

Landscape Visual Aesthetics Measurement, Assessment, and Improvement of Street Pedestrian Spaces in Mountainous Cities —Case Study on the Historic Downtown of Jinan, Shandong Province

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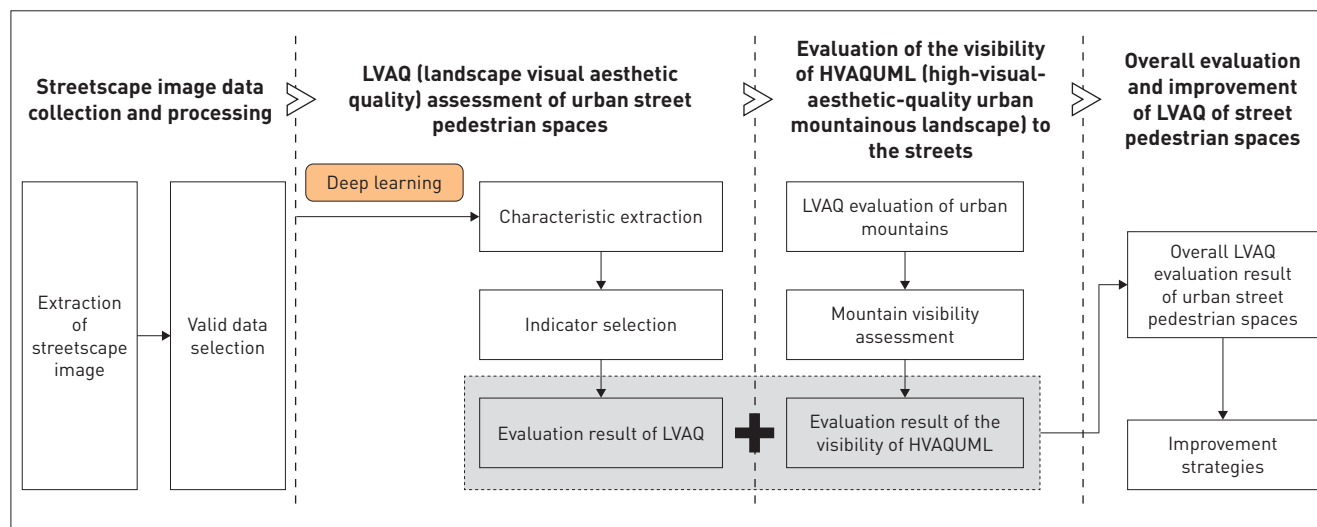
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GRAPHICAL ABSTRACT



HIGHLIGHTS

- Measures landscape visual aesthetic quality of urban streets based on streetscape data
- Evaluates the visibility of high-visual-aesthetic-quality urban mountainous landscape to streets with viewshed analysis
- Suggestions on improving landscape visual aesthetic quality of street pedestrian spaces based on the spatial structure of mountain-city integration

ABSTRACT

Urban streets support citizens' daily commuting and social and recreational activities. Streetscape is also a visual resource and an important part of urban landscape appearance. Serving as an important ecological base and natural components of urban spatial structure, mountains often determine a city's spatial layout and landscape identity so as to promote mountain-city integration. The study focuses on the historic downtown of Jinan, a typical mountainous city, analyzes the landscape aesthetic visual characteristics of street pedestrian spaces, and measures their landscape visual aesthetic quality by using panoramic images; the research then evaluates the visibility of high-visual-aesthetic-quality urban mountainous landscape to urban streets; finally, based on the overall landscape visual aesthetic quality evaluation results of urban street pedestrian spaces, the paper proposes a series of optimization suggestions of the streets at different levels to improve the harmony with urban mountain landscapes. The study hopes to provide a reference for the creation of mountain-city-integrated urban landscapes, as well as the healthy and sustainable urban development.

KEYWORDS

Mountain-City Integration; Street Pedestrian Space; Landscape Visual Aesthetic Quality; Visibility of High-Visual-Aesthetic-Quality Urban Mountainous Landscape; Quantitative Assessment; Urban Streetscape

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1 Introduction

With the increasing demand of urbanization for land, Chinese cities and towns are gradually growing from plains to mountainous areas^[1]. Most studies on the mountain–city relationship derive from the idea of “Landscape City,” which advocates building human settlements through the integration of natural environment (mountain) and artificial environment (city)^[2]. Many experts and scholars have highlighted the importance and discussed the construction methods of mountain–water–city spatial patterns from perspectives of city image and cultural identity^{[3]~[5]}. Serving as an important ecological base and natural components of urban spatial structure, mountains partly determine a city’s overall landscape layout and appearance, especially to mountainous cities. The spatial structure of “mountain–city integration”^{[2][6][7]} refers to planning and building urban pattern by taking mountains as structural elements at the city scale, and embodies as an urbanized spread towards the mountains at the neighborhood scale^[2].

Urban streets support citizens’ daily commuting, leisure and recreation, cultural exchange, and environmental protection. The landscape of pedestrian spaces greatly affect pedestrians’ visual aesthetic perception^[8], which is defined by people’s visual interaction and feedback with the landscape^[9]. Currently, there are increased studies on measurement and assessment of landscape visual aesthetic quality (LVAQ hereafter) of urban streets, and most of them focus on analyzing the city’s spatial composition of artificial landscape elements (e.g., buildings, roads, and structures) and natural landscape elements (e.g. vegetation, sky)^{[9]~[11]} within limited visual range. In the context of promoting mountain–city integration, research on LVAQ assessment of urban mountains in a relatively further visual range is expected. Based on the spatial structure of mountain–city integration, this paper conducts a city-scale analysis with mass open-source data such as streetscape images and by refined measurement criteria, to examine the overall LVAQ of street pedestrian spaces in typical mountainous cities, and then proposes suggestions on improving the landscape quality of street pedestrian spaces.

2 LVAQ Assessment of Urban Street Pedestrian Spaces

2.1 Visual Characteristics of Urban Landscape Aesthetics

As part of cultural ecosystem services, landscape aesthetic experience service is a non-material benefit that human obtained from the environment through senses of vision, hearing, and smell, usually perceived as sensory pleasure or spiritual comfort^[12].

