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A Study on Spatial Differentiation of Landscape Pattern Based on Three-Dimensional Morphology of Urban Buildings

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Abstract

Urban buildings are an important part of urban morphology, and building height has an important impact on the three-dimensional spatial morphology of cities. At present, research on the two-dimensional morphology of cities is relatively abundant, but there are fewer studies on the characteristics of the three-dimensional undulating morphology of cities and their spatial distribution patterns, and thus knowledge of the degree of utilization of the airspace above the city and its developmental pattern is still relatively lacking.Based on the multi-scale urban agglomeration, the landscape pattern is converted from two-dimensional to three-dimensional, and the overall spatial differentiation can be analyzed more intuitively. The purpose of this paper is to explore the three-dimensional spatial differentiation law of urban architectural landscape pattern. Through in-depth spatial analysis of the architectural landscape in urban areas, it is found that the landscape patterns in different areas show significant differences, and the interrelationship between them and the urban landscape pattern is revealed through the study of three-dimensional characteristics of urban buildings, such as height, density, form and layout. It is found that the different characteristics of urban buildings have a significant impact on the landscape pattern, which leads to the differentiation of urban space. This study provides more comprehensive spatial information for urban planning, contributes to a better understanding of the complexity of urban architectural landscapes, and provides a scientific basis for future urban design and planning.

1. INTRODUCTION

Urban landscape is one of the most complex and spatially heterogeneous landscapes. With the acceleration of urbanization process and the continuous growth of urban population, the contradiction of insufficient space and resources is becoming more and more prominent, and the horizontal expansion of the city can no longer satisfy the current demand, resulting in the continuous expansion of the city in the vertical direction. Traditionally, the study of urban landscape pattern usually starts from the two-dimensional plane perspective, focusing on its landscape composition, pattern evolution and its driving force, spatial heterogeneity, etc., while the city as a highly complex space, simply limiting the spatial pattern to two dimensions will result in partial loss of information and one-sided reconstruction of the spatial pattern.Therefore, a more reasonable and effective urban landscape pattern should cover both planar and three-dimensional dimensions, i.e. three-dimensional urban landscape pattern.Overseas scholars have found that three-dimensional urban landscapes will play an important role in future urban development and planning(Domingo Darío,2023).Maosu Li (2023)proposed a bi-objective analysis of 3D visualization of high-rise, high-density neighborhoods with physical-natural exposures to built landscapes for a holistic assessment to identify buildings and urban neighborhoods with low priority landscape management and urban planning values.Wenjing Ren (2021)adopted two new architectural landscape metrics - landscape height variable coefficient and building roughness index - for landscape pattern analysis, while a rigorous and comprehensive three-dimensional architectural landscape metrics system was established using principal component analysis.Some scholars focus on the dynamic simulation of urban 3D landscape, while others focus on the study of 3D visualization of urban landscape(Jun Yang,2017). Yimin Chen (2022)improved the 3D metacellular automata model of urban spatial growth and analyzed the law of 3D urban spatial growth.Peifeng Zhang(2019) used principal component and regression analysis to study the impact of regional socio-economic development on three-dimensional architectural landscape, constructed a three-dimensional urban landscape pattern index, and analyzed the changes in three-dimensional architectural landscape at different spatial scales and their driving mechanisms.The acquisition of urban 3D information is the premise and foundation of urban 3D landscape research. As an important carrier of urban material space, architecture is the core element of urban landscape(Jian Guo et al. 2017; Bekele Neway Kifle et al. 2022; Li Zhen et al. 2022).To summarize, city is the gathering place of human social life, as a geographical complex of population, resources, environment and socio-economic factors, city is closely related to people's life. Landscape pattern determines the form of distribution of resources and environment in the landscape and influences the landscape ecological process, which is the key content of environmental issues and one of the hot spots of current domestic and international research. Urban landscape pattern reflects the shape of the city, including the layout, density, land use type and architectural style of the city. The spatial organization describes the relative position and relationship between different elements in the city, including the distribution of various types of land, the organization of road network, and the arrangement of buildings. Good design and management of urban landscape patterns are crucial to the livability, sustainability and development of cities. Urban planners and designers need to consider various factors comprehensively in order to create an organic and unified urban landscape pattern.

