Research Paper

Study on the Influence Mechanism of Urban Green Space Pattern on Noise Spatial Distribution and Planning Response

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Abstract

With the rapid development and expansion of the city, noise pollution has seriously affected the physical and mental health of urban residents. Although existing studies have confirmed that urban morphology and green space layout have a significant impact on noise distribution, they mainly focus on the macro scale, ignoring the relationship between micro scale urban morphology, green space pattern and noise distribution. Based on this, this study uses a small-scale grid precision of 60m to explore the impact mechanism of urban morphology, green space pattern and other indexes on noise distribution at this scale. The crowdsourcing acoustic data based on the noise planet platform was used to obtain the noise distribution data. The pattern index of buildings, water bodies, green space and roads was quantified based on FRAGSTATS. The influence mechanism of urban form and green space pattern index on noise distribution was explained from three aspects: the identification of influencing factors, the analysis of influence degree and the synergy of two factors. It is found that PAFRAC, AI, NP, LSI, Ta, Shape_mn, IJI, Cohension and PD have significant effects on the noise distribution. Green space coverage is the most important factor affecting the distribution of urban noise, and its regulating effect on noise is far more than other morphological indexes. In addition, the dispersion of architectural form (NP), the complexity of shape (LSI) and the connectivity of green space (Cohension) also play a great potential in noise control. In addition, for the control of noise distribution, there is a strong synergistic effect between urban morphology and green space pattern index, that is, when combined with complex architectural morphology or highly connected green space, the noise reduction potential of green space is significantly enhanced, resulting in "1+1>2" effect in noise reduction. These findings suggest that isolated planning may not be enough. This study provides a quantitative basis for promoting urban acoustic governance from a wide range of regulatory measures to more accurate and spatial response design methods.

Keywords

Urban Morphology; Green Space Pattern; Noise Pollution; Sustainable Urban Planning

1. Introduction

Urban planning and design is the core link to shape the urban environment and enhance the well-being of residents. In the context of global rapid urbanization, the complexity and diversity of urban built-up environment has increased significantly, which is not only closely related to residents' activities, urban microclimate and urban morphology, but also exacerbates the challenges of various environmental problems (Fritschi et al., 2011). Among them, noise pollution has become the second largest environmental problem affecting the health of urban residents after air pollution, seriously threatening public health, quality of life and even work efficiency (Si et al., 2022). Therefore, how to effectively control the noise in urban areas through reasonable spatial planning means is a key issue in the current research of urban sustainable development.

The role of urban morphology is to identify the repeated patterns of structure, formation and evolution from the complex and diverse built environment, so as to understand the interaction between various elements (Burian et al., 2005; Wang et al., 2011). A large number of studies have confirmed that the morphological characteristics of the urban built environment have a significant impact on the noise distribution (Tawayha et al., 2019). Noise mainly comes from urban traffic, construction activities and other social and economic activities (Weber et al., 2014). Urban morphology has a complex and important correlation with the generation and distribution of noise by affecting the transmission, reflection and absorption mechanism of sound waves. The study found that higher building height and larger total building area can effectively reduce the noise level of the block (Margaritis et al., 2018). At the same time, the improvement of green coverage can also bring better noise reduction effect. These studies reveal the potential value and impact mechanism of urban form factors on noise control. The current research mostly focuses on the quantitative description of urban morphology based on structural indicators (Montalvao et al. 2011), such as building height (Weber et al., 2014), building density (Wang et al., 2011), green coverage (Margaritis et al., 2016,2017,2018), street coverage ratio (Weber et al., 2014), which have been confirmed to have a significant impact on noise distribution. The research of noise control is difficult to be separated from the bottom form of the city, and the characteristics of urban spatial form are of decisive significance to noise control. However, the accurate calculation of structural indicators depends on the detailed urban morphology data, which is difficult to obtain and time limited. More importantly, once the structural elements such as buildings and roads are completed, it is very difficult to change them, which limits the flexibility of intervention at the planning level.