Subject to individuals’ spatial aesthetic experiences and the city’s natural–cultural environment, the visual characteristics of urban landscape aesthetics are usually measured by naturalness, diversity, openness, harmony, and disturbance^[13], with complex correlations between each other. Despite the variety in types and scales, as well as the disparity of individuals’ visual aesthetics preferences, generally landscapes of higher naturalness, greater diversity, better harmony, more open views, and lower disturbance are more popular^{[14]~[16]}. In addition, for mountain–integrated cities, the mountains with high visual aesthetic quality serve as the base of the overall urban landscape, and provide unique aesthetic experience services in form of rich visual relationships formed by natural landscape elements of the mountain itself (e.g. forests, bushes) and surrounding artificial landscape elements (e.g. urban buildings) within a certain viewshed.

2.2 Quantitative Assessment Method of LVAQ of Urban Streets

Aesthetic experience is one of the most easily perceived cultural ecosystem services^[16]. However, due to the difficulty in monetizing such services, relevant research mostly conducts quantitative assessments on the service capacity of different landscape types with varying indicators that describe visual characteristics of landscape aesthetics^[12].

1) Naturalness: The effect of naturalness is commonly recognized as the higher naturalness the landscape has, the better visual aesthetic experience people have. Naturalness can be measured by the visual proportion of natural elements such as vegetation to the streetscape, and is usually positively correlated with vegetation coverage^[17].

2) Diversity: Diversity is mainly defined by the complexity of landscape elements. When the composition of landscape elements of a site is visually rich, people would have a better aesthetic experience. The study by Han Junwei et al. verified that visual entropy and complexity of landscape elements are significantly positively correlated^[11], so it can be used as an indicator to reflect the diversity of streetscapes.

3) Harmony: Harmony measures the perceived visual aesthetic experience of the landscape by the coordinated degree among constituent elements. Inspired the study by Wu Jiansheng et al., the area ratio of natural and artificial landscapes in a city can be assigned as a quantitative indicator of landscape harmony^[13].

4) Openness: The openness refers to a certain visual range that the pedestrian perceive in the street pedestrian spaces. Usually, a relatively open viewshed leads to a better perceived visual aesthetics. Li Xueying et al. evaluated openness by measuring the

ratio of sky area in streetscape pictures photographed at human eye's level, and found out that the larger proportion of sky area in the picture, the better openness and visual aesthetic quality of the corresponding street space^[18].

And 5) disturbance: People's aesthetic experience and walking activities on the streets are affected by their safety feelings, and less non-motor vehicles help enhance the restorative capacity of streetscapes^[19]. Tang Jingxian et al. evaluated street motorized level by the proportion difference between motor vehicle lanes and vehicles with sidewalks^[20].

Analyzing visibility of quality mountainous landscapes is effective to LVAQ measurement of mountains^[21]. Existing research mostly adopts the Scenic Beauty Estimation Method and technical means such as GIS, and examines factors affecting the landscape views of the mountain, such as the vegetation coverage of the mountains and the height limits of their surrounding buildings. Through questionnaires on residents' aesthetics preference, Chen Zirui et al. found that most of them recognized the effect of diversified mountain topography and landscape texture on the aesthetic quality of mountain^[22]. As key aspects to these two visual characteristics of mountains, the growth and the coverage of vegetation are often quantified by indicators such as NDVI (Normalized Difference Vegetation Index)^[23]. Meanwhile, visible exposed or bare mountain parts caused by sudden changes (from natural occurrences or construction activities) in local topography, geomorphology, and vegetation coverage are also affecting factors to people's visual perception in street pedestrian spaces, where the larger the area of the visible exposed part contrasting to the surroundings, the severer the perceived visual impact and pollution^[24]. The LVAQ impact caused by such exposed parts can be quantified combining evaluations on surrounding traffic environment, the area, and the visible condition of the exposed part, etc.^[24] Compared with the visibility and view control of individual buildings, that of urban mountains should focus on the visual relationship between building clusters and mountains from the streets, and related factors can be quantified through view corridor/viewshed analyses^[25].

In addition, the advance of computer vision field and machine learning algorithms allows disciplines such as Urban Planning, Landscape Architecture, and Architecture to use relevant machine learning methods to address urban settlement issues. The method of semantic segmentation of images using convolutional neural network tools based on machine learning algorithms to extract the features of streetscape image elements has been widely applied in research on LVAQ, including street greening and urban landscape

evaluation. The application of deep learning methods in analyzing and calculating massive streetscape data obtained by open-access platforms such as Google and Baidu has not only seen improvement in data acquiring and processing, but also provided technical support for large-scale and detailed evaluation on urban street element characteristics and visual aesthetic quality^{[26][27]}.

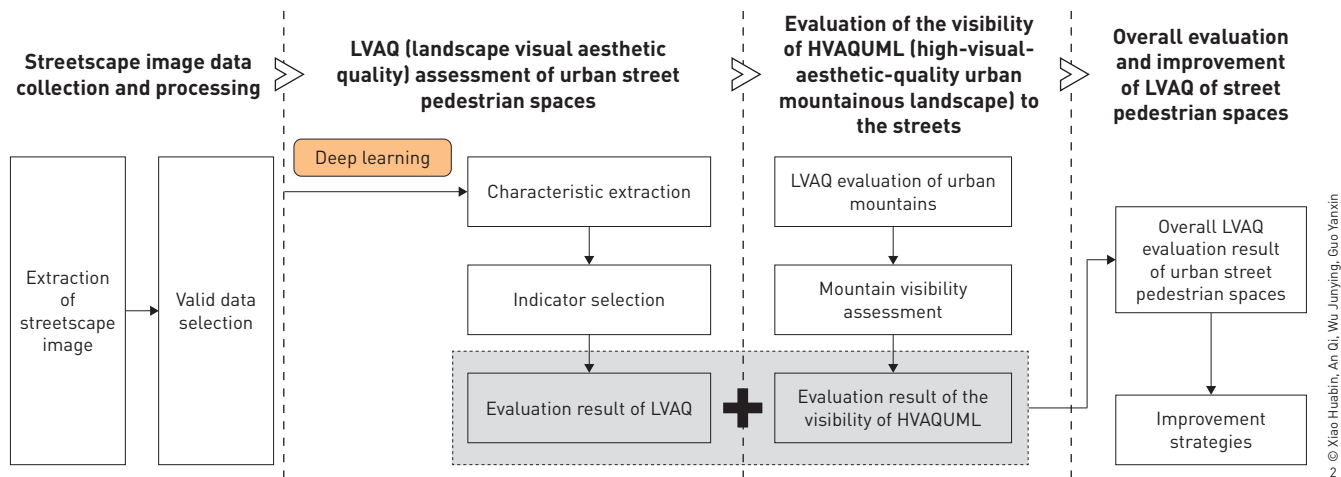
3 Study Area and Research Method

3.1 Study Area

In this study, the historic downtown (the most populated area with the densest road network in the city) of Jinan, Shandong Province was selected as the study area, which covers an area of about 203.51 km² and more than 1,300 streets^[28] (Fig. 1). The study area sits in the region of the Taishan Mountains and accommodates a number of mountain parks and urban scenic



