

Evaluating Urban Green Spaces for Urban Heat Island Mitigation Effects in the Yangtze River Delta

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Abstract: The urban heat island (UHI) effect is a prominent environmental issue constraining the sustainable development of the Yangtze River Delta urban agglomeration (YRD), and green space construction is a critical approach to mitigating this effect. Based on panel data from 41 prefecture-level cities in the YRD across eight selected years between 2000 and 2020, this study constructs a multi-dimensional green space evaluation system encompassing scale, quality, and pattern, then employs a two-way fixed effects model to analyze its impact on UHI intensity. The findings reveal that green space coverage and vegetation quality exert significant negative effects on UHI mitigation, with each unit increase in green space coverage associated with an average reduction of approximately 0.54°C. In contrast, landscape pattern indicators (patch density and edge density) are positively correlated with UHI effects, indicating that, at the scale of the YRD urban agglomeration, the spatial aggregation and shape regularity of green spaces do not enhance cooling effects. This study provides a scientific basis for mitigating UHI effects through optimizing green space scale and vegetation quality in the Yangtze River Delta and similar highly urbanized regions, offering valuable insights for improving urban green space planning.

1. Introduction

The urban heat island effect is one of the severe environmental issues arising from urbanization [1]. The Yangtze River Delta urban agglomeration (YRD), as one of China's most economically dynamic and highly urbanized regions, is confronting numerous risks posed by the UHI effect to urban development [2]. Various strategies exist to mitigate the UHI effect, among which urban green space construction is a crucial measure [3]. Consequently, the relationship between urban green spaces and the UHI effect has become a research hotspot [4].

Early studies on the association between urban green spaces and the UHI effect primarily focused on overall quantitative characteristics of green spaces, examining relationships between indicators such as green space area and layout with the UHI effect. Some studies specifically identified threshold effects, noting that after green space area exceeds 10⁶ m², the marginal cooling effect of urban green spaces gradually diminishes [5]. With the advancement of remote sensing technology, increasing attention has been directed toward the role of green space quality in UHI mitigation, with remote sensing indices such as the Normalized Difference Vegetation Index (NDVI) widely employed to assess green space quality. Existing research has found that cooling magnitudes in areas with high NDVI are significantly greater than those in low-NDVI areas [6]. As research deepens, scholars have expanded their focus to include green space pattern

characteristics, investigating the pathways through which urban green space scale, shape, and spatial patterns influence the UHI effect. For instance, analyses of blue-green landscape patterns using indicators such as the largest patch index and mean patch area have revealed that higher green space dominance and lower landscape fragmentation enhance cooling effects [4]. Other studies indicate that green space area and the largest patch index are two of the most critical landscape pattern factors affecting the urban thermal environment, with higher landscape fragmentation intensifying warming effects, while greater aggregation of green space patches amplifies cooling effects [7]. Furthermore, most current research centers on individual cities, with relatively few studies addressing urban agglomerations due to challenges such as complex spatial heterogeneity and difficulties in cross-scale data integration.

In summary, although existing studies have reached a consensus on the mitigating role of urban green spaces on the UHI effect, research gaps remain. These gaps primarily manifest in two aspects: first, a lack of multi-dimensional studies on how green spaces jointly influence UHI mitigation, with limited comprehensive consideration of the differential effects of green space scale, quality, and pattern; second, a scarcity of long-term dynamic correlation analyses between green space indicators and UHI effects at the urban agglomeration scale. Therefore, this study analyzes indicators such as green space ratio and edge density across the YRD from 2000 to 2020 (selecting eight-time nodes), aiming to quantify the combined effects of multiple indicators and

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provide scientific support for further exploring the contribution of urban green spaces to UHI mitigation.

2. Materials and methods

2.1 Study Area

The YRD, as a typical region of rapid urbanization, exhibits representative associations between urban green spaces and the urban heat island effect. This study selects prefecture-level administrative units within the YRD in China as the study area, encompassing Shanghai Municipality and a total of 41 prefecture-level administrative units under the provinces of Jiangsu, Zhejiang, and Anhui. The study area is shown in Figure 1.