This paper takes Harbin City, Heilongjiang Province as an example, takes the urban three-dimensional architectural data as the basis, combines the landscape pattern index to quantify the urban three-dimensional landscape pattern in the study area, and adopts the spatial analysis methods of spatial autocorrelation, average nearest-neighbor distance, and multi-distance spatial clustering to analyze the architectural type and spatial pattern of the study area, combines the qualitative and quantitative methods, and explores the spatial differentiation characteristics of the urban three-dimensional landscape pattern in the study area from different perspectives, and the results of the study can provide the scientific basis for the reasonable adjustments of the urban renovation and planning, and can provide certain valuable references and suggestions for the rational improvement of the city's landscape pattern.

2. STUDY POPULATION AND DATA SOURCES

2.1 Overview of the study area and data sources

Harbin is located between longitude 125° 42'~130° 10'and latitude 44° 04'~46° 40'N. It is the capital of Heilongjiang Province, with a mid-temperate continental monsoon climate, and is known as the "Ice City". Harbin, as a study area, exhibits rich spatial heterogeneity in landscape patterns, and has formed a unique and diverse urban landscape due to its geographic location and climatic conditions.

All urban building blocks in the main urban area of Harbin City, Heilongjiang Province, totaling 66,576 buildings, were selected for the study. These buildings form a large and complex urban environment. The research data includes the urban building outline data of the main urban area of Harbin City, and the selection of the research object involves multiple administrative divisions, thus enabling a comprehensive examination of the different characteristics and development of the city. In order to understand and analyze this group of urban buildings more comprehensively, the study goes deeper in the following aspects: detailed characterization and categorization of these urban buildings, such as building types and building heights. This helps to understand the spatial differentiation characteristics of the landscape pattern of urban buildings. Consider the environmental impacts of urban buildings, including plot ratio, building density, etc.; in order to assess the sustainability impacts of urban buildings on the environment. The above aspects of the study will help to comprehensively understand the urban building community in Harbin and provide a scientific basis for urban planning, sustainable development and socio-economic development. At the same time, it also provides methods and experiences for similar studies in the future.

