equality

Metropolization is a process encompassing urban physical expansion, interjurisdictional functional integration, and governance coordination [28]. While this process integrates urban entities and enhances overall economic competitiveness [20], it simultaneously generates fundamental mechanisms that adversely affect children's outdoor physical activity environments and produce pronounced regional inequalities.

Spatial differentiation arises as metropolitan structures evolve into hierarchical, concentric systems [23,24]. In central areas, excessive building density generates safety risks. Conversely, in Periphery, the decline in activity quality stems from a lack of essential sports and recreational facilities [25]. This differential provision creates significant disparities in environmental quality.

Decentralized governance further intensifies these inequalities. Inherent lack of coordination in multi-level and cross jurisdictional governance systems often results in divergent planning standards between the core and the periphery [28]. This policy fragmentation exacerbates disparities in outdoor physical activity environments by allowing local socioeconomic development levels to dictate unequal resource provision.

Economic collaboration between functional zones enhances overall regional competitiveness through industrial division and complementarity [25,50]. However, this same dynamic creates a "siphoning effect" that concentrates high-quality resources in the core [51]. This leaves peripheral areas disadvantaged in attracting investment for outdoor physical activity facilities, which not only creates disparities in children's environments but can also lead to spatial deprivation in less privileged zones.

2.2. Establishment of the Evaluation System

A comprehensive evaluation framework was established to quantify the spatial distribution of children's outdoor physical activity environment quality within the metropolitan area (Figure 1). This framework allows for the simultaneous examination of the positive and negative impacts of metropolization, as well as the resultant interzonal inequalities across the metropolitan structure. All indicators were rigorously tested for multicollinearity (VIF $\leq$ 5) prior to analysis (Table S1), confirming their independent and effective representation of respective dimensions.

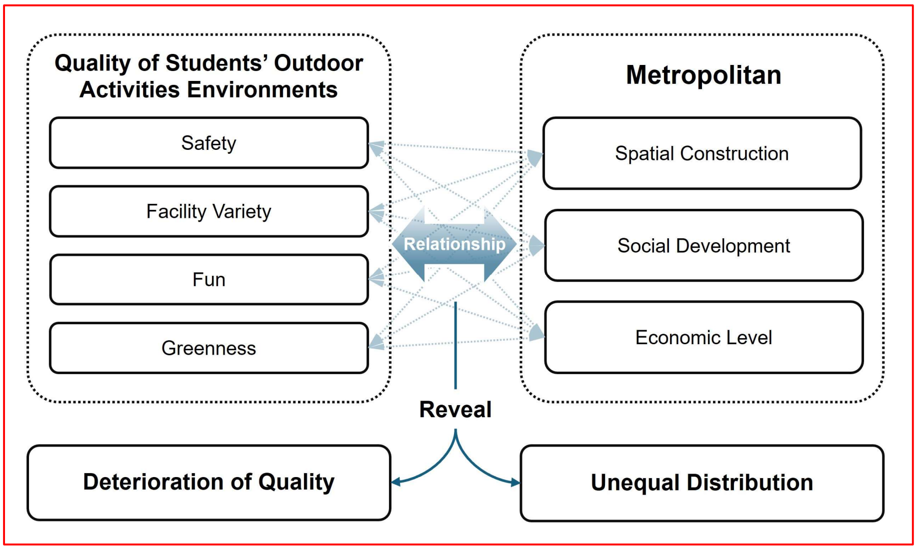

Figure 1. Research concept.

2.2.1. Quality of Children's Outdoor Physical Activity Environments

Based on the conceptual framework linking physical domains to user needs, the evaluation system is constructed around the four core dimensions: Safety, Facility Variety, Fun, and Greenness. The indicators (Table 1) were selected to specifically capture how these dimensions manifest across the three physical domains (on-campus environments, the built environments surrounding campuses, and natural ecological environments outside school).

Safety is the foundational dimension in assessing the quality of children's outdoor environments, aiming to prevent accidents and ensure a secure setting free from physical risks. Since children's activity spaces often overlap with public areas like streets and open grounds, these risks stem primarily from traffic interference and unsafe site conditions. Two indicators measure this dimension: (1) Land Safety, which evaluates the coverage of land uses unfavorable to children's activities, thereby reflecting the inherent safety of activity sites [14,52]; (2) Average Traffic Intensity, which assesses the extent of traffic disturbance to children's activities [13,44,45,52].

Facility Variety measures the capacity of the environment to support a wide range of activities, which is essential for sustaining children's engagement by catering to their varied interests. Facility Variety is measured through three indicators: (1) Size of School Playing Fields, which reflects activity capacity and prevents overcrowding [3]; (2) Types of Sports Fields on Campus, which assesses the diversity of formal sports opportunities [3]; (3) The Number of Informal Sports Spaces in the Neighborhood, which reflects the availability of informal settings for flexible and spontaneous activities [14].

The Fun dimension highlights the importance of creative and distinctive design, shifting engagement from passive to proactive exploration. Two indicators operationalize this dimension: (1) Number of Campus-Specific Sports Spaces, such as water landscapes, experimental farms, or animal gardens, etc., reflecting the uniqueness and attractiveness of campus spaces [3,15,17]; (2) Number of Dedicated Children's Activity Areas in Neighborhoods, which captures the provision of adventurous and playful environments supporting gamified activity experiences [15,17].

Greenness emphasizes natural element integration for health, microclimate regulation, and psychological restoration. Three indicators measure this dimension: (1) Campus Tree Coverage Rate, representing the natural atmosphere on campus [22,53]; (2) Neighborhood Tree Coverage Rate, assessing greenery in the surrounding built environment [54,55]; (3) Natural Space Accessibility, reflecting opportunities for children to access large-scale ecological spaces [49,56].

Table 1. Evaluation Indicators of Children's Outdoor Physical Activity Environments.

Dimension	Indicator	Calculation Method	Data Source	Reference	Weight
Safety	Land Safety	Negative count of hazardous land uses for children's activities within the buffer (industrial, transportation, medical, chemical, commercial, hospitals, etc.)	Baidu API https://lbsyun.baidu.com/, 2024	[14,52,57,58]	11.537
	Average Traffic Intensity	Negative average traffic congestion of roads accessible within the buffer, calculated from 7:00–19:00 on non-holiday weekdays in October 2024	Gaode API traffic data	[13,44,45,52]	10.063
Facility Variety	Size of School Playing Fields	Area of standard sports fields within the campus	Baidu Maps, manually identified and recorded, 2024	[3]	8.066
	Types of Sports Fields on Campus	Number of types of standard sports fields within the campus	Baidu Maps, manually identified and recorded, 2024	[3]	14.437
	The Number of Informal Sports Spaces in the Neighborhood	Number of pocket parks and street-side play areas within the buffer	Beijing Park and Greenery Bureau, 2022	[14]	15.860
Fun	Number of Campus-Specific Sports Spaces	Number of specialized sports spaces on campus, such as water features, experimental farms, and animal gardens	Baidu Maps, manually identified and recorded	[3,15,17]	7.327
	Number of Dedicated Children's Activity Areas in Neighborhoods	Number of dedicated children's play areas within the buffer (e.g., children's playgrounds, outdoor play areas, children's parks)	Gaode API POI data https://lbs.amap.com/api/webservice/guide/api/search	[15,17]	10.571
Greenness	Campus Tree Coverage Rate	Proportion of tree coverage within the campus	ESA 10 m land cover dataset https://esa-worldcover.org/en	[22,53]	5.326
	Neighborhood Tree Coverage Rate	Proportion of tree coverage within the buffer	ESA 10 m land cover dataset https://esa-worldcover.org/en	[54,55]	7.591
	Natural Space Accessibility	Proportion of comprehensive parks, ecological parks, and natural parks within the buffer	Beijing Park and Greenery Bureau, 2022	[49,56]	9.222

2.2.2. Measuring Metropolization Level

To capture the multidimensional characteristics of metropolization, an assessment framework was constructed across three key dimensions: Spatial Construction, Social Development, and Economic Level. Each dimension is represented by critical indicators that quantitatively reflect metropolitan processes at different scales (Table 2).

Table 2. Metropolization Indicators.