1. Study area and spatial distribution of urban streets and mountains within it.



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areas^[29]. Although Jinan government has gradually launched projects such as the remediation of damaged mountains and the construction of mountain parks since 2017, the study area, typically mountain-integrated, still faces the challenge of how to organically improve the quality of urban slow-lifestyle spaces including street pedestrian spaces. This study uses massive streetscape data and deep learning methods, combined with an overlay analysis on the visibility of high-visual-aesthetic-quality urban mountainous landscape (HVAQUML hereafter), to conduct overall LVAQ evaluation of urban street pedestrian spaces of multiple characteristics based on a large sample size and in an efficient method, in order to provide a reference for improving urban landscapes of mountain-integrated cities^[30].

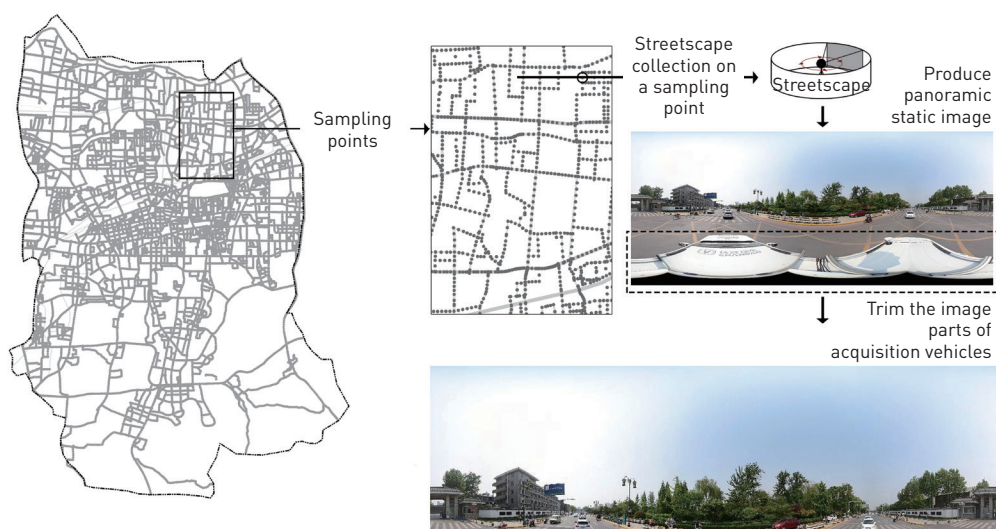
3.2 Research Path and Methodology

This study mainly consists of four stages: data collection and

processing of streetscape images; LVAQ assessment of urban streets pedestrian spaces; evaluation of the visibility of HVAQUML to the streets in the study area; and overall evaluation and optimization of LVAQ of street pedestrian spaces in the study area (Fig. 2).

3.2.1 Streetscape Image Data Collection and Processing

Based on the Open Street Map (OSM) data collected in May, 2019, the number of expressway, arterial road, secondary arterial road, and branch road in the study area were 24, 81, 237, and 1,043, respectively. The turning points and the nodes at every 100-meter interval of each street were located in the coordinates with the assistance of ArcGIS 10.4 software platform. Based on Python 3.5 and PyCharm platform, Baidu Map API was accessed to capture panoramic static streetscapes (1,024 × 512 pixels) of each located point. To simulate the visual perception of pedestrian's perspective, the vertical angle was set to 0° and the horizontal angle was



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2. Research path
3. The process of taking streetscape images at a sampling point in the study area
4. Results of crawling and semantic recognition of panoramic streetscape images in the study area

360°. Invalid streetscapes of non-pedestrian environments such as elevated roads and tunnels, and the image parts showing the acquisition vehicles were trimmed. A total of 20,847 urban streetscape images (1,024 × 290 pixels) in the study area were finally acquired (Fig. 3).

3.2.2 LVAQ Assessment of Urban Street Pedestrian Spaces

DeepLab v3+, a semantic segmentation tool developed by Google, was used for streetscape image feature extraction. The tool combines probabilistic graphical model of DenseCRFs with Diffusion-Convolutional Neural Networks (DCNNs), and its Mean Intersection over Union (MIoU) is 82.1% on the Cityscapes dataset^[31], which has been used in research on Chinese urban streetscapes and demonstrated a high accuracy for image segmentation^[32]. This study employed DeepLab v3+ open-source image semantic segmentation deep learning model based on Python 3.5 platform and Tensorflow AI learning system, an open-source library for deep learning developed by Google. Based on the Cityscapes with fine annotations, the processed panoramic streetscapes static images are decoded for elements, and the proportion of pixel points occupied by each element in the image is identified. With considerations on the visual characteristics of urban streetscape aesthetics, evaluation indicators were selected and calculated with corresponding quantification methods. Finally, the spatial distribution of LVAQ assessment results of the urban streets in the study area was visualized with ArcGIS.

3.2.3 Evaluation of the Visibility of HVAQUML to the Streets

In this study, the visibility of HVAQUML to the streets refers to the urban streets where pedestrians can visually perceive the mountain and the mountain is of quality landscape aesthetics, i.e. the evaluation of HVAQUML visibility is based on both LVAQ and mountain visibility assessment results. According to the analysis of relevant elements affecting people's visual aesthetic perception of urban mountains mentioned above, the degrees of mountain vegetation coverage and exposed parts were quantified respectively, and then superimposed with the results of LVAQ evaluation of mountain natural elements to evaluate the aesthetic quality of the mountain. Based on viewshed analysis, this research measured the visibility of each mountain from the street sampling points, and multiplied the result by the corresponding mountain aesthetic quality rating, and matched the mean values of the sampling points with corresponding streets, so as to evaluate the visibility of HVAQUML to the streets in the study area.