Therefore, more and more scholars take the green space pattern as a more operational quantitative index of urban morphology into the study of the correlation between urban morphology and noise. Green space pattern indicators show significant advantages in data acquisition and calculation efficiency in quantitative analysis of land use and ecological environment by using classification map and specific spatial algorithm (Weber et al., 2014). Early studies combined structural indicators with landscape pattern index, and found that indicators such as patch density, edge density, Shannon diversity index and Shannon evenness index can effectively indicate the noise exposure level Weber in urban housing structure (Wang et al., 2011). Subsequently, the study focused more on the regulation effect of green space morphology on noise. From the perspective of land cover, efstathios margaritis and others analyzed the cases of European cities on a multi-level scale and confirmed the correlation between green space related parameters and traffic noise pollution (Margaritis et al., 2014). Further studies focused on urban parks, and found that green space indicators (such as tree coverage and grassland coverage) were significantly negatively correlated with noise levels, indicating that they have noise reduction potential; However, the influence of green space shape index (such as average patch fractal dimension and average shape index) is not significant (Margaritis

et al., 2016). The research based on the European environmental information and observation network also revealed the potential role of green space ratio, porosity, forest ratio and other macro and micro scale green space indicators in regulating noise (Margaritis et al., 2014,2017). In addition to a single dimension, the study also began to try to synthesize the joint impact of multiple factors on noise. For example, sakieh et al. Found through spatial statistical analysis that the compact performance of green space mode significantly alleviates noise propagation (Sakieh et al., 2017). Xu x et al. Found that road density (PD) and green space dispersion (split) were positively correlated with noise, while green space connectivity was negatively correlated (Xu et al., 2024). In addition, Han et al. Conducted a comprehensive study on the three main land cover types of buildings, greening and roads, and found that road density (PD) was positively correlated with noise, while green space connectivity (cohesion) and aggregation (AI) were negatively correlated with noise (Han et al., 2018). However, although the landscape pattern indicators show great potential, the current research is still mainly limited to single or two-dimensional discussion, ignoring the comprehensive impact of multi factor interaction on noise distribution in cities, resulting in the lack of universality and pertinence of research results in the face of complex urban spatial patterns.

In recent years, the intervention of open source noise data has made multi-scale research more convenient (Wang et al., 2011; Song et al., 2024; Job et al., 2016), which plays an important role in the study of urban morphology and plays a theoretical guiding role. Although some studies have begun to compare the correlation between urban morphology and noise at various scales, most of these studies focus on the macro scale, such as the overall or regional level of the city, emphasizing the analysis of the overall distribution law and trend. In contrast, small-scale research is more in line with outdoor sound transmission distance on the one hand, and more close to people's daily life on the other hand, which is directly related to residents' comfort and happiness (Isbell F et al., 2017; Jackson et al., 2015). However, there is still a lack of research on the relationship between small-scale landscape indicators and noise distribution, especially in discussing the characteristics of near human scale noise distribution. This deficiency not only limits our understanding of the micro relationship between noise and urban morphology, but also hinders the scientific planning and practice of optimizing the sound environment based on individual perception. Therefore, it is urgent to carry out a more systematic study on the correlation between small-scale landscape indicators and noise distribution, and deeply reveal the multi-level impact mechanism of urban form factors on noise at a small scale, providing a scientific basis for more efficient and accurate urban noise management.

Therefore, this study uses a small-scale grid precision of 60 m *60 m to deeply reveal the multi-level impact mechanism of urban form elements, especially green space pattern, on noise at the near human scale, and provide a scientific basis for more efficient and accurate urban noise management. This study will focus on answering the following core scientific questions: (1) key influencing factors of noise distribution: in a small scale, determine the green space pattern index that has a significant impact on urban noise distribution. (2) Quantification of index impact weight: determine the impact intensity and relative weight of each green space pattern index on noise distribution. (3) Quantification of synergy mechanism: quantify the synergy of different green space pattern factors on noise. The results of this study will help to make up for the lack of small-scale acoustic environment research, and provide more refined and scientific design guidance for the near human scale noise control strategy in future urban planning.