Metropolization Dimension	Indicator	Calculation Method	Data Source	Reference
Spatial Construction	Building Density	Proportion of building area within the buffer	Baidu API https://lbsyun.baidu.com/	[19,59]
	Land Use Mix	Entropy of POI types within the area	Gaode API POI data https://lbs.amap.com/api/webservice/guide/api/search	[59,60]
	Centrality Index	Distance to the nearest municipal center	Baidu API https://lbsyun.baidu.com/	[19,20,24]
Social Development	Service Facility Density	POI density Number of POIs per square kilometer within the buffer	Gaode API POI data https://lbs.amap.com/api/webservice/guide/api/search	[19,24]
	Educational Level	Proportion of population with university (college and above), high school (including vocational), junior high, and primary education	7th National Population Census Bulletin, 2020	[19]
Economic Level	Housing Price	Average selling price of houses within the buffer	Collected from Lianjia https://bj.lianjia.com/xiaoqu/	[19,59,61]
	Fiscal Revenue	Annual government fiscal investment in the school's district	District government statistical yearbooks 2020	[19,59,62,63]

Spatial Construction focuses on the physical form of metropolitan spaces, reflecting spatial integration and expansion. It includes three indicators: (1) Building Density, measuring the intensity of land use and the degree of development in built-up areas [19,59]; (2) Land Use Mix, assessing the integration of residential, commercial, and public service functions [59,60]; (3) Centrality Index, indicating the spatial importance and radiating influence of a location relative to the regional center [19,20,24].

Social Development highlights the degree of social resource allocation and institutional development in metropolitan areas. It includes two indicators: (1) Service Facility Density, reflecting accessibility and equality of public services, thereby serving as a direct measure of social welfare [19,24]; (2) Educational Level, capturing the quality of human capital and a region's capacity to attract talent, which reflects sustainability of social development [19].

Economic Level measures regional economic strength and capacity for wealth generation. It includes two indicators: (1) Housing Price, representing the market's direct valuation of regional attractiveness and degree of resource agglomeration [19,59,61]; (2) Fiscal Revenue, reflecting the economic capacity of local governments to regulate development and provide public services, directly influencing infrastructure investment [19,59,62,63].

3. Materials and Methods

3.1. Research Framework

The research design is structured into five sequential steps, as shown in Figure 2. First, the quality of children's outdoor physical activity environments was comprehensively evaluated by quantifying and integrating four key dimensions namely, Safety, Facility Variety, Fun, and Greenness. The metropolization level of Beijing was assessed based on Spatial Construction, Social Development, and Economic Level. Subsequently, an equality analysis was conducted across the four quality dimensions to identify regional disparities.

Finally, Geographically Weighted Regression (GWR) was employed to examine the spatially heterogeneous relationships between metropolization and environmental quality, with the synthesized results guiding the proposal of potential optimization strategies across different metropolitan areas. ArcGIS Pro (v2024) was used for the processing and analysis of geographic data.

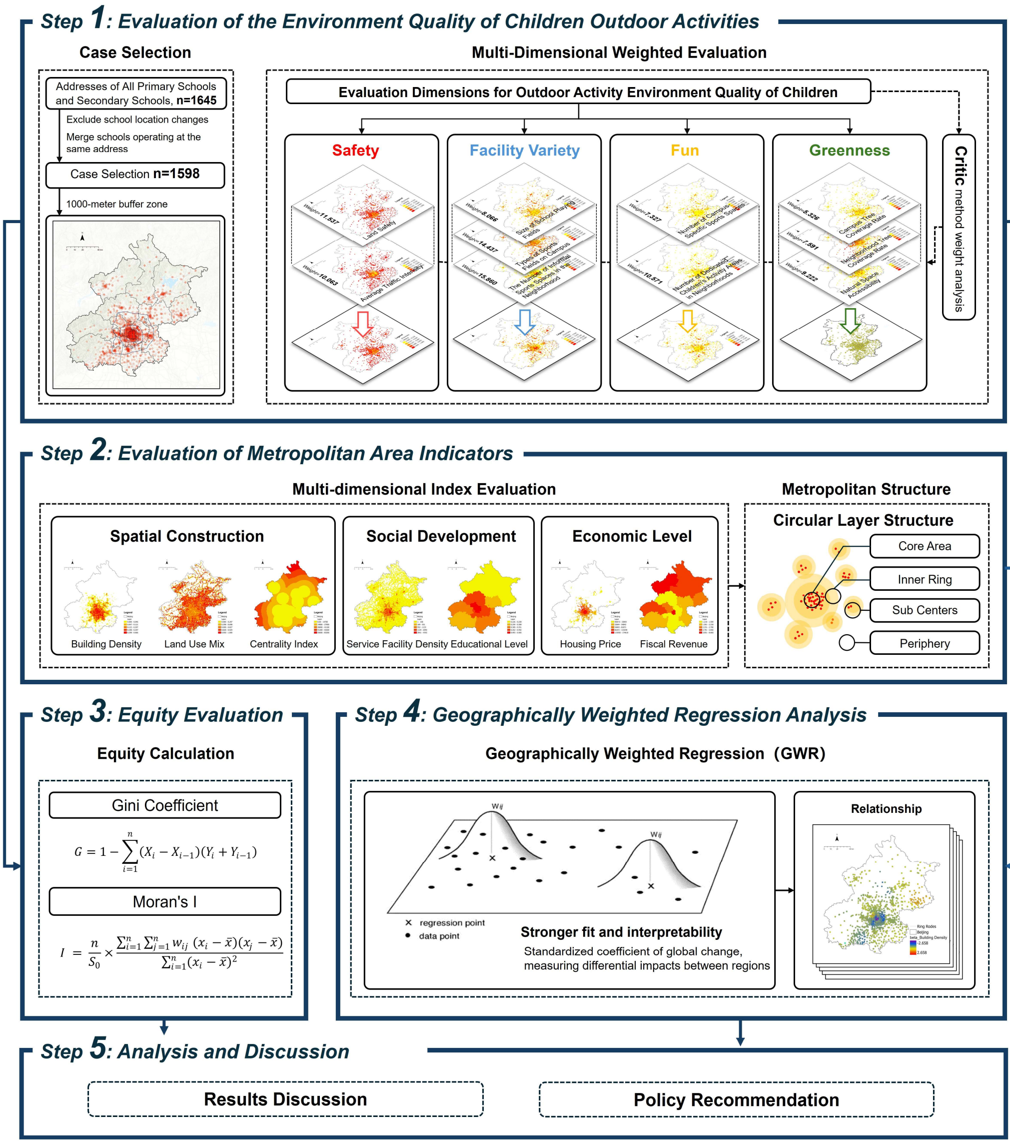

Figure 2. Research flow.

3.2. Case Selection and Data Collection

Beijing is a representative metropolitan region for this study due to its substantial child population and its urban development structure, which mirrors the typical distribution of educational resources found in many large cities [4,19,32,63]. Based on the school directory published by the Beijing Municipal Education Commission, 1598 primary and secondary school locations were collected. Beijing's "Attending Nearby Schools" policy mandates that children attend campuses within a reasonable walking distance of their households [64,65]. This distance is commonly standardized to a 15 min walk, which is spatially equivalent to a 1000 m buffer zone [66,67]. Consequently, in this study, the spatial catchment of each school representing its immediate service area was precisely delineated as a 1000-m buffer centered on the school's campus boundary (Figure 3).