3.2.4 Overall Evaluation and Optimization Strategies of LVAQ of Street Pedestrian Space

According to the above results of LVAQ and HVAQUML visibility evaluation of urban streets in the study area, an overall LVAQ evaluation of street pedestrian spaces was finally obtained. By analyzing the visual aesthetic quality characteristics of streets at different levels, this paper also proposed optimization strategies accordingly.

4 LVAQ Evaluation of Urban Streets

4.1 LVAQ Measurement of Urban Streets Based on Streetscapes and Deep Learning Method

Through element identification of the panoramic static streetscapes in the study area, a total of 18 categories of elements (Fig. 4) such as plants, buildings, sky, sidewalks, and

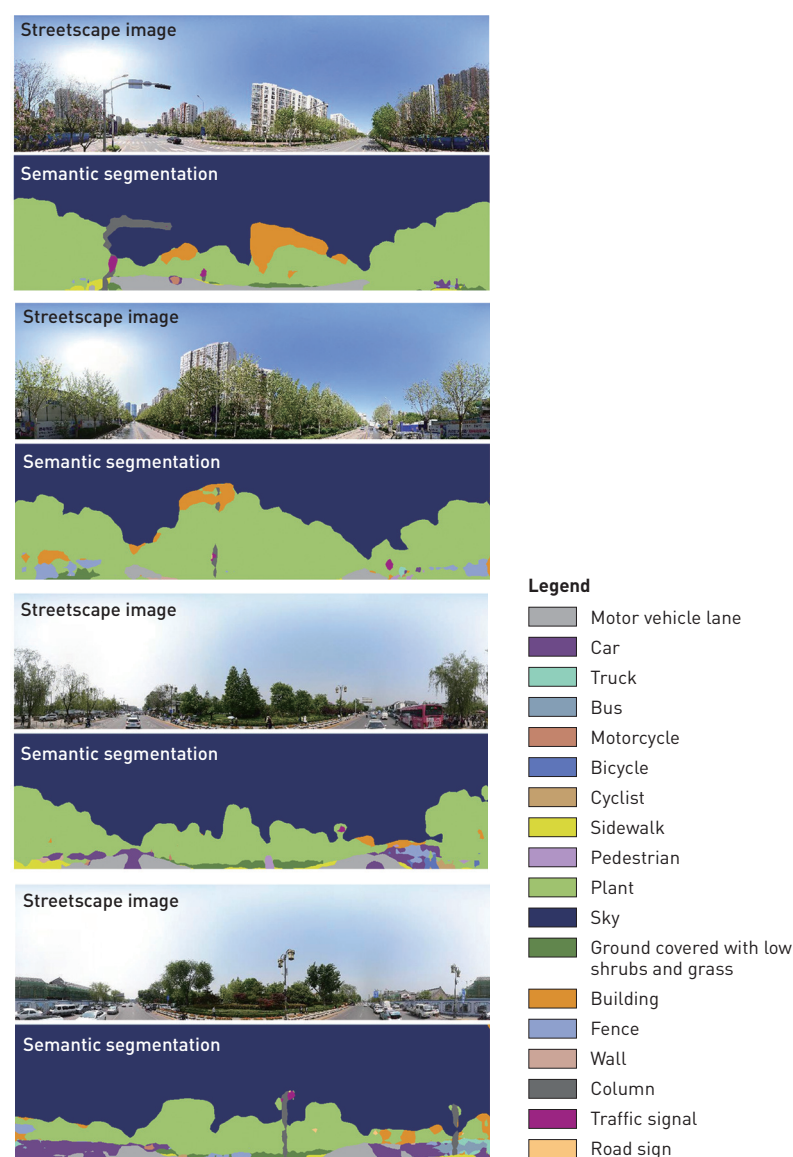


Table 1: Indicators of LVAQ evaluation of urban street pedestrian spaces

Indicator	Impact correlation	Indicator interpretation
Naturalness	Positive	Pixel count proportion of plant elements
Diversity	Positive	Visual entropy of natural elements
Coordination	Positive	Ratio of natural elements to artificial elements
Openness	Positive	Pixel count proportion of sky
Interference	Negative	Ratio difference between vehicular environmental elements with pedestrian environment elements

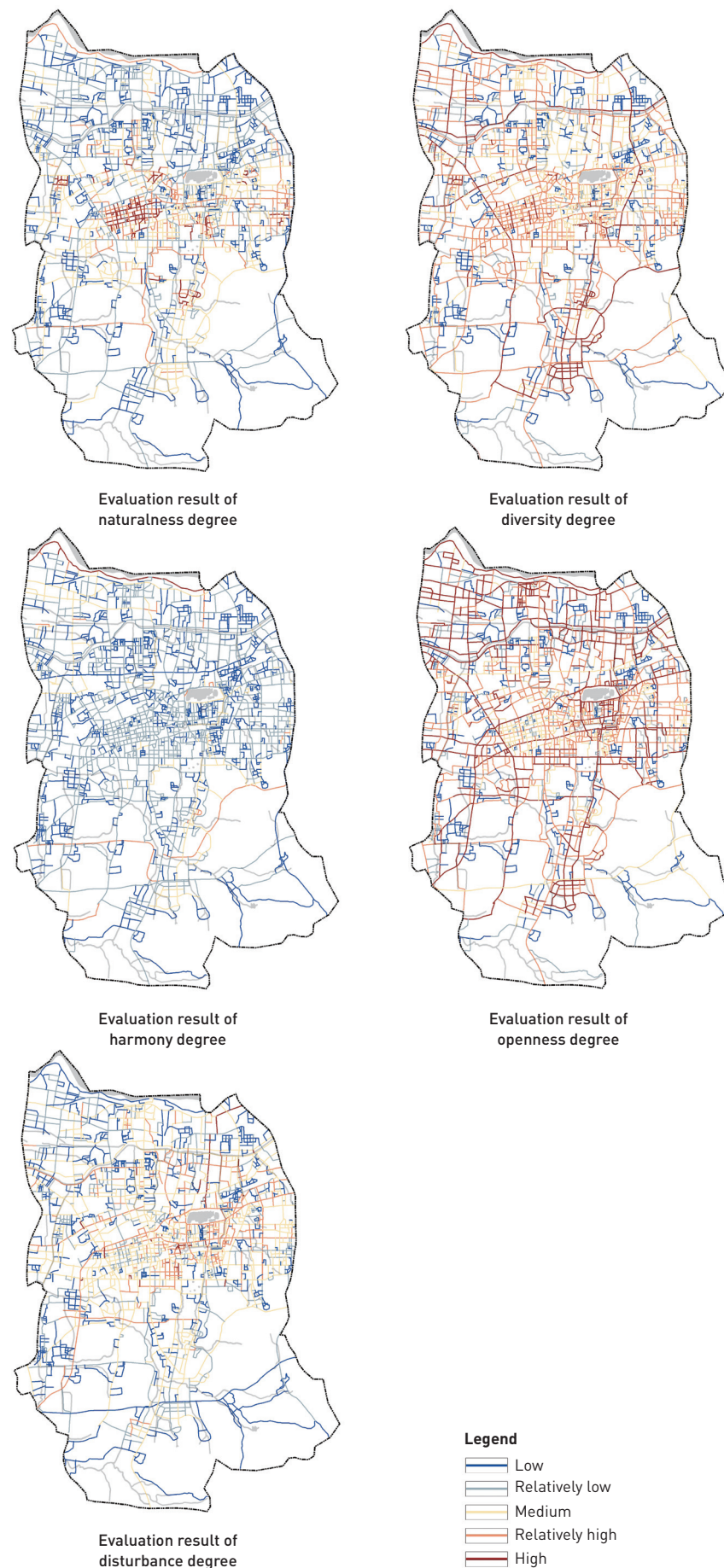
motor vehicle lanes were obtained after excluding insignificant element categories^[33]. The five landscape aesthetic characteristics of urban streets, i.e. naturalness, diversity, harmony, openness, and disturbance, were quantified respectively, as the indicators of LVAQ evaluation of urban street pedestrian spaces (Table 1).