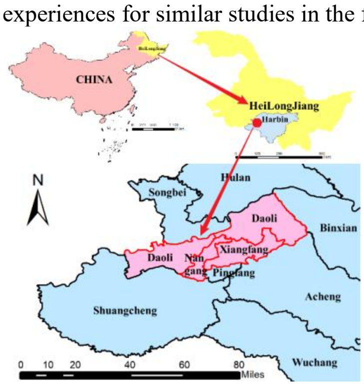

Figure 1. Location of study area

3. SPATIAL DIFFERENTIATION OF LANDSCAPE PATTERNS IN THREE-DIMENSIONAL FORMS OF URBAN BUILDINGS

3.1 Research flow chart

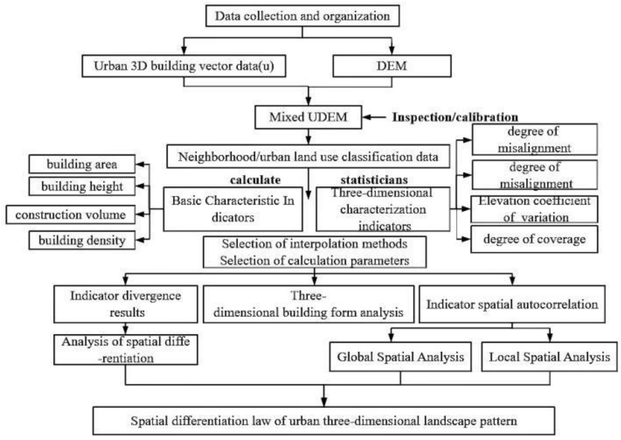

Figure 2.Flowchart of the method of this paper

3.2 A study of spatial differentiation of urban three-dimensional architectural forms

3.2.1 Construction of Quantitative Indicators for Urban Three-Dimensional Architectural Morphology

The three-dimensional architectural form of the city is a unique form formed after the transformation of the natural ground surface by human social activities, and its vertical spatial characteristics are the spatial reflection of the city's historical process, stage and level of development. At the same time, it is also the projection of the city's economic structure, social composition and functions in the regional space. The complexity and variability of this spatial form are also the main features that distinguish it from the natural terrain. The construction of quantitative indicators of urban three-dimensional building form involves many aspects, including building height, volume, coverage, etc., which can help reveal the spatial characteristics and layout of urban buildings.

numerical	formulas	descriptive
Number of buildings(NB)	NB=N	Total number of buildings in the landscape
high occupancy rate(HBR)	$HBR = \frac{N_h}{N} \times 100\%$	Proportion of buildings exceeding 24 meters in height to the total number of buildings
Average projected area of buildings(MAPA)	$MAPA = TAPA / N$ TAPA is Total Architectural Projected Area	Average area of buildings projected vertically onto the ground
Average building height(MAH)	$MAH = \sum_{i=1}^{n} H / n$	Average height of all buildings in the study area
Standard deviation of building height(ADSH)	$AHSD = \sqrt{\sum_{i=1}^{n} (H_i - MAH)^2 / n}$	Degree of building variability in the study area
Building coverage(BCR)	$BCR = \sum F / A$ F is the building footprint and A is the area of the study area	Building density in the study area

floor area ratio(FAR)	$FAR = \sum_{i=1}^{n} (C \times F) / A$	Land development intensity in the study area
Landscape shape index(LSI)	$LSI = 0.25E / \sqrt{F}$ E is the total length of patch edges (building projections) within the unit Complexity of landscape shape	

Table 1. Urban three-dimensional landscape pattern index.

The basic characteristics of three-dimensional buildings are used to describe the most basic qualities of urban building groups in spatial form, including the average height and average volume of building groups, which reflect the degree of concentration of building groups in the city over the concentration of the trend. High heterogeneity is the main feature of studying the three-dimensional form of urban space, which is also different from the two-dimensional planar form, and the study of the heterogeneity of the height difference of urban architectural groups in space is the starting point for analyzing the three-dimensional architectural form of the city. The same kind of heterogeneous elements composed of different forms of buildings are distributed in urban space, and effective quantitative mathematical expressions need to be selected to respond to the height difference characteristics of building clusters.

The basic index of urban 3D building form is to describe the basic shape of the building in space, including height, volume, etc. The basic index is different from the combination of multiple characteristics, such as undulation and composition, which only consider one single characteristic of the building form. In contrast to the undulation and compositional indicators, which are combinations of multiple characteristics, the basic indicators only consider one single characteristic of the building form. At the same time, the surface morphology constituted by urban building groups is a discontinuous and discrete surface, which has obvious mutation characteristics. Therefore, in the process of extracting basic indicators, other factors are ignored and the characteristics of the indicators to be studied are abstracted as point objects, which not only can preserve the original characteristics of the indicators, but also facilitates the extraction and calculation of the indicators.

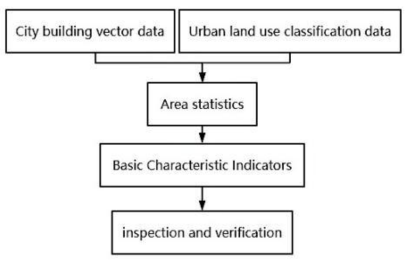

Figure 3. Calculation process for basic characterization indicators

3.2.2 Spatial autocorrelation analysis research methods

Spatial autocorrelation refers to the fact that the attributes (variables) of objects existing in the same area have some correlation with each other, and their correlation varies with the distance between these variables. Spatial autocorrelation is the first law of geography, which describes the degree of interrelationship or spatial dependence between data and variables in different spatial locations. The most important characteristic of spatially correlated things or phenomena is that the closer their spatial locations are to each other, the more similar they are. The most commonly used spatial autocorrelation methods include Moran's I, Geary's C, G-statistics and so on. Moran's I index is the most commonly used and matured in urban morphology research. Spatial autocorrelation is mainly categorized into global autocorrelation and local autocorrelation in applications.