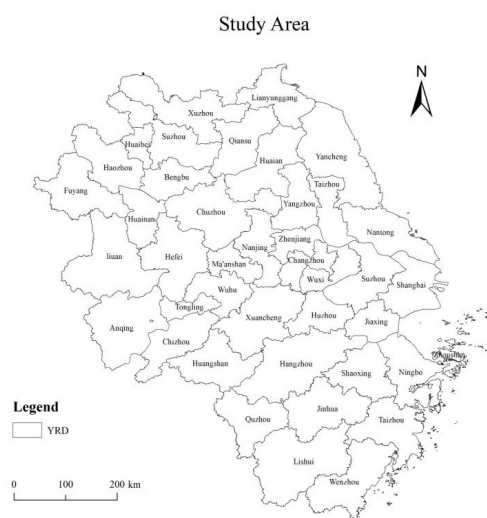


Figure 1. Map of study area in YRD, China

2.2 Data Sources

The study period covers eight specific years: 2000, 2005, 2008, 2010, 2013, 2015, 2018 and 2020. Greenspace data and urban boundary vector data are derived from the China Multi-Period Land Use Remote Sensing Monitoring Dataset (CNLUCC, <https://www.resdc.cn/DOI/DOI.aspx?DOIID=54>).

Forestland and grassland are selected as green space components, while urban land is used to delineate urban boundaries. Temperature data are obtained from the Global 1 km Universal Thermal Climate Index dataset (GloUTCI-M) developed by Yang et al. (GloUTCI-M, <https://zenodo.org/records/8310513>).

Normalized Difference Vegetation Index data are sourced from NASA’s MODIS (MODIS, <https://modis.gsfc.nasa.gov/data/dataproduct/mod13.php>).

2.3 Construction of Relevant Variables

2.3.1 Construction of an Urban Green Space Evaluation Indicator System

A multi-dimensional evaluation of urban green spaces is conducted using four indicators that reflect overall scale,

quality, and spatial pattern: green space ratio (GSR) captures total extent, NDVI represents vegetation growth conditions, and patch density (PD) together with edge density (ED) describe the spatial distribution characteristics and morphological complexity of green spaces. Indicators are standardized using formulas for positive indicators (e.g., GSR, NDVI) and negative indicators (e.g., PD, ED — higher values typically indicate less favorable patterns), as follows:

$$\text{For positive indicators: Standardized value} = \frac{(A - \min)}{(\max - \min)}$$

$$\text{For negative indicators: Standardized value} = \frac{(\max - A)}{(\max - \min)}$$

Indicator weights reflect the relative importance of each indicator and significantly affect the accuracy and reliability of evaluation results. This study combines subjective and objective weighting methods: subjective weights are assigned via equal weighting, while objective weights are derived using the entropy method. The results are presented in Table 1 below:

Table 1. The list of variables and weights

Variable	Final Weight	Entropy Weight	Calculation Method
GSR	0.3872	0.5245	(Total green space area) / (Total urban area)
NDVI	0.1301	0.0103	Regional mean NDVI value
PD	0.2046	0.1591	(Total number of green space patches) / (Total urban area)
ED	0.2781	0.3061	(Total green space perimeter) / (Total urban area)

It should be noted that the comprehensive urban green space evaluation index developed in this study is not intended for subsequent regression analysis, but rather serves descriptive spatial analysis (see 3.1 and Figure 6). Its primary purpose is to visually present the multidimensional spatial patterns of urban green spaces in the YRD, revealing their north-south differentiation and evolutionary trends. When identifying the specific mechanisms by which green spaces influence the heat island effect, this study employs single-indicator regression (see 3.2). This design is based on the following considerations: While using a composite index for regression could test the overall impact of green spaces, it would fail to distinguish whether the effects stem from scale expansion, quality improvement, or spatial optimization – the key mechanisms this study aims to elucidate. The use of single indicators helps clarify the differentiated contributions of green space scale, quality, and spatial configuration to heat island intensity, thereby avoiding the masking of heterogeneous effects among variables by a composite index.