Specifically, vehicular environmental elements include motor vehicle lanes, cars, trucks, buses, motorcycles, bicycles, and cyclists; pedestrian environmental elements include sidewalks and pedestrians; natural elements include plants, sky, and ground covered with low shrubs and grass; artificial elements include buildings, sidewalks, motor vehicle lanes, fences, walls, columns, traffic signals, and road signs. The visual entropy of natural elements is calculated as follows:

$$H = - \sum_{i=1}^n p_i \ln p_i , \quad (1)$$

where H is the visual entropy value of natural elements of streetscape images, p_i is the probability of occurrence of the i th natural element ($i = 1, 2, 3, \dots, n$, n is the total number of study objects), when $p_i = 0$, $\lim_{p_i \rightarrow 0} p_i \ln p_i = 0$.

The mean value of LVAQ evaluation results of each sampling points was assigned to their corresponding streets using the ArcGIS spatial connection function. According to the visualization of LVAQ evaluation results (Fig. 5) where Natural Breaks method was used, it was found that the streets of higher naturalness level in the study area accounted for 17%, mainly distributed in north of Lvyou Road (in the southeastern part of the study area) and the south of Xiaoqing River (in the central and southern part of the study area). The streets of higher level of diversity accounted



5. The evaluation result of each LVAQ indicator of the streets in the study area

for 7% and were mainly in the center of the study area and some expressways and arterial roads. The streets of a higher level of harmony accounted for 5% and mainly included Lvyou Road and South Second Ring Road (in the southeast of the study area) and North Second Ring Road (in the north of the study area). The streets of a higher level of openness accounted for 61% and largely found among expressways and arterial roads. The proportion of the streets of a lower disturbance was 70% and widely found in all streets in the study area.

4.2 LVAQ Evaluation of Urban Street Pedestrian Spaces

The entropy method is an assignment approach that can reduce the interference of subjective factors compared with methods such as expert scoring and hierarchical analysis^[34]. The study used the entropy method to calculate the weights of each indicator, which mainly includes three steps: data standardization, information entropy calculation of indicators, and indicator weight determination. The data standardization formula is:

$$S_{ij} = (x_{ij} - x_{min.i}) / (x_{max.i} - x_{min.i}), \quad (2)$$

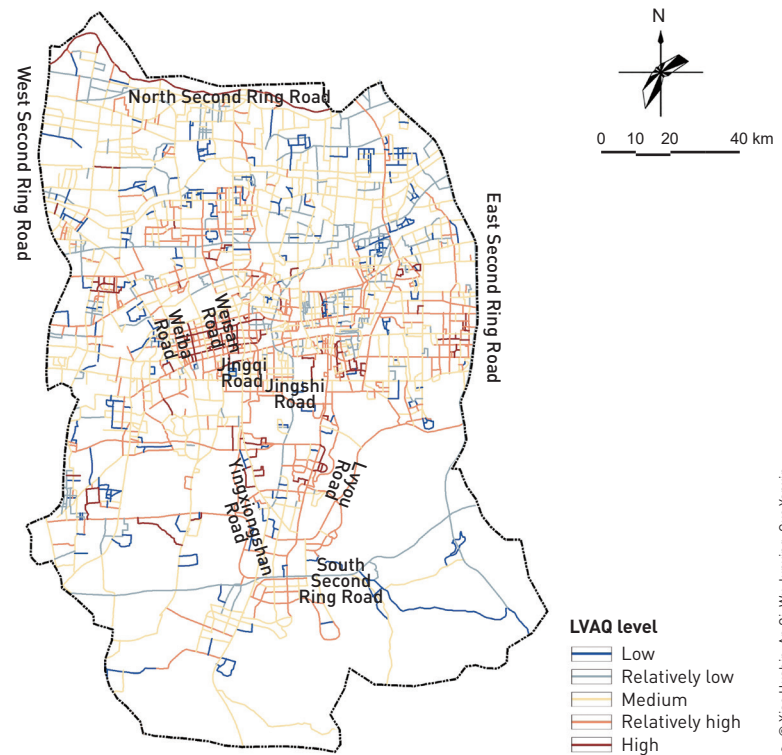
$$S_{ij} = (x_{max.i} - x_{ij}) / (x_{max.i} - x_{min.i}). \quad (3)$$