2. Methodology

In order to solve the problem that the current research on the correlation between urban morphology and noise distribution focuses on a large scale, this study selects a square plot with a side length of 2km as the

sample unit, which matches the range of people walking for 15 minutes. It is suitable for the fine research of small-scale urban noise, and can better meet the needs of small-scale noise regulation. In addition, in order to ensure the scientific and representativeness of the study, a 2km * 2km site in Milan was selected from two aspects of land cover type richness and noise data coverage. The site includes four types of land cover: buildings (44.29%), water (6.27%), green spaces (39.67%), and roads (9.77%).

2.1. Origin of Noise Data

The noise data of this study comes from the noise planet platform （ https://noise-planet.org/ ） The platform collects the noise measurement data obtained through field survey around the world. Most of the data acquisition work is completed through its noise capture application, which can record the sound pressure level data and use the built-in GPS of the mobile phone to locate the position of each measurement point. As shown in Figure 1, the noise data provided by the platform are mainly presented in the form of dots, and most of them are distributed in a linear trajectory, which can relatively completely describe the noise distribution characteristics in urban space. Compared with the traditional field measurement methods, the noise planet platform data has the following significant advantages: first, the data acquisition process is simple, and it can be completed only by smart phones, which greatly reduces the dependence on professional measurement equipment, and is especially suitable for researchers of architecture, urban and rural planning and other non acoustic backgrounds; Secondly, the data cover a wide range and provide a large-scale continuous updating noise data set, which is conducive to large-scale and multi-scale noise research; In addition, the compliance and scientificity of the data have been widely verified. Compared with complex and expensive high-precision measurement methods, noise planet data has outstanding performance in universality and practical application potential.

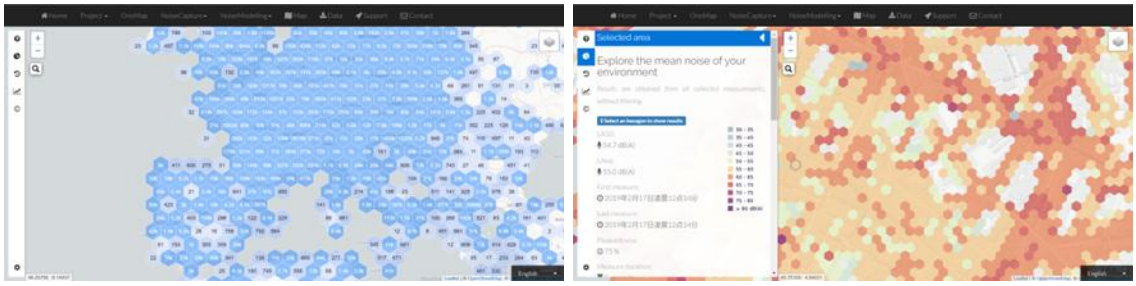


Figure 1. Noise-Planet （https://noise-planet.org/）

2.2. Urban Form and Green Space Pattern Indicators

Based on the existing literature, this study selected the indicators of urban morphology and green space pattern that have a significant impact on noise distribution from four aspects of water, buildings, green space and roads according to the types of land use and cover. For water bodies, PAFRAC is used to reflect the boundary complexity of water patches, division is used to describe the dispersion degree of water bodies, and AI is selected to measure the aggregation degree of water bodies. For building areas, LSI is used to describe the shape complexity of buildings, NP reflects the density and dispersion of buildings, and LPI describes the largest single building patch; These indicators cover shape measurement and fragmentation measurement. For green areas, TA is selected to investigate the total area of green space, Shape_mn is used to evaluate the complexity of green space shape, IJI is used to understand the spatial adjacency of different green patches, cohesion reflects the spatial connectivity of green space, and split represents the degree of fragmentation of green space. For road areas, plan describes the road area, and PD reflects the

road network density. In this study, FRAGSTATS 4 was used to calculate the 13 selected indicators (Appendix 1).