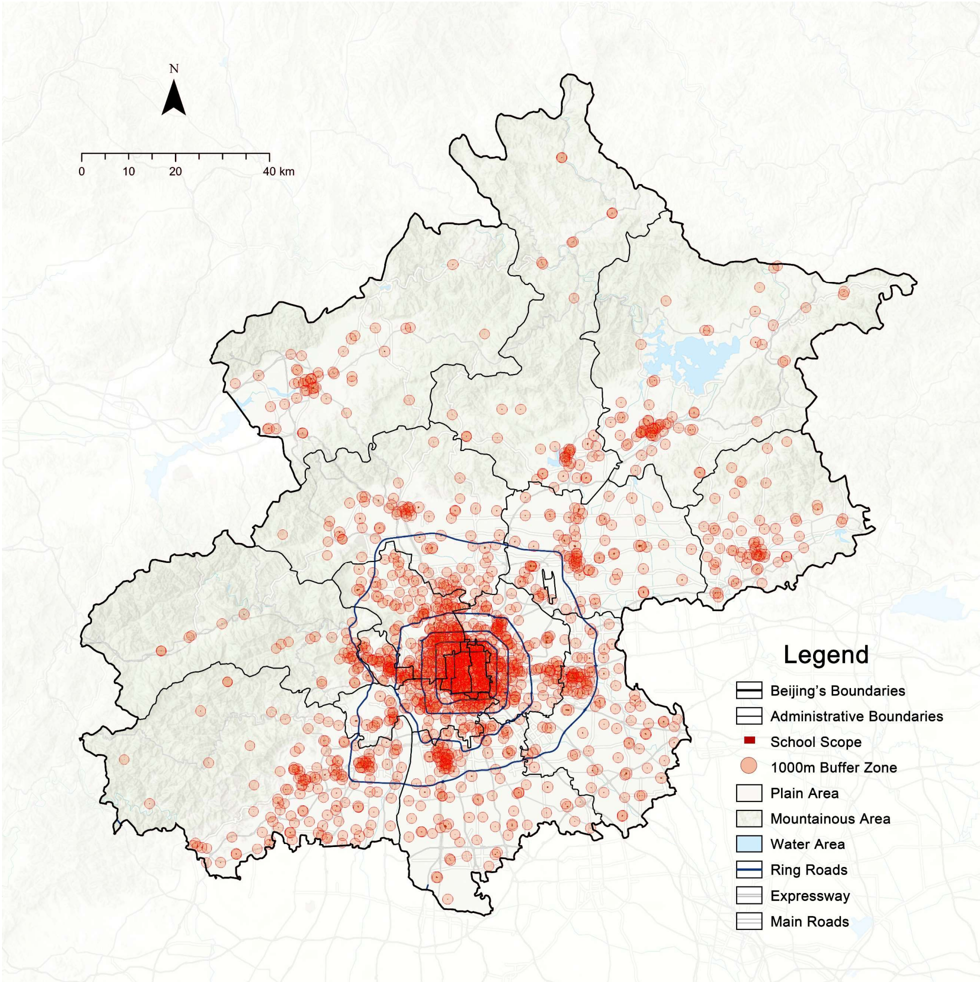

Figure 3. Beijing and the research case schools.

3.3. Evaluation of the Equality of Children's Outdoor Physical Activity Environment Quality

3.3.1. CRITIC Method

All indicators were standardized using the min-max normalization method to ensure comparability while preserving proportional information from the original data. The Criteria Importance Through Inter-criteria Correlation (CRITIC) method was employed to assign weights objectively, calculating them by simultaneously accounting for both the internal variability of each indicator and the conflicts among indicators. Compared with subjective weighting approaches, it minimizes human bias by relying on the intrinsic properties of the data [68,69]. Following the data normalization, the weight of each indicator was calculated using the following equations:

$$S_j = \sqrt{\frac{\sum_{i=1}^{n}\left(r_{ij} - \overline{r_j}\right)^2}{n-1}} \tag{1}$$

$$R_j = \sum_{k=1}^{m}\left(1 - r_{jk}\right) \tag{2}$$

$$W_j = \frac{S_j \times R_j}{\sum_{j=1}^{m}\left(S_j \times R_j\right)} \tag{3}$$

where W_j represents the final objective weight of the j-th indicator; S_j is the standard deviation of the j-th indicator, representing its contrast intensity; R_j represents the conflict index of the j-th indicator relative to other indicators; r_{jk} is the Pearson correlation coefficient between indicator j and indicator r_{ij} is the normalized value of the j-th indicator for the i-th spatial unit; $\overline{r_j}$ represents the mean value of the normalized j-th indicator; n and m are the total number of spatial units and evaluation indicators, respectively.

The results (Table 1) demonstrated that the weights were reasonable and objective, providing a reliable basis for subsequent evaluations.

3.3.2. Gini Coefficient

The Gini coefficient was used to quantitatively assess and identify inequalities across each dimension of children's outdoor physical activity environment quality. As a classical indicator of socioeconomic inequality, the Gini coefficient is derived from the Lorenz curve, which depicts the cumulative proportion of population against the cumulative proportion of income or resources after ranking individuals from the lowest to the highest [70]. When resources are perfectly evenly distributed, the Lorenz curve coincides with the diagonal, resulting in a Gini coefficient of 0. Conversely, when resources are highly concentrated among a small group, the curve deviates further from the diagonal and the coefficient approaches 1. This approach has been widely applied in studies of regional equality to assess disparities in various fields, including economic equality [71], resource allocation [72], and accessibility [73].

The calculation formula for the Gini coefficient is as follows:

$$G = 1 - \sum_{i=1}^{n} (X_i - X_{i-1})(Y_i + Y_{i-1}) \quad (4)$$

G represents the Gini coefficient. n is the total number of spatial units. X_i is the cumulative percentage of the population or spatial units indexed i. Y_i is the cumulative percentage of the variable indexed i.

3.3.3. Moran's I Index

Moran's I index was applied to assess spatial equality in children's outdoor physical activity environment quality. Moran's I is a widely used statistic for assessing the degree of spatial autocorrelation in geographic data [71,74], with values ranging from −1 to 1. A significantly positive Moran's I indicates that spatial units with similar attributes tend to cluster together, suggesting that there exist concentrated "high-quality" or "low-quality" areas and revealing spatial differentiation and inequality across the study area. A significantly negative Moran's I suggests clustering of dissimilar attributes, indicating spatial integration of both favorable and unfavorable environments. Values close to 0 reflect random spatial distributions.

The calculation formula for the univariate Moran's I is as follows:

$$I = \frac{n}{S_0} \times \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij}(x_i - \overline{x})(x_j - \overline{x})}{\sum_{i=1}^{n} (x_i - \overline{x})^2} \quad (5)$$

I is the Moran's I index. n is the total number of spatial units. x_i and x_j are the attribute values of the variable at spatial units i and j, respectively. $\overline{x}$ is the mean value of the variable across all spatial units. w_{ij} is the spatial weight between spatial units i and j. S_0 is the sum of all spatial weights, calculated as $S_0 = \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij}$.

3.4. Correlation Analysis Between Children's Outdoor Physical Activity Environment Quality and Metropolization Indicators

The GWR model was employed to analyze the relationship between children's outdoor activity environment quality and metropolization indicators. GWR extends the global linear regression framework by accounting for spatial non-stationarity. This is achieved through the assignment of location-specific weights, which are determined by the proximity of each observation to a given focal point, thereby allowing the estimated regression coefficients to vary across space [71,74,75]. For model specification, a Gaussian kernel function was utilized to define the spatial weights, and the Akaike Information Criterion (AIC) was implemented to determine the optimal bandwidth [76]. Model selection was supported by prior evidence demonstrating that GWR yields superior model fit and enhanced explanatory power compared to conventional linear models [71,76,77]. GWR is particularly effective in capturing the heterogeneous characteristics inherent to metropolitan areas, confirming its suitability for analyzing areas with pronounced spatial heterogeneity (Tables S2–S4). This study uses MGWR 2.2 for the calculations.

4. Multidimensional Evaluation Results

4.1. Metropolitan Spatial Structure

Per Beijing's current and long-term spatial plans, the metropolitan spatial structure presents a distinct hierarchical pattern across functional zones (Figure 4). The Core Area serves as the political and cultural center with extremely high spatial density, hosting central government institutions and major cultural heritage sites. Surrounding this zone is the Inner Ring, which primarily focuses on functional optimization and industrial upgrading and includes Beijing's Second Greenbelt, a planned ecological zone stretching between the 5th and 6th Ring Roads [78]. The Sub-Centers, located in outer administrative districts, serve as strategic anchors, forming a "multi-centric" structure together with the central city. The Periphery, comprising new towns and ecological conservation zones, plays an essential role in accommodating relocated functions, promoting regional coordination, and safeguarding ecological stability [79]. This spatial layout corresponds with the city's natural topography. The majority of urban functions are situated on the southeastern plains, while the primary ecological conservation areas are located in the mountainous northwest.

The metropolitan indicators of Beijing reveal a concentric spatial pattern characterized by a highly centralized core, dispersed multi-centered clusters in the surrounding areas, and networked connections between centers at different levels (Figure 5). Overall, the spatial, social, and economic indicators confirm this hierarchical structure. Spatially, Building Density and Centrality Index in the Core Area and decline concentrically, though the Sub-Centers form intermediate clusters. Socially, high-quality resources such as Service Facilities and Educational Level are heavily concentrated in the Core Area, creating a pronounced disparity with the lagging Periphery. Economically, market-driven indicators like Housing Prices follow this same steep core–periphery decline. Policy-driven indicators, however, show a more complex pattern: Fiscal Revenue, for example, is high in both the Core Area and the Periphery, suggesting a dual policy focus. In summary, these characteristics collectively illustrate a classic hierarchical "core–periphery" structure.

4.2. Inequality in Children's Outdoor Physical Activity Environment Quality

4.2.1. Gini Coefficient Results

The Gini Coefficient indicates that, overall, children's outdoor activity environments in Beijing achieve a moderate level of equality in essential infrastructural provision, though significant disparities persist for certain indicators (Figure 6, Table 3). Among the four overall dimensions, the Fun dimension shows the greatest inequality (0.666), while the Greenness (0.288) and Facility Variety (0.261) dimensions show a certain degree of inequality, and the Safety dimension (0.085) demonstrates a high level of equality.