2.3.2 Calculation of Heat Island Intensity

Heat Island Intensity (HII) is a core metric for quantifying the UHI effect. Based on land use data, this study extracts raster cells corresponding to “urban construction land” and “rural land,” and calculates the mean land surface temperature (LST) for each type. HII is then derived as the

difference between the mean temperature of urban areas and that of rural areas, expressed as:

$$HII = \overline{LST_{urban}} - \overline{LST_{rural}}$$

where $\overline{LST_{urban}}$ and $\overline{LST_{rural}}$ denote the mean land surface temperature of urban and rural areas, respectively, during the study period.

2.4 Regression Models

This study employs a panel data two-way fixed effects model. The baseline model is specified as follows:

$$HII_{it} = \beta_0 + \beta_1 Green_{it} + \mu_i + \lambda_t + \varepsilon_{it}$$

where HII_{it} represents the mean heat island intensity of city i in year t . $Green_{it}$ denotes the core independent

variable, sequentially substituted with GSR, NDVI, PD, and ED. μ_i represents city-specific fixed effects, controlling for time-invariant intrinsic characteristics such as geographical location and topography. λ_t represents year fixed effects, controlling for time-varying shocks common to all cities, including climatic fluctuations and macroeconomic policies; and ε_{it} is the random error term.

3. Results

3.1 Comprehensive Evaluation of Green Spaces in the YRD

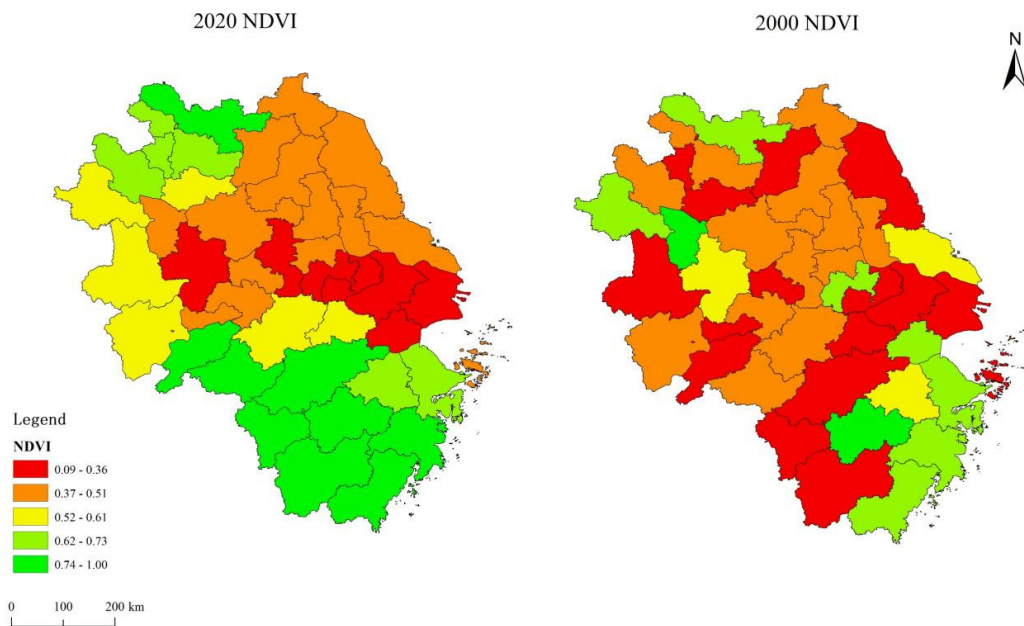


Figure 2. Temporal and spatial changes of NDVI in the YRD in 2020 and 2000

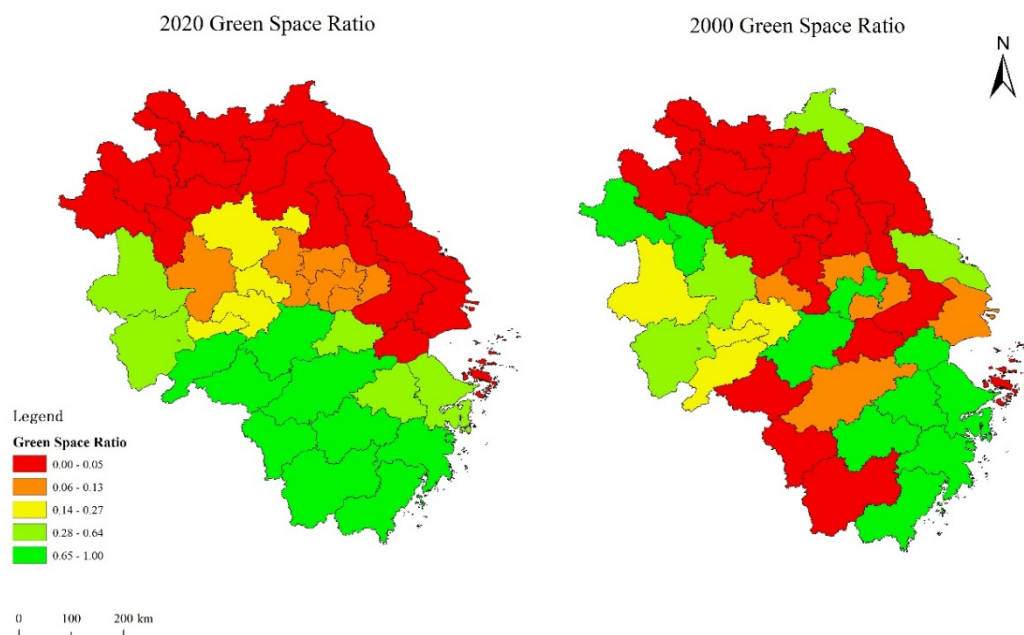


Figure 3. Temporal and spatial changes of green space ratio in the YRD in 2020 and 2000

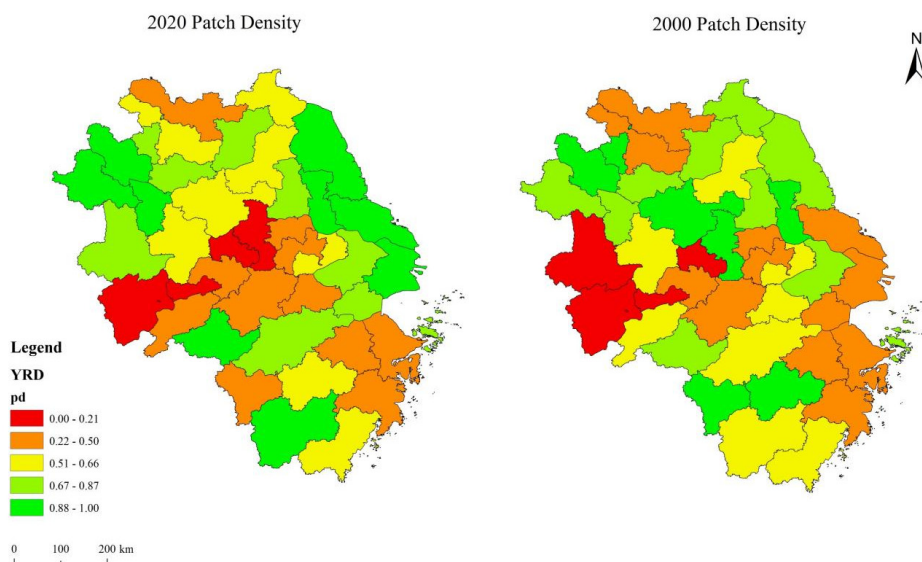


Figure 4. Temporal and spatial changes of patch density in the YRD in 2020 and 2000