2.3. Data analysis

Interpolation processing of noise data: due to the linear distribution of noise data and the missing data in the study area, interpolation method should be used to fill in the missing value. In order to ensure the accuracy of interpolation results, this study uses Kriging interpolation method, and completes the interpolation calculation through the "geostatistical analyst" module in ArcGIS 10.8 platform. After interpolation, in order to ensure the accuracy and reliability of data, data cleaning and outlier elimination are required before formal analysis. The cleaning steps mainly include: screening and deleting abnormal noise values (such as data with noise intensity of 0 dB) and measured values that do not conform to the statistical law. After cleaning, the processed noise data is exported to provide accurate and reliable data support for subsequent analysis.

Pearson correlation analysis: This study uses Pearson correlation analysis to quantitatively explore the correlation between the indicators of urban morphology and green space pattern and the noise level, so as to identify the key indicators that have a significant impact on the noise distribution.

Geo detector: in order to deeply explore the mechanism of urban morphology and green space pattern indicators on noise distribution, the geo detector method is introduced in this study. Through factor detection and interaction detection, the influence weight of a single indicator and the interaction mechanism and weight between two indicators are analysed.

3. Result

3.1. Factors affecting noise distribution

Figure 2 shows the Pearson correlation analysis results between urban morphology, green space pattern index and noise distribution. It can be seen that for buildings, the indexes significantly related to noise distribution include: PAFRAC, AI, NP, LSI, TA, Shape_mn, IJI, Cohesion and PD.

In the water area, PAFRAC is significantly negatively correlated with noise distribution, while AI is significantly positively correlated with noise distribution, and the impact of PAFRAC on noise distribution is higher than AI. This indicates that in order to better control noise, priority should be given to ensuring the boundary complexity of patches in water form planning.

In the building area, both NP and LSI have a significant negative correlation with the noise distribution, and their impact on the noise is the same. This shows that in the planning of architectural form, the dispersion of architectural form should be ensured to better control the noise.

In the green area, TA, Shape_mn and cohesion were significantly negatively correlated with the noise distribution, while IJI was significantly positively correlated with the noise distribution, and TA had the greatest impact on the noise. This shows that in the green space pattern planning, in order to better control the noise, we should give priority to ensuring the green space coverage within the site, and then ensure the spatial connectivity between green spaces.

In the road area, PD is significantly positively correlated with the noise distribution, that is, the higher the density of the road network, the more serious the urban noise pollution is. This is because traffic noise is a

typical noise pollution source in urban space. Therefore, in order to effectively control noise, traffic flow control and other methods can be used.

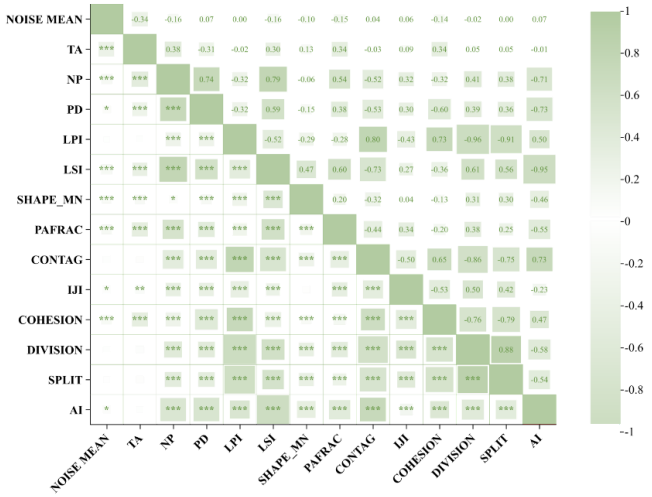


Figure 2. Pearson correlation analysis between urban form, green space pattern indicators and noise distribution

3.2. Importance ranking of factors affecting noise distribution

In order to better guide the planning and design, it is necessary to quantify the impact degree of the main influencing factors of noise distribution and rank the importance (Figure 3). The influence degree of 13 urban morphology and green space pattern index on noise distribution is ranked as follows: TA > NP > LSI > COHENSION > PAFRAC > PD > AI > SHAPE_MN > IJICONTAG > DIVISION > SPLIT > LPI。 It is worth noting that the impact of TA on noise distribution is much higher than other indexes, that is, for small-scale urban noise distribution, green space coverage is the decisive factor affecting noise distribution. Secondly, the dispersion of architectural form also has great potential in further controlling small-scale urban noise pollution.