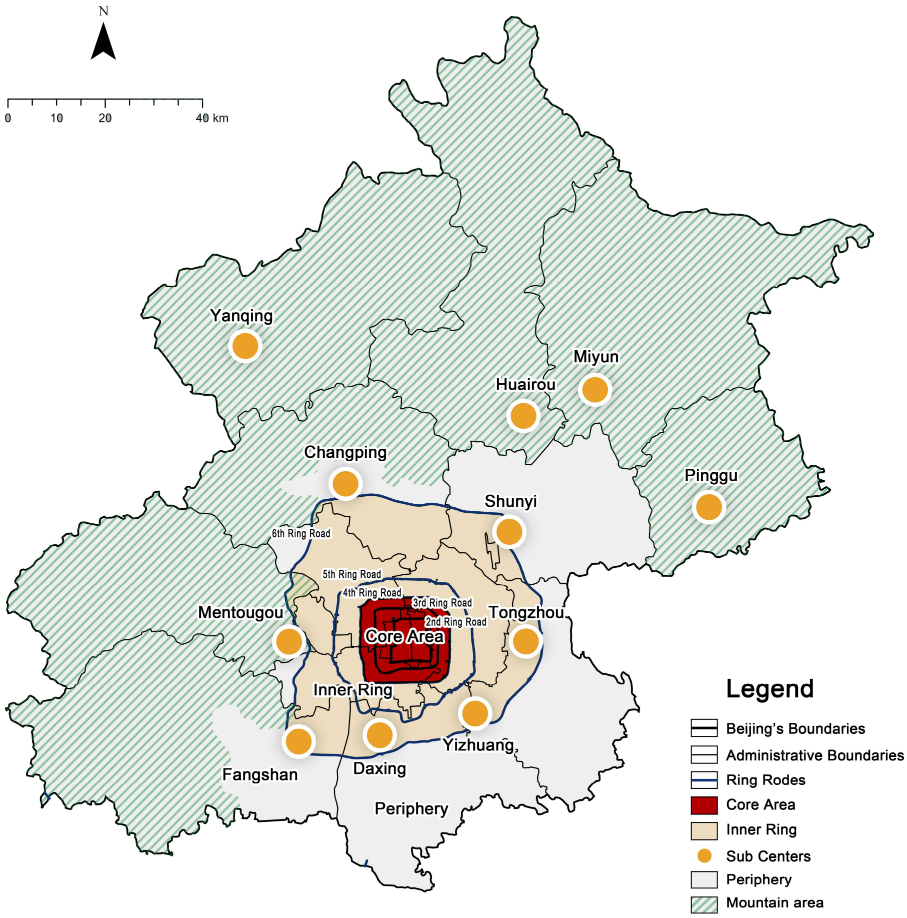

Figure 4. Spatial structure of Beijing.

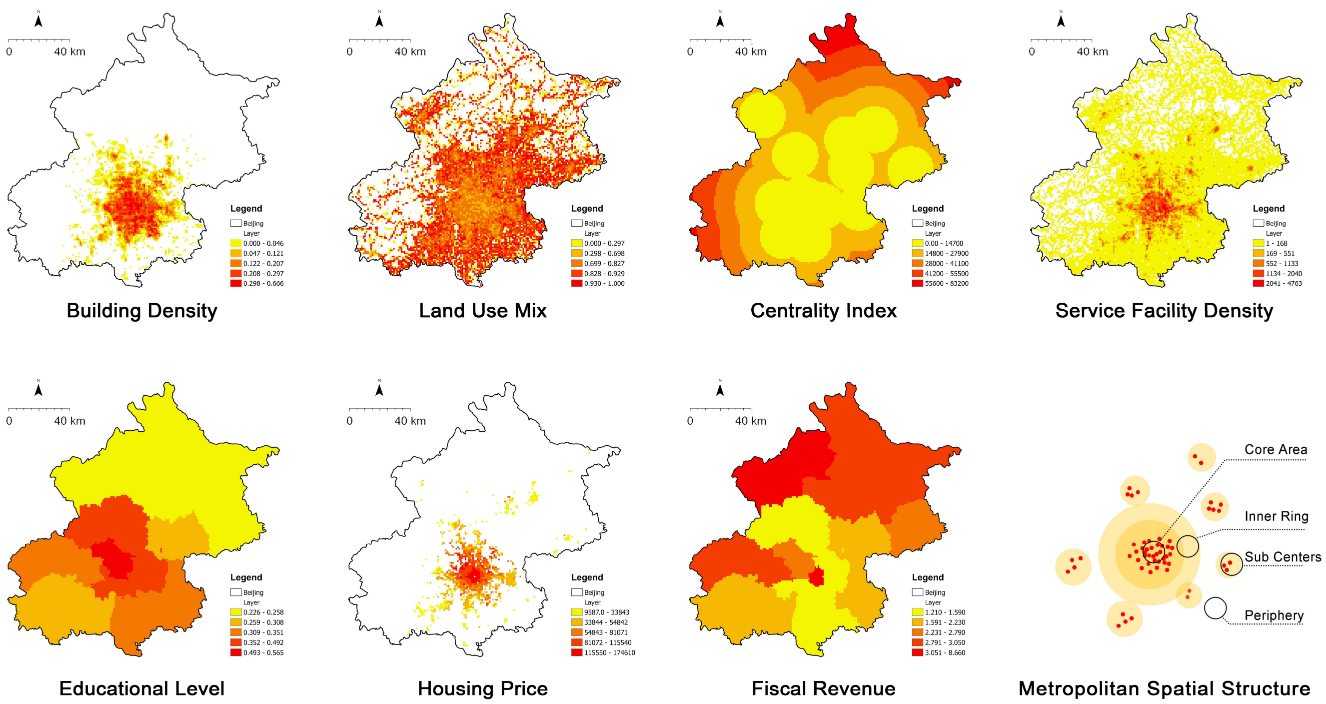

Figure 5. Metropolitanization characteristics of Beijing.

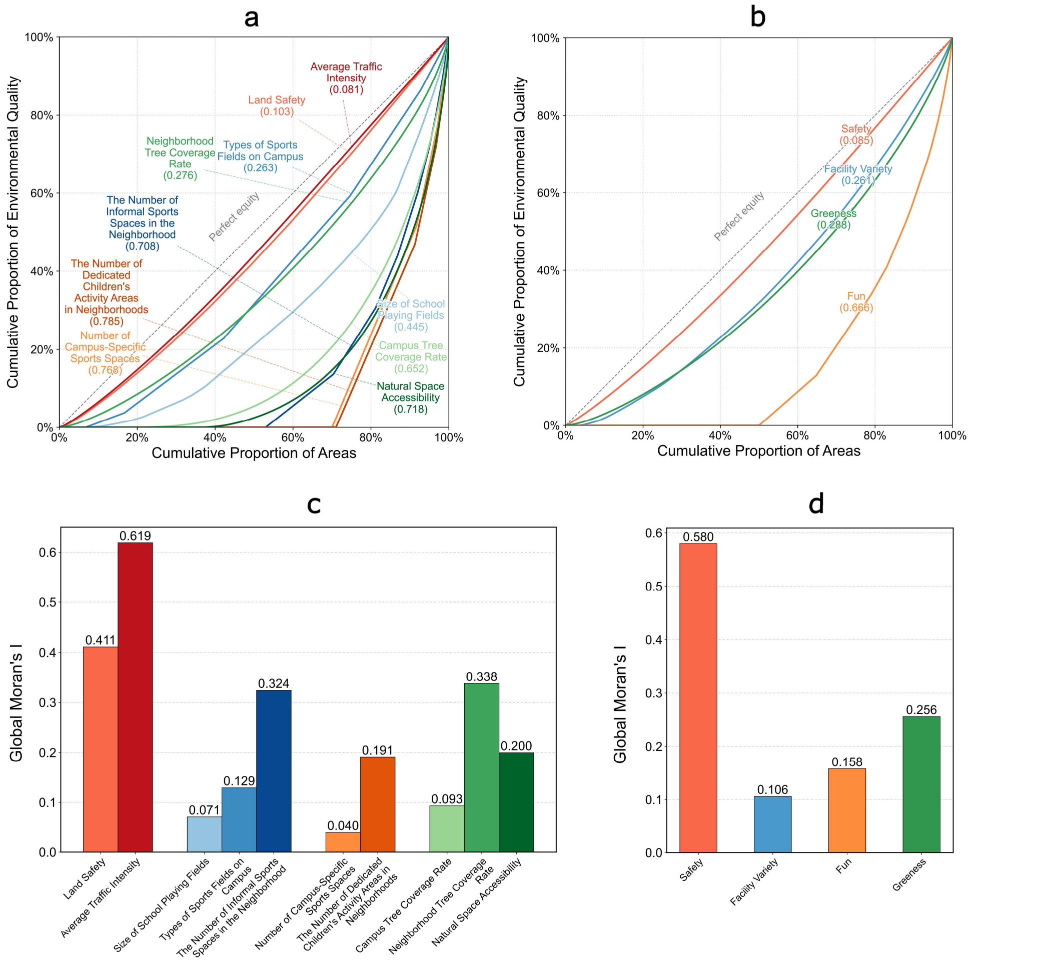

Figure 6. Gini coefficients and Lorenz curves for the (**a**) individual indicators and (**b**) four dimensions. Moran's I index for the (**c**) individual indicators and (**d**) four dimensions.