Autocorrelation is a macroscopic description of the things or phenomena under study, showing the distribution of these things or phenomena in space in general, and focusing locally on portraying those areas where the nature is clustered. The most widely used measure at present is Moran's I.

$$Moran'sI = \frac{\sum_{i=1}^{n}\sum_{i=1}^{n} W_{ij}(Y_i - \bar{Y})(Y_j - \bar{Y})}{S^2 \sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}} \quad (1)$$

$$S^2 = \frac{1}{n}\sum_{i=1}^{n}(Y_i - \bar{Y}), \quad \bar{Y} = \frac{1}{n}\sum_{i=1}^{n} Y_i \quad (2)$$

Where Y represents the attribute value of the research unit, i and j represent different research domains, n is the total number of attribute values of the research unit, andW_{ij} denotes the spatial weight matrix corresponding to W, which is able to express the weight relationship between the two spatial locations of i and j. $\sum\sum W_{ij}$ is the total spatial weight, and S2 denotes the total variance in the dataset. $\sum\sum W_{ij}$ is the total spatial weight and S2 denotes the total variance in the data set. If Yi and Yj are both above or below the mean (on the same side of the mean), the covariance coefficient is greater than zero, on the contrary, if one of them is above and the other is below the mean (on both sides of the mean), the covariance coefficient is less than zero, and the absolute value of the result obtained from the calculation depends on the degree of proximity between Y and Wij = 1 if the region where i and j are located is spatially neighboring, and Wij = 0 if the region where i and j are located is not spatially neighboring.

In general, if most of the attribute values of the spatial neighborhood are simultaneously located on one side of the overall mean, it means that the spatial elements are positively correlated with each other and Moran's I is greater than zero, and vice versa Moran's I is less than zero. In practice, if the Z value of the normal statistic of Moran's I is greater than the critical value of the normal distribution function, it means that a certain type of attribute of the elements in the study area has strong spatial autocorrelation in space, and this type of attribute of this type of element appears to be clustered in this area.

$$I_i = \frac{n(x_i - \bar{x})\sum_j W_{ij}(x_j - \bar{x})}{\sum_i (x_i - \bar{x})^2} = \frac{nZ_i\sum_j W_{ij}Z_j}{z^T z} = Z_i' \sum_j W_{ij} Z_j' \quad (3)$$

Where: Zi and Zj are the attribute values of the computational units after normalization. The higher the local Moran's I, the higher the degree of spatial clustering in the region, i.e., there are many polygons with similar attribute values in the region, e.g., a concentration of high values or a concentration of low values.

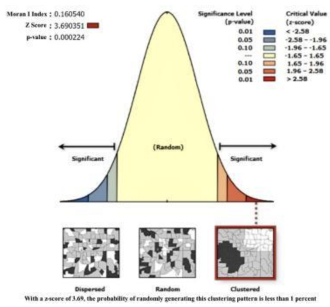

Figure 4. Spatial autocorrelation statement of the overall architectural ensemble in the main urban area of Harbin City

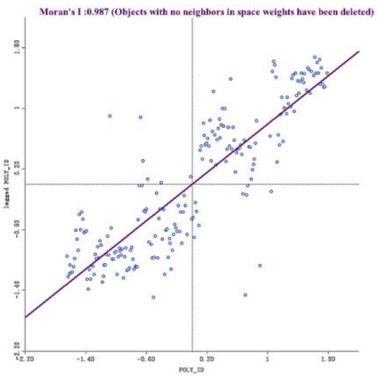

Figure 5. Scatterplot of the Moran Index

Z-score (standard deviation)	P-value (probability)	Confidence Level
<-2.58 or >+2.58	<0.01	99%
<-1.96 or >+1.96	<0.05	95%
<-1.65 or >+1.65	<0.10	90%

Table 2. Table of confidence levels corresponding to Z and P values.