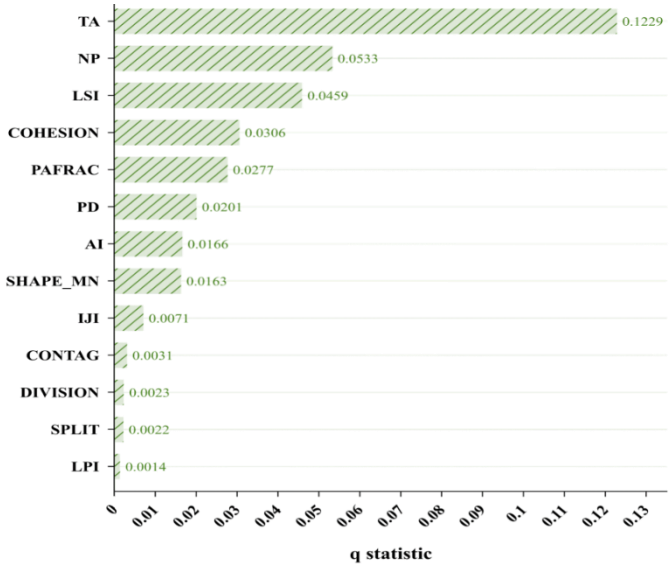


Figure 3. Importance ranking of factors affecting noise distribution

In urban central areas with limited land use, priority should be given to ensuring the planning and layout of large-scale central green spaces (such as urban parks and core green spaces). Using linear greenways and strip vegetation as the core, an ecological corridor is constructed to enhance the connectivity of green spaces (COHESION), thereby forming a continuous ecological noise reduction barrier and avoiding a decrease in noise reduction efficiency due to excessive fragmentation (reducing SPLIT index).

In areas with high noise risks such as near major transportation arteries, it is advisable to avoid constructing "slab" building complexes with wide and flat interfaces. It is recommended to deconstruct the building volume (increase NP), adopt point or staggered layout, and increase interface sawtooth or setback design (enhance LSI) to effectively interrupt, scatter, and consume noise energy using complex multidimensional physical boundaries. In addition, the design of waterfront areas should break through the limitations of traditional hard and straight revetments, promote natural forms of meandering water banks, expand the acoustic diffuse reflection area by increasing the edge tortuosity (improving the PAFRAC fractal dimension), and optimize the acoustic environment quality of waterfront spaces.

3.3. The synergistic effect of dual influencing factors on noise distribution

In order to further analyze the interaction between urban morphology and green space pattern index, whether it will enhance the interpretation ability of noise distribution and which indexes have independent effects on noise distribution. In this study, the 13 indexes were further evaluated by interactive detection analysis (Figure 4 and Figure 5). It is found that the combined effect of urban morphology and green space pattern index can enhance the explanatory power of noise distribution. among TA ∩ COHENSION、TA ∩ LSI、TA ∩ SHAPE_MN、TA ∩ PAFRAC、TA ∩ NP、NP ∩ LSI、NP ∩ PAFRAC、LSI ∩ PAFRAC、LPI ∩ DIVISION、SHAPE_MN ∩ AI It is a two factor enhancement, that is, when these factors are combined together, the explanatory power of the noise distribution is stronger than that of a single factor. When the other indexes act together, the influence on the noise distribution is nonlinear enhancement, that is, when these factors act together, the explanatory power of the noise distribution is stronger than the sum of the two factors.