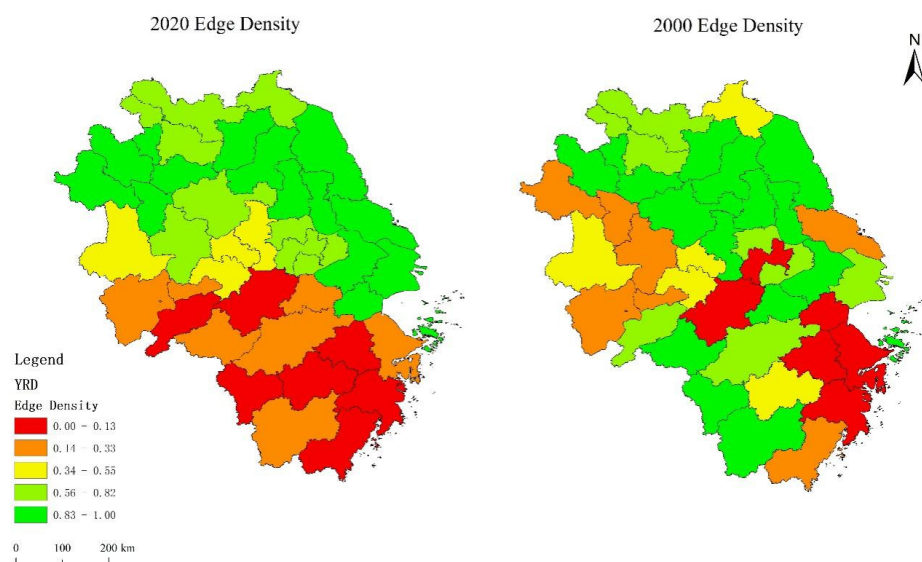


Figure 5. Temporal and spatial changes of edge density in the YRD in 2020 and 2000

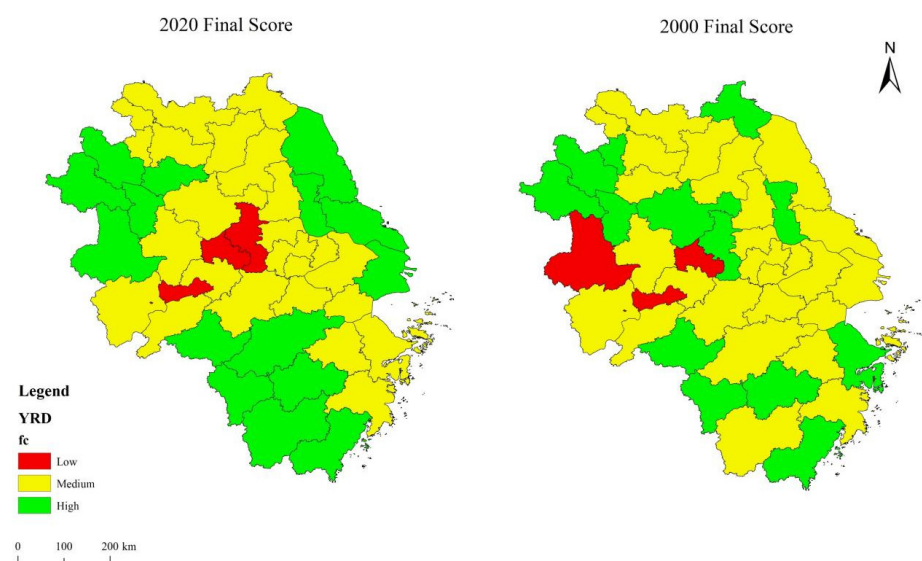


Figure 6. Temporal and spatial changes of final comprehensive scores in the YRD in 2020 and 2000

Significant spatial heterogeneity exists in various green space indicators across the YRD, and it is broadly characterized by a north–south gradient: landscape pattern indicators are lower in the south and higher in the north, while green space quality and quantity are higher in the south and lower in the north. NDVI data reveal that from 2000 to 2020, the vast majority of cities exhibited an upward trend in NDVI (Figure 2). High NDVI values are concentrated in the southern YRD, represented by mountainous cities in southwestern Zhejiang (e.g., Lishui) and southern Anhui (e.g., Huangshan), where NDVI has remained consistently high and increased markedly. In contrast, NDVI values in parts of central and northern YRD as well as core cities (e.g., Suqian, Fuyang, and Shanghai) are generally lower and have increased slowly. Lishui recorded the highest NDVI value in 2020, while Nanjing had the lowest in 2010. GSR shows a distinct low-to-high growth trend in the mountainous cities of the southwestern YRD (Figure 3). The data indicate pronounced inter-city disparities in green space ratio: cities in southern Anhui and western Zhejiang, such as Huangshan, Lishui, and Chizhou, have persistently high GSR, whereas cities like Shanghai and Fuyang remain at very low levels. Lishui had the highest GSR in 2000, while Fuyang recorded the lowest. The high NDVI and GSR values observed in mountainous cities may be attributable to their advantageous ecological environments, whereas core cities may exhibit lower values due to intensive development, rapid urbanization, and industrialization.