From the above results, it can be seen that the Moran's I value of the dependent variable is greater than zero, with a p-value of 0.000224 (taking the significance level of a=0.01), which rejects the null hypothesis (no spatial correlation exists between the variables), and the z-value is 3.69>2.58, which is the possibility of randomly generating this clustering pattern is less than 1%, which indicates that there exists a very strong spatial Autocorrelation.

3.3 Statistical and architectural delineation of three-dimensional urban landscape patterns

Spatial differentiation is a method of statistical analysis of spatial variability that aims to identify specific features in spatial objects bounded by an administrative spatial unit. Spatial differentiation can be used to identify various types of positive and negative trends and has important applications especially in the decision-making process. Spatial differentiation accomplishes the visualization of spatial structure by calculating the characteristics of the distribution of each spatial unit and its variations in order to construct its values to characterize the spatial structure. Spatial relationships for interpretation and visualization can also be identified by calculating multivariate relationships and patterns between spatial variables.

Architecture is an important component of the urban landscape, and in the overall regional characterization of the architectural landscape, four indicators were selected from the two-dimensional level and the three-dimensional level. The indicators at the two-dimensional level include built-up area, building density, and the indicators at the three-dimensional level are volume ratio and building form factor.

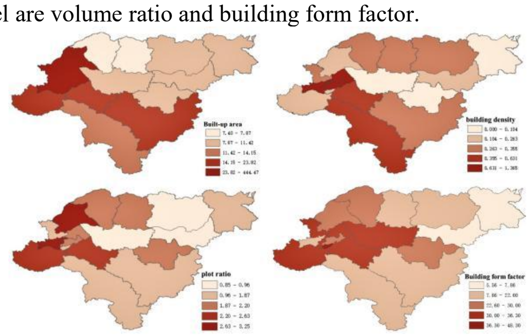

Figure 6. Harbin City Indicator Impact Factor Cluster Distribution

The clustering results based on the impact factor measurements show that the main urban areas of Harbin city show a higher trend in building density, floor area ratio and building area, which is relatively high compared to other urban areas, indicating that the land use in these areas is more compact and the building space is utilized more efficiently. This may reflect the central position of the main urban areas in urban development and the efficient utilization of land resources. The trend of high levels of building density, floor area ratio, and floor area may be due to their central position in the urban system and the concentration of demand for urban functions. Therefore, the measurement of relevant indicators for buildings in the main urban areas has higher accuracy and completeness of data because they usually have better urban planning and management systems. Therefore, choosing the data of the main urban area for the experiment can provide a more comprehensive understanding of the development status of the city and provide an important reference for urban planning and land use.

3.4 Point pattern analysis for multi-distance spatial clustering

Based on the multi-distance spatial clustering method, the point pattern was analyzed in depth. The complex spatial correlation and clustering characteristics of point elements were revealed by comprehensively considering the spatial distribution patterns under different distance scales. First, a multi-scale spatial clustering algorithm was used to cluster the point data in the study area, and the clustering results under different scales were obtained. Then, using spatial statistical analysis tools, the clustering results under each scale were analyzed in terms of point patterns, and the spatial distribution characteristics and clustering structure of point elements under different scales were explored. The results show that under the analytical framework of multi-distance spatial clustering, it is possible to understand the spatial distribution pattern and clustering pattern of point elements more comprehensively Visual coupling is a comprehensive observation and analysis m ethod in the study of urban architectural landscapes, aiming at a deeper understanding of the interactions between different visual elements and how they work together to shape the overall visual effect of the urban space.