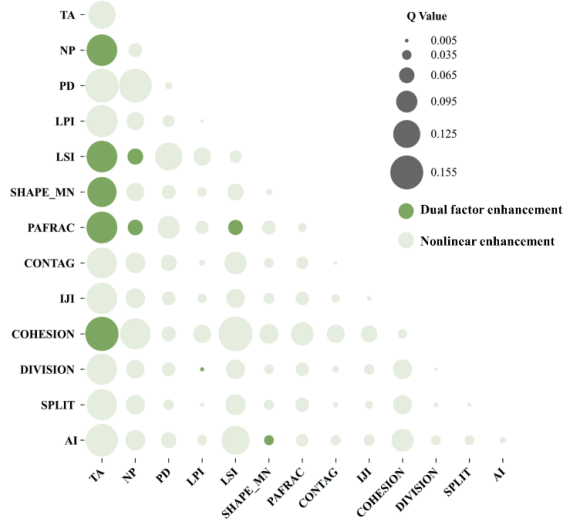


Figure 4. The synergistic effect of dual influencing factors on noise distribution

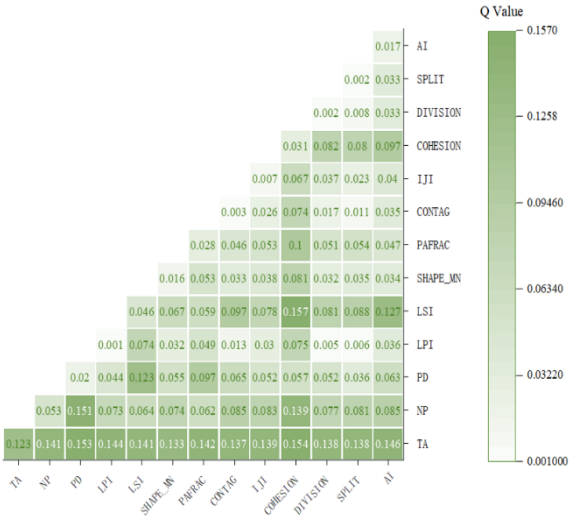


Figure 5. Importance ranking of collaborative effects

4. Conclusion

Based on the small-scale analysis framework (grid accuracy: 60m), this study systematically investigated the influence mechanism of urban morphology and green space pattern on noise distribution, identified the key influencing factors, quantified their relative importance, and revealed the synergy among multiple factors. The main conclusions are as follows:

First of all, there is a significant correlation between the noise distribution and the four kinds of spatial form indicators of green space, buildings, water and roads. It is worth noting that the total green area (TA), as the most critical impact factor, is significantly negatively correlated with the noise level. This finding shows that increasing green space coverage is the most effective strategy to alleviate noise pollution. In addition, the number of building patches (NP) and architectural landscape shape index (LSI) also showed a strong negative impact, indicating that dispersing the building layout and enhancing its morphological complexity can help reduce noise. At the same time, increasing the complexity of water boundary (PAFRAC) can effectively control noise, while road density (PD) will significantly aggravate noise pollution, which proves that traffic noise is the main source of urban sound environment.

Secondly, the impact of total green area (TA) is significantly greater than other indicators, emphasizing that maintaining sufficient green area in a small-scale environment is essential for noise control. Building dispersion (NP and LSI) and green space connectivity (cohesion) also have an important impact, indicating that in built-up intensive areas, optimizing building layout and enhancing green space connectivity play a key role in improving the quality of the acoustic environment.

Finally, the synergetic mechanism analysis shows that the interaction of two factors usually enhances its explanatory power to the noise distribution. The interaction between total green area (TA) and cohesion, LSI, PAFRAC and other indicators has a significant synergistic effect. This shows that while increasing the green space coverage, taking into account its spatial connectivity, combined with the complexity of the architectural form and the design of the water boundary, the noise propagation can be more effectively suppressed. Some factor combinations (such as NP ∩ LSI, LPI ∩ Division) show nonlinear enhancement effect, indicating that under the specific configuration, the joint action of multiple factors may produce a noise control effect that exceeds the expected "1+1>2".

The future urban design and renewal should ensure sufficient green space scale, and optimize the interactive relationship between green space, buildings, water and other spatial elements in the form and layout, so as to build a noise reduction spatial system with reasonable structure and functional coordination. This study provides quantitative basis and design guidance for improving the acoustic environment quality of human scale in high-density built-up areas, and promotes the transformation of urban noise control from extensive control to precise and spatial control strategy.