Specific indicators further highlight this unevenness. The highest Gini coefficients are observed for Number of Dedicated Children's Activity Areas in Neighborhoods (0.785), Number of Campus-Specific Sports Spaces (0.768), Natural Space Accessibility (0.718), and The Number of Informal Sports Spaces in the Neighborhood (0.708). Conversely, the lowest Gini coefficients are found for Land Safety (0.103), Types of Sports Fields on Campus (0.264), and Neighborhood Tree Coverage Rate (0.277). This suggests that basic, essential facilities, such as safe and standard sports fields, are distributed more equitably.

Overall, the findings suggest that Beijing provides a basic level of equality in fundamental infrastructure, with children across the metropolitan area enjoying relatively fair access to standard facilities such as running tracks, basketball courts, and football fields, supported by an adequate safety framework. Yet, significant equality gaps remain in the availability of higher-quality facilities, including fun-oriented play spaces and natural experience areas. Previous research has shown that while structured facilities can yield predictable benefits for physical health, unstructured green spaces or informal play areas can also foster children's cognitive creativity, social autonomy, and psychological resilience [15–17]. The significant disparities in these indicators suggest that children in resource-poor areas may be limited to repetitive and formulaic activities, lacking the flexible environments necessary for autonomous exploration. This emphasizes the need for targeted improvements to enhance the overall quality, diversity, and uniqueness of children's outdoor activity environments.

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Table 3. Equality results of children's outdoor physical activity environment quality.

	Max	Min	Mean	SD	Gini Coefficient	Moran's I Index
Safety	21.600	7.715	18.588	2.885	0.085	0.580
Land Safety (number)	0.000	−19.00	−3.088	3.043	0.103	0.411
Average Traffic Intensity (number)	0.000	−132.560	−14.971	18.684	0.261	0.619
Facility Variety	25.987	0.000	9.582	4.483	0.261	0.106
Size of School Playing Fields (m^2)	46,265.710	0.000	6441.572	5756.501	0.445	0.071
Types of Sports Fields on Campus (number)	6.000	0.000	2.673	1.279	0.264	0.129
The Number of Informal Sports Spaces in the Neighborhood (number)	10.000	0.000	1.278	1.926	0.708	0.324
Fun	10.903	0.000	1.201	1.682	0.666	0.158
Number of Campus-Specific Sports Spaces (number)	7.000	0.000	0.420	0.765	0.768	0.040
Number of Dedicated Children's Activity Areas in Neighborhoods (number)	6.000	0.000	0.432	0.844	0.785	0.191
Greenness	13.140	0.000	2.922	1.604	0.288	0.256
Campus Tree Coverage Rate (100%)	0.937	0.000	0.066	0.095	0.652	0.093
Neighborhood Tree Coverage Rate (100%)	0.851	0.010	0.208	0.107	0.277	0.338
Natural Space Accessibility (100%)	1.006	0.000	0.041	0.075	0.718	0.200

4.2.2. Moran's I Index Results

The evaluation results of Moran's I index confirm that nearly all indicators display strong spatial dependence, meaning campuses with similar outdoor physical activity environments (either high or low quality) tend to cluster together (Figure 5, Table 3). At the dimension level, Safety (0.580) and Greenness (0.256) exhibit higher Moran's I values, indicating more pronounced spatial clustering. Conversely, Fun (0.158) and Facility Variety (0.106) have lower Moran's I values, reflecting weaker spatial clustering and a tendency toward scattered distribution.

At the individual indicator level, strong positive spatial correlation is observed for Average Traffic Intensity (0.619) and Land Safety (0.411). This pattern is primarily driven by the metropolitan built environment: high land use mixing and traffic density in the urban core versus the Periphery result in a clear "high in the center, low in the periphery" spatial differentiation. Moderate positive correlations for Informal Sports Spaces (0.324) and Neighborhood Tree Coverage (0.338) are influenced by regional policies and natural conditions. Indicators reflecting on-campus features, such as Size of School Playing Fields (0.071), Number of Campus-Specific Sports Spaces (0.040), and Campus Tree Coverage Rate (0.093), show weak positive correlations. This suggests that the spatial distribution of these indicators is primarily driven by school-specific factors, such as autonomous planning and historical construction, rather than by the broader metropolitan structure.

These findings reveal two distinct scales of inequality in children's outdoor physical activity environments. On-campus inequalities are small-scale, reflecting localized disparities between individual schools. In contrast, off-campus inequalities are large-scale, manifesting in the built and ecological spaces across the entire city.

4.3. Spatial Distribution of Children's Outdoor Activity Environment Quality Across Metropolitan Structure

4.3.1. Safety Dimension

The overall results are shown in Figure 7. The Safety dimension exhibits a clear spatial gradient across Beijing, decreasing from the Periphery toward the Core Area. This pattern can be explained by two main factors. First, land use in the Core Area is dominated by commercial functions, which attracts a high concentration of consumers [57,58,80]. In these commercially dense zones, public open spaces are limited, thus reducing the availability of safe venues for children's outdoor physical activities. Second, the Core Area experiences high traffic intensity, marked by dense arterial roads and heavy motor vehicle flows [81], which fundamentally increase the risk for outdoor activities. However, this clear gradient is interrupted by Sub-Centers, particularly those in southwestern Beijing, which exhibit lower safety scores compared with the Periphery. This deviation is largely due to their unique geographic and developmental characteristics. Situated on plains, these zones have undergone rapid urban expansion, developing into secondary centers and taking on roles similar to those of the Core Area [82]. Such rapid urbanization consequently leads to homogeneous land use, heavy traffic, and a notable decline in regional safety.

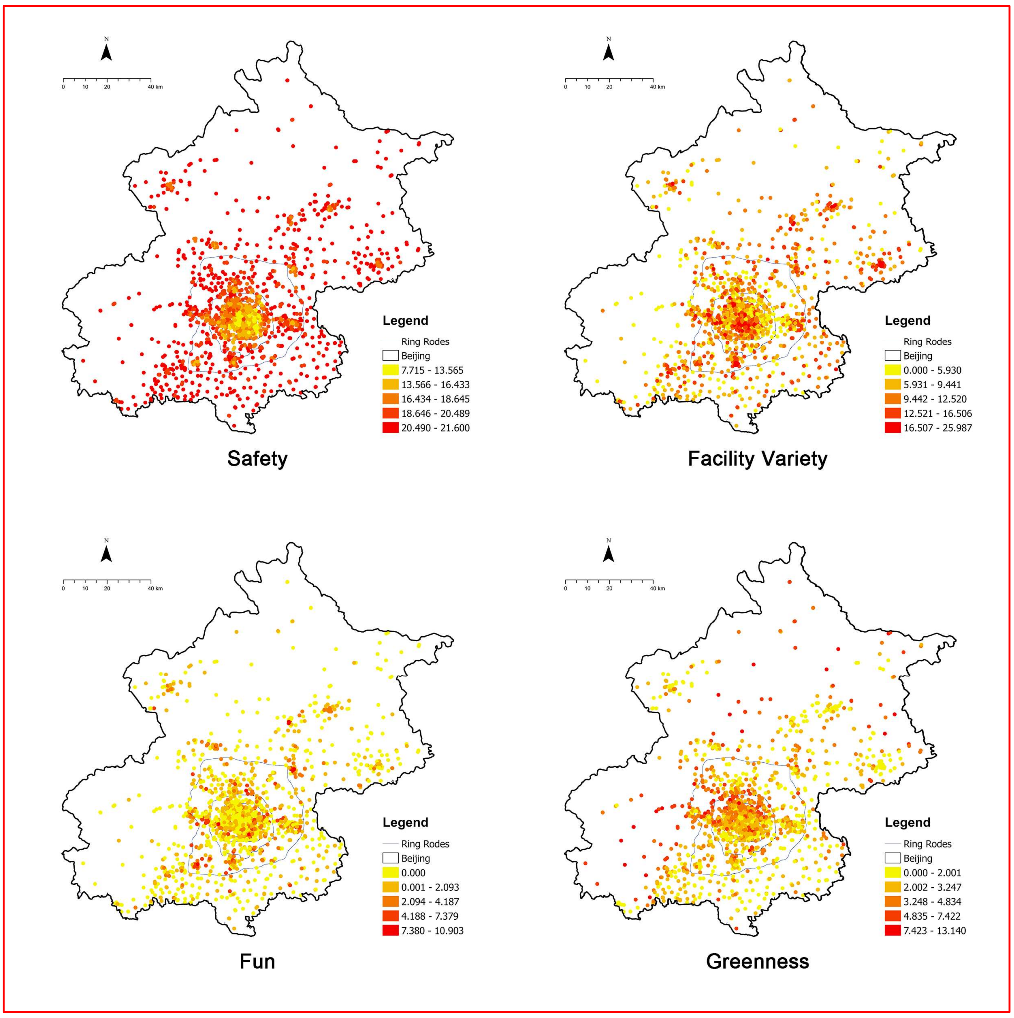

Figure 7. Distribution of children's outdoor physical activity environment quality.