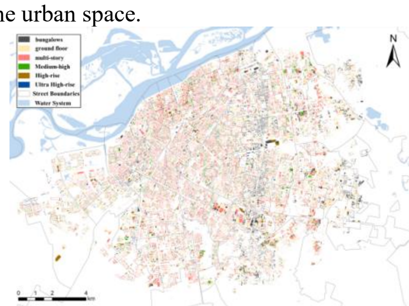

Figure 7. Schematic diagram of building height classification results

The spatial distribution pattern of point elements was thoroughly studied and analyzed by using a multi-distance spatial clustering method. First, point data in the study area, including but not limited to urban buildings, green spaces, water bodies and other elements, were collected. Then, a multi-distance spatial clustering algorithm was applied to cluster the point data by considering the spatial correlation at different distance scales. Then, through spatial statistical analysis tools, the clustering results under each scale were analyzed in terms of point pattern, revealing the spatial distribution characteristics and clustering structure of point elements under different scales. The results show that the analytical framework of multi-distance spatial clustering can provide a more comprehensive understanding of the spatial distribution pattern and clustering pattern of point elements, which provides an important reference basis for geographic information systems, urban planning and resource management.

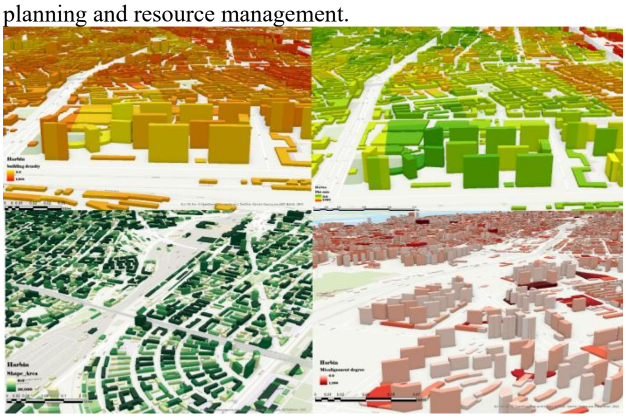

Figure 8. Spatial differentiation based on three-dimensional buildings in the main city of Harbin(a) Building density (b) Building floor area ratio (c) Building footprint (d) displacement

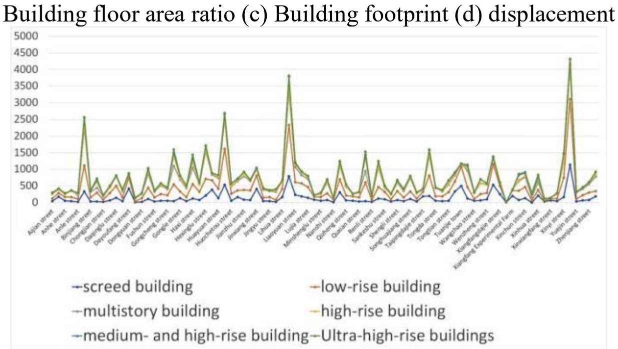

Figure 9. Building statistics for the core area

In the multi-distance spatial clustering distribution graph, the horizontal axis represents the distance d, the vertical axis represents K(d), the green line represents the expected value of K, the blue line represents the observed value of K, and the yellow line represents the confidence interval (99%). If the blue line is on the green line, it indicates that the building points are clustered within the distance, and if, on this basis, the blue line is on the confidence interval, it indicates that the building points are significantly clustered within the distance; on the contrary, if the blue line is under the green line, it indicates that the building points are dispersed within the distance, and if, on this basis, the blue line is under the confidence interval of the yellow line, it indicates that the building points are significantly discrete within the distance; other cases can be regarded as random distribution.