In terms of landscape pattern, PD changed little in most cities over the study period and remained generally stable (Figure 4). Geographically, low PD values are mainly concentrated in cities along the Yangtze River, such as Nanjing, Wuxi, and Ningbo, which may reflect patch coalescence under high urbanization and intensive land consolidation. By contrast, most peripheral cities and those in northern Anhui, such as Bozhou and Fuyang, persistently exhibit high values. Interannual fluctuations in ED are generally small and remain within a narrow range (Figure 5). Higher ED values in northern and central YRD cities, such as Xuzhou and Yancheng, may be related to dense linear artificial boundaries (e.g., roads and field ridges) that increase the green space edge. Southern and western mountainous cities, such as Lishui and Huangshan, exhibit relatively low ED, possibly due to strong landscape continuity and low boundary complexity in natural forest land. The comprehensive evaluation results of urban green spaces (Figure 6) indicate that the overall green space level in YRD cities has gradually exhibited a spatial distribution pattern characterized by low values in the central region and high values in the surrounding areas. Between 2000 and 2020, the comprehensive green space level of prefecture-level cities remained relatively stable, with limited fluctuation in the number of cities classified into high, medium, and low intervals. In 2000, low-scoring cities were scattered across northern and central Anhui (e.g., Fuyang, Bengbu, Hefei), exhibiting low comprehensive green space levels; high-scoring cities were concentrated in southwestern Zhejiang and southern Anhui. By 2020, low-scoring cities had contracted and clustered in central Anhui, with Hefei ascending to a medium level, thereby intensifying spatial

differentiation; high-scoring cities remained steadily distributed in peripheral ecological barrier areas. Lishui, Huangshan, and Hangzhou consistently achieved high-level comprehensive scores, primarily benefiting from high GSR and NDVI values. In contrast, low-scoring cities (e.g., Fuyang, Bengbu) are generally constrained by relatively low GSR and NDVI values; even when pattern indicators are not disadvantageous, their overall scores remain difficult to raise, suggesting that quantity and vegetation quality are the binding constraints in these contexts.

3.2 Analysis of Green Space Mitigation of the Urban Heat Island Effect in the YRD

The effects of various urban green space indicators on HII exhibit pronounced divergence, manifesting centrally as significant mitigating effects of green space scale and vegetation quality, alongside positive associations between landscape pattern indicators (PD, ED) and heat island intensity. GSR exerts the most significant negative impact on heat island intensity (coefficient: -0.54), indicating that each unit increase in green space coverage corresponds to an average reduction of approximately 0.54 °C in heat island intensity. The vegetation index likewise demonstrates a significant negative effect (coefficient: -0.024), suggesting that improved vegetation growth conditions contribute to UHI effect mitigation, albeit with a smaller unit effect than green space ratio. Notably, standardized negative indicators demonstrate that higher PD values indicate lower original PD (i.e., more clustered green spaces), while higher ED values suggest lower original ED (i.e., more regular-shaped green spaces). The coefficient for PD is highly significant at 0.10, this result implies that a decrease in patch density unexpectedly leads to an increase in heat island intensity. The coefficient for ED is 0.17, which signifies that reduced ED and more regular patch shapes are associated with weaker cooling — indicating that irregularly shaped green spaces provide superior cooling effects. The R² values of all models approach 0.98, indicating that the models demonstrate exceptional explanatory power for heat island intensity. The high goodness-of-fit reflects the rationality of the model specifications and confirms the reliability of the model's estimation of the relationship between green space indicators and heat island intensity. The regression results for each indicator are reported in Table 2.