4.3.2. Facility Variety Dimension

The Facility Variety dimension exhibits better performance in the central Core Area compared to its fringe zones. This pattern likely reflects that campuses in the central Core Area are predominantly long-established, prestigious institutions whose founding predates the era of rapid urbanization, enabling them to secure superior land resources. The Inner Ring demonstrates a slightly superior performance compared to the fringe zones of the Core Area. This discrepancy is primarily driven by disparities in land availability and development conditions: campuses in the Core Area's fringe zones are constrained by land scarcity and high built density, resulting in limited expandable space and inadequate sports infrastructure. In contrast, campuses in the Inner Ring benefit from relatively abundant urban land reserves and lower land acquisition costs compared to the Core Area [29]. These favorable land conditions support the development of larger, modernized facilities and more optimal outdoor physical activity environments. Nearly all Sub-Centers outperform the Periphery significantly in the Facility Variety dimension, with some matching the central Core Area. This pattern arises primarily from two factors. First, the development level and economic conditions in the Sub-Centers are clearly superior to those in Periphery, having long provided sufficient resources to meet most local demands [78,79]. Second, these areas concentrate relatively high-quality educational resources, both on-campus and regionally, thereby contributing to better-equipped and more diverse campus facilities.

4.3.3. Fun Dimension

The Fun dimension demonstrates overall spatial convergence, though a distinct cluster of campuses exhibits exceptionally high values, primarily located in the Inner Ring and Sub-Centers. This clustered pattern is attributed to three structural factors: a general facility deficit across most campuses, which lack specialized spaces for engaging activities; the concentration of newly built campuses in the Inner Ring and Sub-Centers, which occupy larger areas and incorporate advanced planning with specialized outdoor facilities; and the development of high-quality, dedicated children's activity areas through modern real estate amenity investment in the Sub-Centers. In other words, these factors demonstrate that high values in the Fun dimension are structurally tied to recent urban development, strategic educational planning, and commercial amenity provision.

4.3.4. Greenness Dimension

The Greenness dimension exhibits a distinct spatial gradient, with campuses in the Core Area scoring lowest. This low performance is a direct result of high building density and limited land availability in the urban core, which severely restricts the provision of parks and natural spaces. This scarcity ultimately reduces children's access to large-scale ecological environments for outdoor physical activities. The Inner Ring performs significantly better, particularly in its northern part. Campuses here benefit from proximity to Beijing's Second Greenbelt, a planned ecological zone stretching between the 5th and 6th Ring Roads [78]. These resources not only enhance local vegetation coverage and ecological value but also improve accessibility to large, well-equipped natural spaces, providing high-quality outdoor activity opportunities for nearby children. In contrast, campuses in Sub-Centers and the Periphery generally register low Greenness values, with only isolated campuses near parks achieving relatively high scores. The overall low performance is attributed to limited availability of public green spaces and low neighborhood accessibility, despite the presence of substantial total vegetation cover in some areas.

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5. Relationship Between Metropolitan Development Level and Children's Outdoor Physical Activity Environment Quality

5.1. Spatial Construction

The GWR results reveal two distinct spatial patterns for the model's key variables. Firstly, the correlation of both Building Density and Centrality Index with environmental quality follows the metropolitan spatial structure. Secondly, the correlation pattern for Land Use Mix is closely tied to the city's functional zones, creating a different spatial distribution (Figure 8).

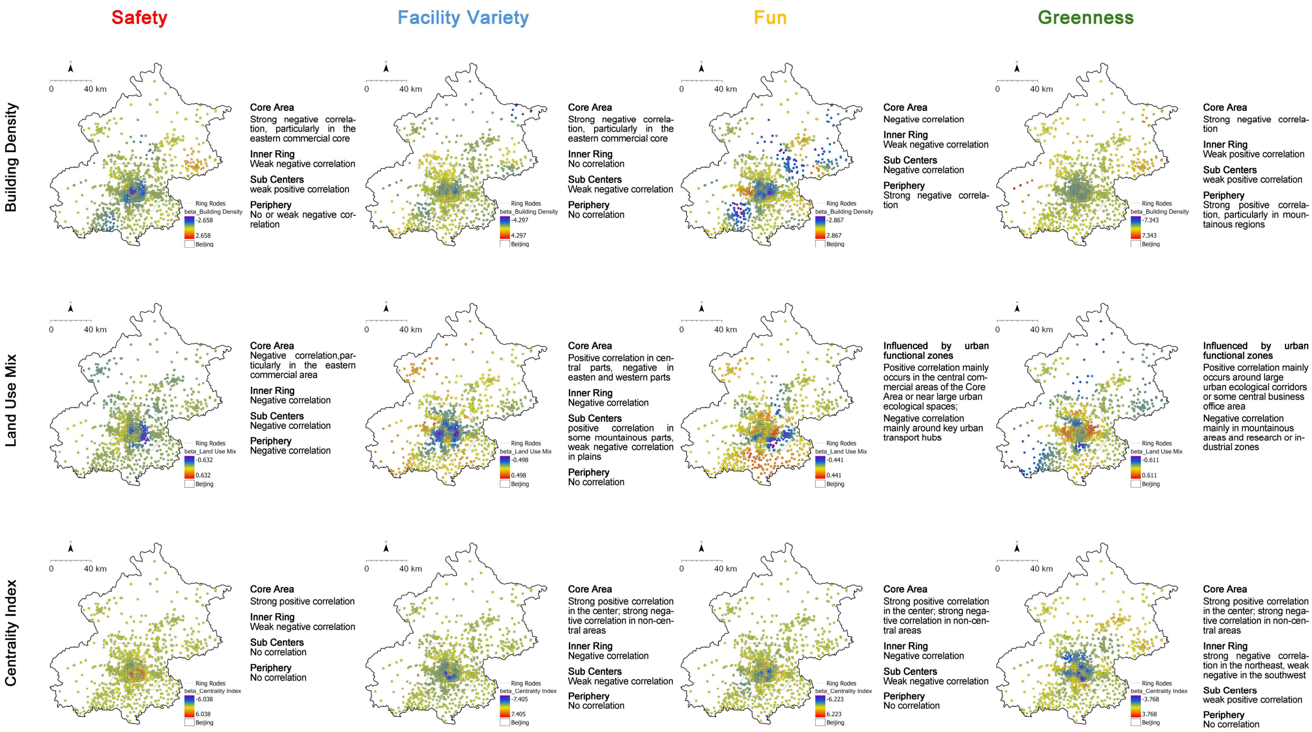

Figure 8. GWR regression results of Spatial Construction and children's outdoor activity environment quality.

5.1.1. Building Density

The correlation between Building Density and the four dimensions of outdoor physical activity environment quality exhibits clear spatial differentiation. A pronounced negative association is observed in the Core Area. This relationship weakens in the Inner Ring and shifts to a slight positive one in the Sub-Centers. In contrast, the Periphery shows either no significant correlation or a negative one. This negative association is particularly strong with the Fun dimension at the interface between mountainous and plain area in the Periphery.

This pattern highlights the acute scarcity of spatial resources for children's outdoor activities in the Core Area, where high population density and intensive land development severely constrain children's outdoor physical activity environments across all dimensions [80]. In the Inner Ring, lower land prices attract new development projects [81], providing comparatively more ample and higher quality spaces. In the Sub-Centers, development is guided by Beijing's polycentric strategy [29]. Here, advanced land development ensures that higher building density is accompanied by elevated urban construction standards, resulting in comparatively better outdoor physical activity environment quality.