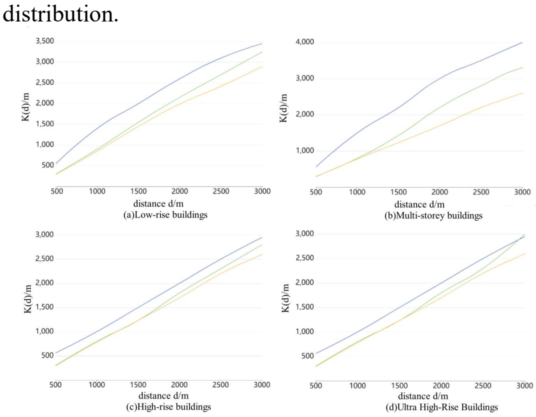

Figure 10. Multi-distance spatial clustering map of building points

As can be seen from Figure 10: all four types of building points show aggregated distribution within a certain spatial scale, and the order of aggregation is as follows: multi-storey buildings > low-rise buildings > high-rise buildings > ultra-high-rise buildings. The distribution pattern of ultra-high-rise buildings will be "aggregated-dispersed" with the increase of spatial scale. Figure 10(a) shows that the observed value of K for low-rise buildings is always higher than the expected value of K, and the observed value of K is higher than the confidence interval, which indicates that the distribution of low-rise buildings is always significantly aggregated, and basically has a linear trend of growth. Figure 10(b) shows that multi-storey buildings also always present a significant aggregated distribution. Figure 10(c) shows that high-rise buildings also always present a significant aggregated distribution state, and with a linear trend growth. In Fig. 10(d), when the distance of ultra-high-rise buildings is less than 2900 meters, the observed value of K > K expected value, at this time, the ultra-high-rise buildings in the spatial distribution of the aggregation state, while the distance is greater than 2900 meters, the observed value of K < K expected value, the spatial distribution of the performance of the discrete state. The spatial scale of the highest aggregation is the largest for low-rise buildings and multi-story buildings, followed by high-rise buildings and finally ultra-high-rise buildings. This spatial scale of the highest aggregation can provide a basis for the most suitable unit for urban planning and management.

4. CONCLUSION AND PROSPECT

Based on the three-dimensional building data in the core area of Harbin city, this paper explores the spatial differentiation characteristics of the three-dimensional landscape pattern of urban buildings in the core area by using the three-dimensional landscape pattern index, spatial autocorrelation of ArcGIS spatial analysis, the average nearest neighbor distance, and the multi-distance spatial clustering analysis. The conclusions are as follows.

(1) The three-dimensional landscape index of buildings in each street of the study area has more obvious spatial differentiation characteristics. The number of buildings and landscape shape index within the study area show the trend that the city center is the highest and decreases gradually to the periphery, and the high building rate, building area, building height, and floor area ratio all show the trend that the main urban area of the study area is the highest value.

(2) The main types of buildings in the study area are low-rise and multi-storey buildings, with relatively few high-rise buildings, and even fewer super-high-rise buildings, and the distribution of building types is more reasonable, with central protection and peripheral development going hand in hand. Center protection and peripheral development in parallel, but there is an imbalance between the area of each street area and the number of buildings, you can moderately optimize the adjustment of the street scale, so as to adapt to the needs of fine management, while focusing on the protection of the old city and the basis of organic renewal, pay attention to the high-rise buildings in the city, especially the protection of the skyline, so that it can be optimized to the maximum extent of the study area of the urban pattern.

(3) In the macro scale, the spatial distribution pattern of the four types of building sites in the core area of Harbin City is a significant aggregation; the spatial scale has an effect on the aggregation of building distribution: with the increase of the spatial scale, the aggregation degree of low-rise, multi-storey and high-rise buildings increases and then decreases, and the ultra-high-rise buildings will be "aggregated and disaggregated" with the increase of the spatial scale. The super high-rise

building will be "aggregated and disaggregated" with the increase of spatial scale. The highest spatial scale of aggregation of low-rise buildings and multi-storey buildings is the largest, followed by high-rise buildings, and finally ultra-high-rise buildings, and this highest spatial scale of aggregation can provide a basis for the most suitable unit for urban planning and management.

The future research can be explored in depth from the following aspects: further digging into the factors affecting the architectural landscape pattern, and introducing the time parameter 't' to more comprehensively understand the formation mechanism of the urban architectural landscape pattern. Through the above in-depth study, we will be able to grasp the evolution law of urban architectural landscape pattern more comprehensively, provide a more scientific basis for urban planning and design, and promote the practice of sustainable urban development.

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