When the basic data with the total number of standardized evaluation objects and indicators is m and n respectively, S_{ij} is the standardized value of the i th indicator of the j th evaluation object, x_{ij} indicates the value of the i th indicator of the j th evaluation object, $x_{max.i}$ and $x_{min.i}$ are the maximum and minimum values of the i th indicator, respectively, where $i = 1, 2, 3, \dots, n, j = 1, 2, 3, \dots, m$. Equation 2 is used when the indicator has a positive correlation, and Equation 3 for negative correlation. The information entropy of indicators is calculated as follows:

$$p_{ij} = S_{ij} / \sum_{j=1}^m S_{ij}, \quad (4)$$

$$e_i = -(1/\ln m) \sum_{j=1}^m p_{ij} \ln p_{ij}. \quad (5)$$

In Equation 4 and 5, p_{ij} is the contribution of the j th evaluation object by the i th indicator, and e_i is the information entropy value of the i th indicator—the greater the difference of the indicator value S_{ij} , the greater the contribution to the evaluation of the evaluation object, and the smaller the entropy value. Therefore, the indicator weights are calculated as follows:



6. LVAQ evaluation results of the streets in the study area

$$w_i = (1 - e_i) / \sum_{i=1}^n (1 - e_i), \quad (6)$$

where $(1 - e_i)$ is the coefficient of variation of the i th indicator, the larger $(1 - e_i)$, the more important the indicator is; w_i is the weight of each indicator, $i = 1, 2, 3, \dots, n$.

According to the information entropy calculation of indicators, the weights of naturalness, diversity, harmony, openness, and disturbance are 0.17, 0.07, 0.51, 0.05, and 0.2, respectively. Through an ArcGIS overlay analysis on LVAQ evaluation results of each street and with natural breakpoint method, the overall LVAQ spatial distribution in the study area was obtained (Fig. 6).

The evaluation results show that the overall LVAQ of the urban street pedestrian spaces in the study area is high. A total of 390 streets had a relatively high or high aesthetic quality, accounting for about 28%, and the proportion of street at every level was similar. The number of streets of medium aesthetic quality was 511, accounting for 37%; they were commonly found among expressways, arterial roads, and secondary arterial roads. 484 streets were evaluated low or relatively low in aesthetic quality, accounting for about 35%, mainly found among branch roads.

5 Overall LVAQ Assessment of Urban Street Pedestrian Spaces

5.1 Evaluation of the Visibility of HVAQUML to the Streets

5.1.1 LVAQ Evaluation of Urban Mountains

LVAQ evaluation of the natural elements of urban mountains measures two indicators (Table 2). The research first identified the mountaintops according to the DEM data and the specific edge of each mountain in the study area upon the contours. To measure the vegetation coverage, the mean NDVI of each urban mountain was obtained with the aid of ENVI (a remote sensing image processing platform). To measure the damage degree, Maximum Likelihood Estimation was used to classify the separable training samples based on image data to obtain the spatial distribution of bare areas of the mountains and calculate the proportion.

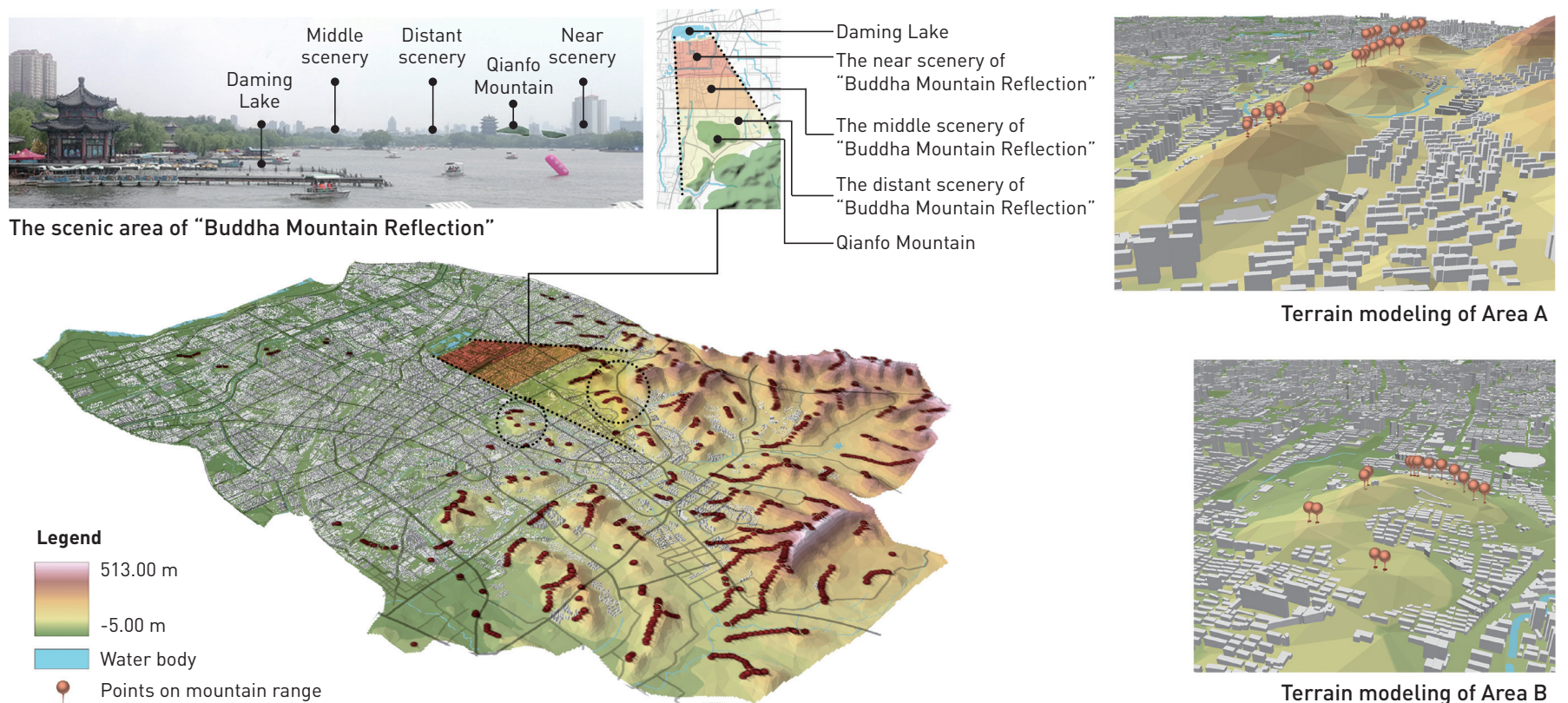
Entropy value method was used to calculate the weights of each indicator to grade the LVAQ of the 26 mountains in the study area. The results showed that 12 mountains had a higher LVAQ, including Qianfo Mountain, Jinji Mountain, Yingxiong Mountain, Ma'an Mountain, Wuli Mountain, Liuli Mountain, Jinniu Mountain, North