5.1.2. Centrality Index

The overall correlation between Centrality Index and the four dimensions is very strong, exhibiting two distinct patterns based on the specific dimension. First, Centrality Index shows a strong positive correlation with the Safety dimension in the Core Area, this shifts to a weak negative correlation in the Inner Ring and shows almost no correlation in Sub-Centers and Periphery. Second, Centrality Index displays a strong positive correlation with the Facility Variety, Fun, and Greenness dimensions at the center of the Core Area; correlations are negative in the Inner Ring and weakly negative toward the Sub-Centers and Periphery.

This distribution is primarily driven by the unique functional attributes of Beijing's Core Area. As a long established administrative center, the area is dominated by specialized land uses serving governmental and administrative functions [79]. This requires and benefits from superior support, while adverse commercial uses remain limited. Consequently, the Core Area performs better across all four dimensions. Outside the Core Area, administrative centers in Periphery also function as regional economic hubs, characterized by high traffic volumes and complex land use, which impose stress on outdoor physical activity environment quality.

5.1.3. Land Use Mix

The overall association between Land Use Mix and children's outdoor physical activity environment quality is weak, with global correlations deviating significantly from the layered metropolitan structure. This weak relationship indicates that the effect of mixing land uses is highly contingent upon the specific urban function of a zone, rather than its concentric location. The correlation with Safety is negative across the city, being strongest in dense commercial districts, and the relationship with Facility Variety is generally weak and negative, though partially positive in some western Sub-Centers. Conversely, the correlation with Fun and Greenness shifts to positive in areas favorable to children, such as central commercial districts adjacent to large urban ecological spaces and ecological corridors, while turning significantly negative in zones dedicated to urban efficiency, like major urban transport hubs and high density industrial or research functional zones.

These results indicate that high Land Use Mix only translates to a better outdoor environment when the dominant functional purpose of the mixing explicitly includes or accommodates child-oriented activities. In child-friendly areas like residential zones, open spaces, and parks, increased Land Use Mix adds beneficial amenities and improves the quality of activity spaces [14]. However, in functional zones like transport hubs and commercial districts, high Land Use Mix serves urban efficiency, which often conflicts with children's needs by increasing risks such as traffic and noise.

5.2. Social Development

The relationship between Social Development and environmental quality changes depending on the distance from the core area, creating a clear pattern of alternating concentric rings. Moving outward from the city center, zones of positive correlation are interspersed with zones of negative correlation. Service Facility Density demonstrates a moderate correlation, and Educational Level shows a strong correlation, with all four evaluation dimensions (Figure 9).

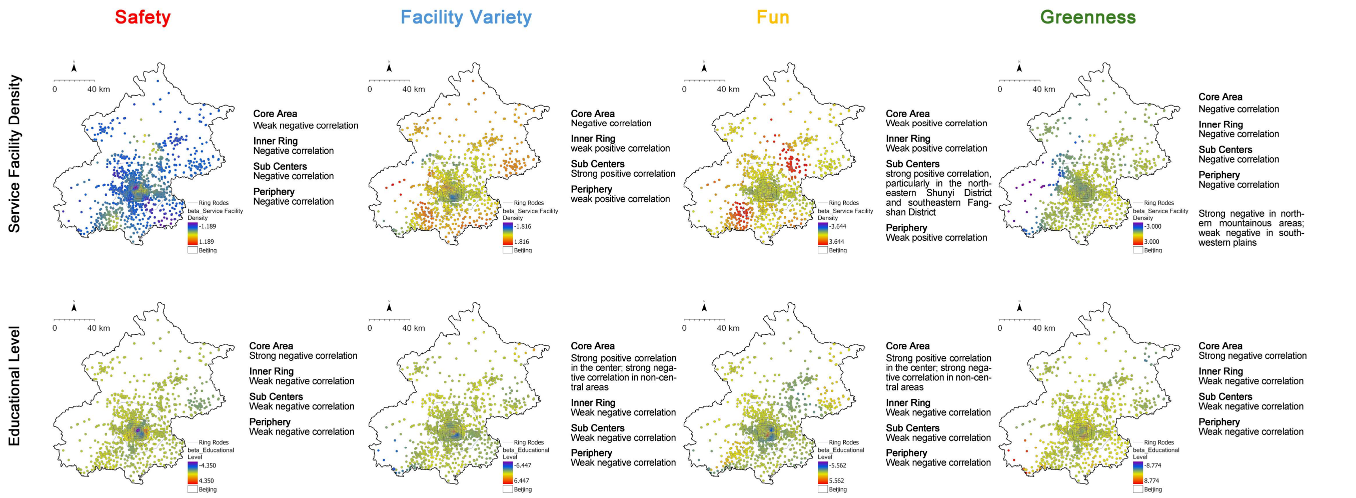

Figure 9. GWR regression results of social development and children's outdoor activity environment quality.

5.2.1. Service Facility Density

The correlation between Service Facility Density and the four dimensions exhibits distinct spatial patterns. Service Facility Density shows a citywide negative correlation with the Safety and Greenness dimensions, with the association being strongly negative for Greenness in northern mountainous areas. Conversely, the correlation with Facility Variety shifts from negative in the Core Area to positive toward the Sub-Centers. For the Fun dimension, a strong positive correlation exists only in the Sub-Centers, with correlations in other areas being weak.

This pattern occurs because the density of service points in the Core Area is extremely high. These individual points are so closely located and interconnected that they form a comprehensive service network [83,84]. However, this network is primarily oriented towards the needs of commerce and tourism, offering limited direct support for children's outdoor physical activity environments. In the Inner Ring, Sub-Centers, the focus shifts to supporting the diverse needs of daily life. A key feature of these areas is the presence of multiple university districts. For example, in the area surrounding Xueyuan Road, located in the northwest section of Beijing's 4th Ring Road, the Fun dimension shows a strong positive correlation with Service Facility Density. These academic hubs naturally give rise to a variety of services and amenities aimed at students' outdoor activities, such as playgrounds and recreational spaces. As a result, these areas provide a richer and more engaging outdoor environment for children and students.

5.2.2. Educational Level

The spatial correlation patterns between Educational Level and the four evaluation dimensions display two consistent trends across Beijing's metropolitan structure. Educational Level exhibits a strong negative correlation with the Safety and Greenness dimensions in the Core Area, and weak negative correlations in the Inner Ring, Sub-Centers, and Periphery. Second, Educational Level shows a strong positive correlation with the Facility Variety and Fun dimensions at the main center of the Core Area. Conversely, in all other zones, including the Inner Ring and Sub-Centers, this relationship shifts to a weak negative correlation across the Facility Variety and Fun dimensions.

The positive correlation between Educational Level and the environmental scores for Facility Variety and Fun is not causal but rather reflects a spatial coincidence. In the Core Area, highly educated populations tend to cluster in neighborhoods that already feature high-quality public spaces [85]. Because these areas are often well-funded to serve affluent residents, they offer more diverse and playful outdoor facilities. Conversely, in the Inner Ring, Sub-Centers, and Periphery, highly educated populations are primarily distributed near the industrial or Research and Development functional zones. In these zones, children-related outdoor facilities are insufficient, and the increased population density reduces environmental quality, resulting in the observed weak negative correlations in the outer rings.

5.3. Economic Level

A strong positive or negative correlation exists between Economic Level and children's outdoor physical activity environment quality, and the spatial heterogeneity is relatively weak. Most indicators exhibit globally consistent correlations, with few areas showing significant deviation (Figure 10).