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Appendix 1 Overview of urban morphology and green space pattern index

Type	Landscape metrics	Calculation	Description
Construction Land	Number of patches (NP)	-	The total number of patches in the landscape
	landscape shape index（LSI）	$\mathrm{LSI} = \frac{P}{2\sqrt{\pi A}}$	P is the perimeter of the landscape patch; A is the area of the landscape patch.
	Division Index（DIVISION）	$\mathrm{Division} = \frac{\sum_i P_i}{A}$	P_i is the perimeter (boundary length) of the i-th patch;A is the total area (or total pixel count) of the landscape.
Greenland	TA（Total Area）	$\mathrm{TA} = \sum_{i=1}^{n} A_i$	A_i is the area (or pixel count) of the i-th landscape unit (or patch);n is the total number of the landscape units (or patches).
	Largest patch index (LPI)	$\mathrm{LPI} = \frac{A_{\max}}{A} \times 100$	A_{max} is the area (or pixel count) of the largest patch in the landscape;A is the total area (or total pixel count) of the landscape.
	Mean shape index (SHAPE_MN)	$\mathrm{SHAPE_MN} = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{Perimeter_i}{\sqrt{\pi \times Area_i}}\right)$	n is the total number of patches;$Perimeter_i$ is the perimeter (boundary length) of the iii-th patch;$Area_i$ is the area of the iii-th patch.
	Interspersion and juxtaposition index (IJI)	$\mathrm{IJI} = \frac{\sum_i \sum_j \lvert P_{ij} - \frac{A_i A_j}{A} \rvert}{A}$	P_{ij} is the number of adjacent cells between the i-th and j-th landscape types,A_i and A_j are the areas (or pixel counts) of the i-th and j-th landscape types, respectively;A is the total area (or total pixel count) of the landscape.
	Patch cohesion index (Cohesion)	$\mathrm{COHESION} = \left(1 + \sum_{i=1}^{m}\left(\frac{g_{ii}}{g_{i\,\max}}\right) \times P_i\right) \times 100$	g_i is the number of similar adjacent patches for landscape type i;g_i max is the maximum number of adjacent patches for landscape type i;P_i is the proportion of landscape type i in the landscape;m is the total number of patch types in the landscape.
	Splitting index (Split)	$\mathrm{SPLIT} = \frac{\sum_i \sum_j P_{ij}}{A}$	P_{ij} is the number of adjacent units (or patches) between the i-th and j-th landscape types;A is the total area (or total pixel count) of the landscape.
	Aggregation index (AI)	$\mathrm{AI} = \frac{\sum_{i=1}^{n} A_i^2}{A \cdot N}$	A_i is the area (or pixel count) of the i-th landscape unit (or patch);A is the total area (or total pixel count) of the landscape;N is the total number of patches in the landscape.
Road Land	Patch density (PD)	$\mathrm{PD} = \frac{n}{A}$	n is the total number of patches in the landscape;A is the total area (or total pixel count) of the landscape.
Waterbody	CONTAG	$\mathrm{CONTAG} = \frac{-\sum_{i=1}^{n}\sum_{j=1}^{n} p_{ij} \cdot \log(p_{ij})}{\log(n)}$	P_{ij} is the proportion of adjacent units between the i-th and j-th landscape types. Specifically, it represents the proportion of cells that belong to landscape type i and are adjacent to cells of type j;n is the total number of landscape units.
	PAFRAC	$PAFRAC = \frac{2}{\frac{[n_{ij}\sum_{j=1}^{n}(\ln p_{ij} - \ln a_{ij})] - [(\sum_{j=1}^{n} p_{ij})(\sum_{i=1}^{n} a_{ij})]}{(n_i \sum_{j=1}^{n} \ln p_{ij}^2) - (\sum_{j=1}^{n} \ln p_{ij})^2}}$	P is the perimeter of the landscape patch;A is the area of the landscape patch.