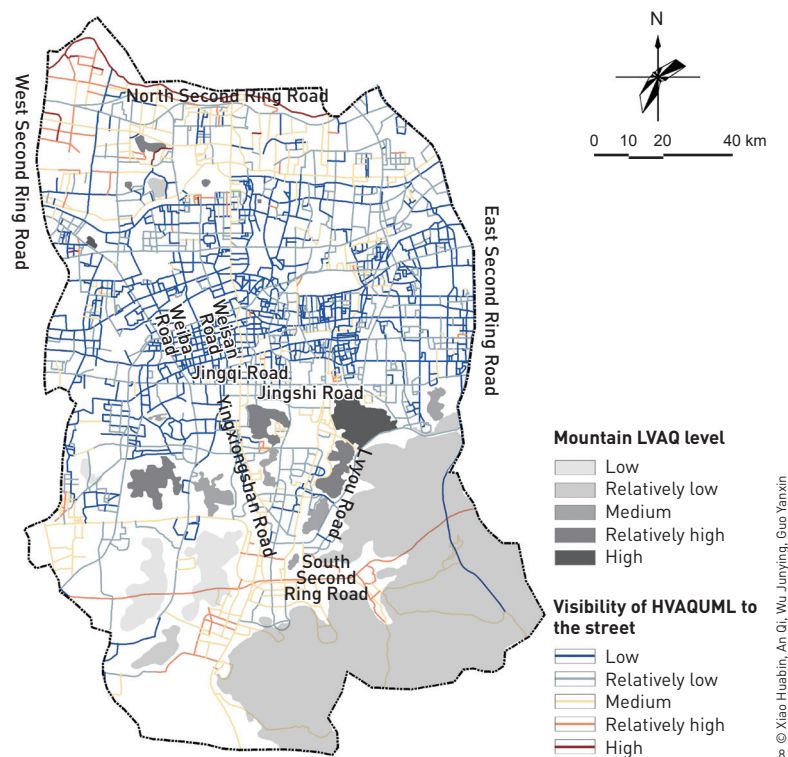
Table 2: Indicators of LVAQ evaluation of natural elements of urban mountains

Indicator	Impact correlation	Indicator interpretation
Degree of vegetation coverage	Positive	The mean NDVI values of each mountain
Degree of damage of the mountains	Negative	Percentage of bare area of a given mountain

Fenghuang Mountain, Yaoshan Mountain, Kuangshan Mountain, Sushan Mountain, and Qinglong Mountain; 6 medium-LVAQ mountains, including Dingzhi Mountain, Langmao Mountain, Qili Mountain, Wohu Mountain, Guishan Mountain, and Yanzi Mountain; and 8 lower-LVAQ mountains, including North Ma'an Mountain, Biaoshan Mountain, Baima Mountain, Mawuzhai Mountain, Wanling Mountain, Shuangding Mountain, Fohui Mountain, and Pingding Mountain.

7. 3D model of the study area and the viewshed analysis of the scenic area of "Buddha Mountain Reflection"





8. Evaluation results of the visibility of HVAQUML to the streets in the study area

5.1.2 Evaluation of the Visibility of HVAQUML to the Streets

To measure the visibility of each mountain to each sampling point, points on the ridgelines of each mountains at every 40 m intervals were taken as target points, and a 3D model of existing buildings and terrain in the study area constructed by ArcScene was used for viewshed analysis. The results revealed that Qinglong Mountain, Langmao Mountain, Qianfo Mountain, Fohui Mountain, Pingding Mountain, Wanling Mountain, and Mawuzhai Mountain were widely and clearly visible, especially the scenic area of the “Buddha Mountain Reflection” including Qianfo Mountain, Fuhui Mountain, and Pingding Mountain, which enjoyed the highest visibility in the study area (Fig. 7).

The visibility of HVAQUML to the streets can be evaluated by combining the evaluation results of the visibility of each mountain to the street sampling points with the LVAQ grade of each mountain (as the coefficient), calculating mean values of the corresponding streets, and then grading with Natural Breaks method in ArcGIS (Fig. 8). The results showed that the streets where HVAQUML is less visible were mainly found in the north-central part of the study area (between Xiaoqing River and Jingshi Road, accounting for about 66% of the total number of streets). Generally, the visibility