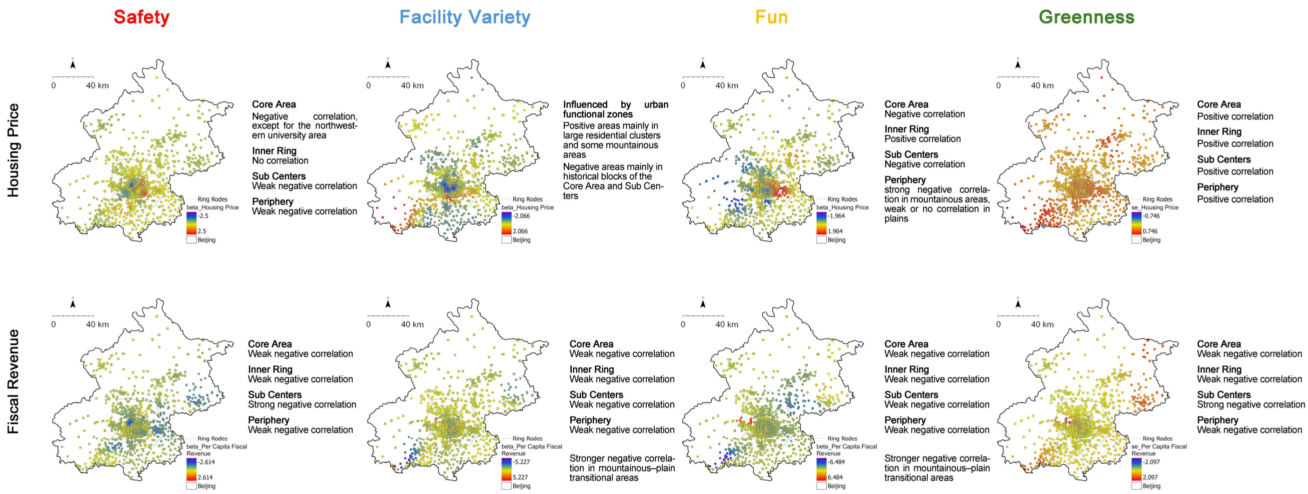

Figure 10. GWR regression results of Economic Level and children's outdoor activity environment quality.

5.3.1. Housing Price

Housing Price exhibits a moderate positive or negative correlation with outdoor physical activity environment quality. The correlation with the Safety and Fun dimensions shows distinct concentric zone differences, while the association with Facility Variety and Greenness displays little spatial variation across the metropolitan area. Specifically, Housing Price is strongly positively correlated with Safety in the Core Area. The correlation is insignificant in the Inner Ring and weakly negative in Sub-Centers. For Facility Variety, the correlation pattern alternates negative in the Core Area, positive in the Inner Ring, and negative again in Sub-Centers. The association with Fun fluctuates across the city, being positive in large residential communities and some mountainous areas, but negative in Core Area historical districts and Sub-Centers. Housing Price is positively correlated with Greenness across the entire area.

The influence of Housing Price on children's outdoor physical activity quality is highly location and urban function dependent. In the Core Area, high Housing Prices are associated with lower Facility Variety and Fun due to scarce land and the prioritization of high value projects, such as commercial offices and school district housing, which severely limits public outdoor physical activity spaces [86,87]. Conversely, in the Inner Ring and Sub-Centers, high Housing Prices correlate with higher Safety, Facility Variety, and Fun, reflecting refined urban planning, preferential public resource allocation, and high quality private outdoor facilities. This price filtering effect often confines lower income families to less developed areas, where environmental quality is lower [88,89]. In the Periphery, Housing Prices are shaped more by natural and ecological resources than public services, providing limited improvement for children accessible outdoor spaces.

5.3.2. Fiscal Revenue

The relationship between Fiscal Revenue and children's outdoor physical activity environment quality is relatively consistent across the city and largely shaped by topography. Fiscal Revenue exhibits a generally negative association with Safety across all areas. This negative relationship also extends to Facility Variety and Fun, particularly in the Sub-Centers and the transitional areas between mountains and plains. In contrast, the Greenness dimension and Fiscal Revenue show a stronger positive correlation in the Sub-Centers than in other areas.

This pattern reflects the regional differentiation in Fiscal Revenue allocation and its effects on children's outdoor physical activity environments. Sub-Centers show stronger negative effects may be due to fiscal focus on large scale infrastructure and industrial development. Facility Variety and Fun are constrained in mountainous plain transitional areas, where complex terrain and high development costs direct resources toward basic needs rather than engaging outdoor physical activity spaces [90]. In contrast, Greenness benefits from targeted fiscal support, particularly in Sub-Centers, where investments in parks, ecological corridors, and suburban green spaces enhance the quality of the outdoor green environment for children.

6. Discussion and Conclusions

Using Beijing as a case study, this study systematically evaluates the spatial distribution of quality and equality in children's outdoor physical activity environments at the metropolitan scale and examines their respective associations with metropolization. Firstly, the study introduces a user-centered evaluation framework by integrating four key dimensions: Safety, Facility Variety, Fun, and Greenness. This approach expands the assessment from single indicators to a more comprehensive, multi-dimensional system, which is also designed to be highly replicable in other contexts.

While the distribution of fundamental physical activity equipment for children in Beijing is relatively equal, the inequality analysis uncovers a significant deficit in the quality and provision of facilities designed to meet more advanced needs. Analysis using the Gini coefficient and Moran's I showed Safety and Facility Variety were relatively equal, whereas Fun and Greenness exhibited significant inequalities. Specifically, studies in other cities consistently find that green space accessibility is unequal and declines from the urban core to the periphery [91]. Economically affluent areas tend to have greater green exposure, a phenomenon that aligns with current research findings in Beijing. [22,56,92,93]. The study thus contributes supplementary evidence to these global discussions on school environment equality.

Furthermore, the GWR analysis demonstrated that environmental quality exhibits significant spatial heterogeneity closely coupled with Beijing's "core–periphery" metropolitan structure. This suggests that the observed inequalities in children's outdoor physical activity environment quality are not solely driven by differences in regional economic development [22] or service facility provision [94]. Crucially, these findings reveal that the associations between urban development and environmental quality are highly context-dependent. It implies that the influence of key factors is structurally conditioned by the zone's location, meaning the metropolitan structure acts as a defining spatial context that shapes these relationships. Specifically, significant disparities persist between core and peripheral areas, as well as urban centers and suburban zones, reflecting differences in development history and urbanization level [32,95].

Methodologically, by verifying the strong spatial non-stationarity of environmental determinants, this study highlights the limitations of standardized planning standards. It validates the necessity of a spatially differentiated governance approach, where policy interventions are tailored to the specific structural characteristics of the Core and Periphery, rather than applying a uniform logic. As metropolitan development shifts from incremental expansion to stock optimization [96–98], enhancing the quality and equality of children's outdoor activity environments requires flexible optimization and spatially differentiated strategies. Highly unequal indicators, such as the number of informal sports spaces and campus-specific sports facilities should be addressed first, as they require low investment [99], are less constrained by fixed spatial structures, and can yield substantial equality gains. For environmental factors with limited spatial adjustability, such as natural space accessibility. equality can be improved indirectly by introducing alternative measures like increasing neighborhood tree coverage [100].

Spatially, differentiated priorities should be adopted according to metropolitan structure:

(1) In Core Areas, priority should be given to micro-renovations and efficient land use. High density, congestion, and limited public space restrict children's outdoor activities. Strategies such as point-based micro-updates, multifunctional activity spaces, and vertical greening can enhance facility variety, playfulness, and green access. Improving safety around campuses, particularly in high-traffic areas, is also essential [101–103].

(2) In Inner Ring areas, the focus should be on integration and spatial relief. Although land is relatively sufficient, facilities are limited, and activities lack diversity. Strategies include adding service-oriented facilities, diversifying activity types, and linking green spaces with children's activities. Building an open-space network with the core area can further ease spatial pressure.

(3) In Sub-Centers, the focus should be on diversification. With sound infrastructure, good environmental quality, and abundant ecological resources, these areas provide favorable conditions for high-quality outdoor spaces. Strategies should make use of the ecological base and modern facilities to introduce eco-friendly and green functions, thereby supporting varied and nature-oriented activities [104].

(4) In Periphery, the priority is support and enhancement. Due to remoteness, weak transport links, and limited public services, children's face shortages of outdoor spaces, often outdated and uniform. Greater financial investment is needed to improve school environments and build sports facilities, while introducing diverse activity spaces can boost engagement and playfulness [105].

This study has several limitations. First, this study primarily focuses on the quantity and quality of facilities relied on environmental indicators; however, the transition from infrastructure supply to active utilization is often mediated by socioeconomic factors. Future research should take children's participation or subjective experiences into account. This is essential for developing more targeted intervention policies for vulnerable groups. Second, while this study analysis identifies disparities based on spatial coverage, the actual benefit of sports fields and play areas in high-density areas may be diminished by crowding. In addition, the indicator system focuses primarily on the 2D layout of cities. Future research should incorporate more human-centered indicators. Third, the current research focuses mainly on Beijing, a city characterized by a typical transition from a monocentric to a polycentric urban structure. Future work should expand the scope to include additional cities with similar or contrasting characteristics for comparative analysis.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land15050748/s1, Figure S1. Evaluation results for the 10 indicators across the four dimensions of children's outdoor physical activity environment quality;

Table S1. VIF test; Table S2. OLS results for the impact of metropolization level on the four dimensions of children's outdoor physical activity environment quality; Table S3. GWR β coefficients for the effect of metropolization level on the four dimensions of children's outdoor physical activity environment quality; Table S4. Model performance comparison: OLS vs. GWR.

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