Table 2. Regression results of the impact of green space indicators on heat island intensity

Variable	(1) Green Space Ratio	(2) NDVI	(3) Patch density	(4) Edge density
HII	-0.54265*** (-0.14084)	-	-	-
HII	-	0.02356*	-	-
HII	-	(-0.01032)	-	-

			0.1010 2***	
HII			(- 0.0370 9)	
			0.17471 **	
HII			(- 0.06625)	
Cons	20.14023*** (3.97076)	6.00282* (0.50867)	- 1.3044 5 (2.2564 8)	- 15.1257 0** (6.46506)
City FE	√	√	√	√
Year FE	√	√	√	√
Observations	328	328	328	328
R ²	0.977	0.976	0.978	0.981

Standard errors in parentheses = “* p < 0.10, ** p < 0.05, *** p < 0.01”.

Note: Both PD and ED underwent negative normalization, with their values increasing corresponding to reduced original PD and reduced original ED, respectively.

In summary, this study finds that the mitigating effect of urban green spaces on the urban heat island effect primarily depends on their coverage scale (GSR) and growth quality (NDVI), both of which contribute significantly, with green space coverage serving as the dominant factor. During urbanization, prioritizing the enhancement of green space coverage area and vegetation ecological quality constitutes a direct and effective core strategy for mitigating the urban heat island.

4. Discussion

This study reveals that the “quantity” and “quality” of green spaces are the primary factors mitigating the UHI effect, and their influence considerably outweighs that of spatial layout and morphology. This finding suggests that, under the growing constraint of urban land scarcity, prioritizing the absolute area of green spaces and the health of vegetation delivers more direct cooling benefits than merely optimizing the distribution and shape of green spaces [8]. We also observe that landscape aggregation and shape regularity are associated with increased HII — a result that partially diverges from the prevailing view in previous studies that “higher aggregation and more compact shapes of green space patches enhance cooling effects.” This discrepancy implies that, across different study scales (e.g., individual city, urban agglomeration, or national scale), the influence of green space spatial structure on the heat island effect may involve more complex mechanisms [9].

The comprehensive evaluation results for urban green spaces increasingly exhibit a spatial pattern characterized by “low in the center, high in the periphery.” High-scoring cities — such as Shanghai and Hangzhou — benefit primarily from sustained and substantial investment in green space construction, favorable vegetation baselines, and the implementation of relevant ecological policies, all of which have significantly improved both the quantity

and quality of their green spaces. In contrast, cities like Nanjing, Ma’anshan, and Tongling likely scored lower because they were undergoing rapid urbanization or industrialization during the study period: while urban construction land expanded swiftly and encroached upon ecological space, newly added green spaces suffered from insufficient area, poor quality, and fragmented layout [2]. Overall, these contrasts reinforce a practical implication for highly urbanized regions: UHI mitigation depends primarily on safeguarding green-space extent and vegetation health, while also avoiding excessive fragmentation and maintaining functional connectivity of green resources.

5. Conclusion

By constructing an integrated analytical framework that combines GIS, landscape metrics, and panel modeling, this study conducts a spatiotemporal analysis of the YRD urban agglomeration. The main findings are as follows: First, the key to mitigating the UHI effect lies in enhancing the “quantity” and “quality” of green spaces. An increase of one unit in GSR can reduce heat island intensity by approximately 0.54 °C, establishing its dominant contribution; improvements in vegetation growth conditions (NDVI) also yield significant cooling benefits. Second, landscape pattern indicators (PD, ED) are positively correlated with HII, indicating that, at the urban agglomeration scale, the aggregation and shape regularization of green space patches do not produce stronger cooling effects.

This study is limited by the spatial dimension and accessibility of the data, and the model failed to incorporate socioeconomic variables such as population density and energy consumption, which restricts the in-depth exploration of the cooling mechanism of green spaces in cities of different types. Future research can focus on improving the data and, based on this, explore more sophisticated model algorithms to analyze more complex spatial patterns, thereby revealing the heterogeneous mechanisms of how blue and green spaces mitigate the heat island effect under different external environments. For urban planning, future construction should focus on enhancing the spatial quality and ecological connectivity of ecologically advantageous areas. For high-density built-up areas, the shortage of green space should be compensated through urban renewal, vertical greening, and other diverse approaches, so as to improve the comprehensive efficiency of urban ecological spaces.

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