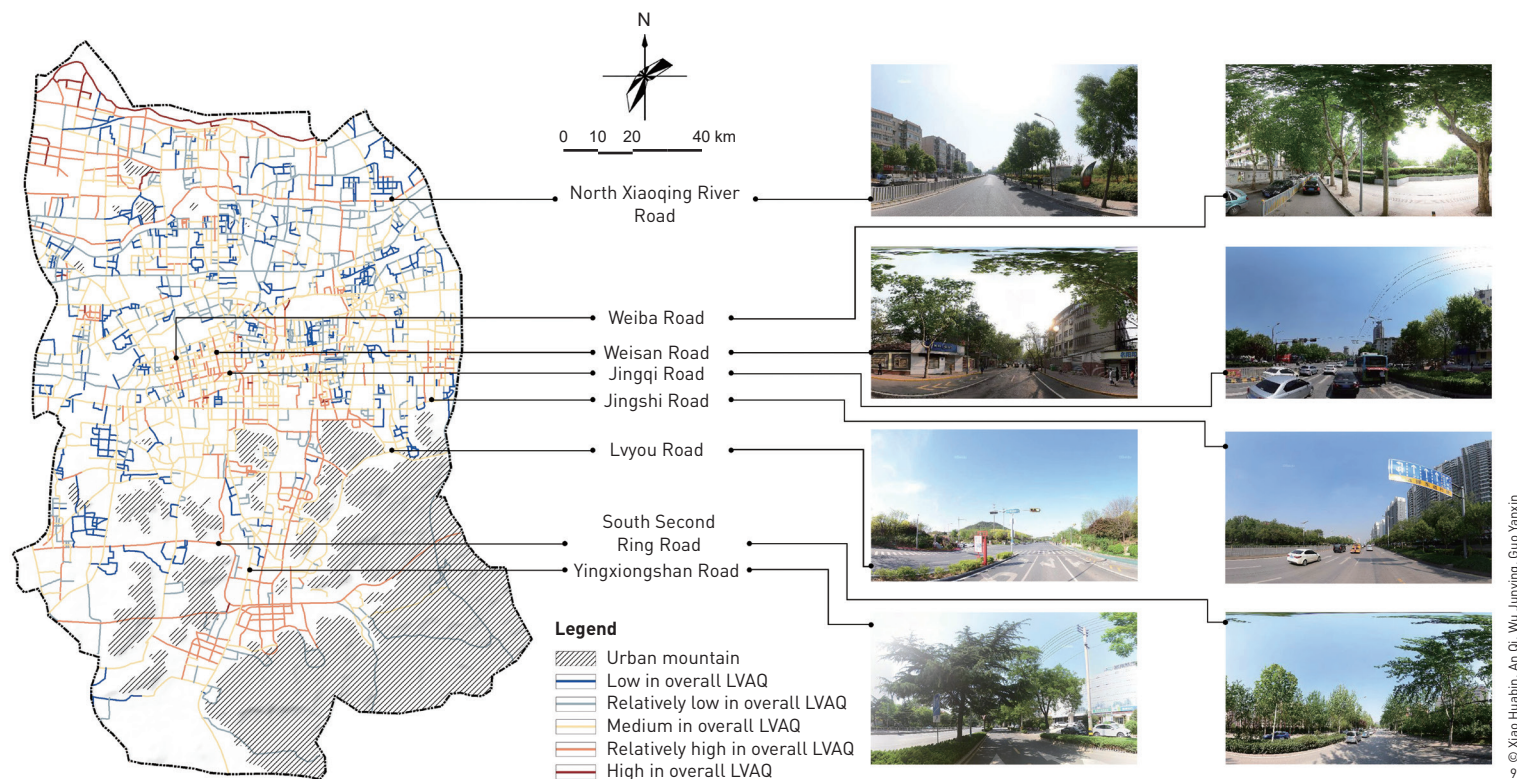
of HVAQUML to the streets at all levels was low or medium. There were 1,083 streets where HVAQUML is poorly visible (low and relatively low visibility, accounting for 78%), which mainly covered arterial roads and branch roads; there were 222 streets where HVAQUML is roughly visible (accounting for 16%), mainly among the expressways and secondary arterial roads in the northern and southern parts of the study area; there were 80 streets where HVAQUML is clearly visible (relatively high and high visibility, accounting for about 6%), mainly including a small number of branch roads and very few secondary arterial roads in the northern and southern parts of the study area.

5.2 Overall LVAQ Evaluation of Urban Street Pedestrian Spaces

The study superimposed the LVAQ and HVAQUML visibility evaluation results of urban streets to analyze the overall LVAQ of the street pedestrian spaces in the study area (Fig. 9). The results evidenced that overall LVAQ of the street pedestrian spaces in the study area was high. 622 streets were evaluated as having a higher (relatively high and high) overall LVAQ (accounting for 45%), mainly including arterial roads and distributed in south of Yaoshan District (in the northwest of the study area), on both sides of South Second Ring Road (in the south of the study area), and Jingshi Road in Shangbu Commercial Area and Mingfu Historic Area (in the center of the study area). The total number of medium LVAQ streets was 390 (accounting for 28%), dominated by expressways and concentrated in the center of the study area. The number of lower (low and relatively low) overall LVAQ streets totaled 373 (accounting for 27%), which were scattered throughout the study area and covered mainly branch roads.

Overall LVAQ of the street pedestrian spaces in the study area showed that the streets with high level of naturalness, diversity, harmony, and openness, and moderate level of disturbance and the visibility of HVAQUML^① are mainly found in and around Jingshi Road, as well as in some historical neighborhoods such as Jingqi Road, Weisan Road, and Weiba Road (in the center of the study area); South Second Ring Road, Yingxiongshan Road, and Lvyou Road (in the south of the study area); and North Xiaoqing River Road (in the north of the study area).

① The analysis results showed that there were few streets with a high level of naturalness, diversity, harmony, and openness, low level of disturbance, and high visibility of HVAQUML in the study area. Combined with field investigation, the research team determined that the streets with better overall LVAQ were the ones with high level of naturalness, diversity, harmony, and openness, and moderate level of disturbance and the visibility of HVAQUML.



9. The results of overall LVAQ evaluation of the urban street pedestrian spaces in the study area with the site photos of several streets

By combining the actual visual experience obtained in the street pedestrian spaces in the study area during field investigation with the results of medium and higher overall LVAQ streets (Fig. 9), it was found that during the actual visual aesthetic experience in the pedestrian spaces of expressways and arterial roads (such as Second Ring Road South, North Xiaoqing River Road, Jingshi Road, Yingxiongshan Road, Lvyou Road, and Jingqi Road), the perceived level of openness and naturalness were high, disturbance was moderate, and the visibility of HVAQUML in open areas were sound. Although most buildings on both sides of these streets were large in size, the perceived harmony level and the overall diversity was good due to the considerable street widths. In the secondary arterial roads and branch roads (especially Weisan Road and Weiba Road in the historical neighborhoods) which had less motor traffic, the overall vegetation coverage was often high, leading to the high and moderate levels of perceived naturalness and openness; Although there were more stores and buildings in the street front, the levels of perceived harmony and diversity was high, due to the current regulations on building height and size limits; Also, the perceived disturbance level was low because these streets had higher-ratio, continuous pedestrian spaces. However, since such

streets were often located within high-density built-up urban areas, the perceived visibility to HVAQUML was poor in the field investigation.

6 Strategies for Optimizing Landscape Visual Aesthetic Experience in Street Pedestrian Spaces in the Study Area

Based on the spatial structure of mountain-city integration in the study area, urban street pedestrian spaces with high LVAQ can not only provide citizens with visual pleasure and slow-lifestyle spaces, but also serve as corridors among mountains and other natural landscape elements in the city, so as to improve the city image by highlighting the aesthetic quality of urban mountains, especially the mountains with high-aesthetic-quality landscapes. Urban street spaces with varied levels and scales were different in terms of their friendliness to walking activities, and the specific elements that affect their visual aesthetics of the landscape also differ. Therefore, for the strategies of optimizing landscape visual aesthetic experience of urban street pedestrian spaces, streets' environmental elements related to characteristics of naturalness,

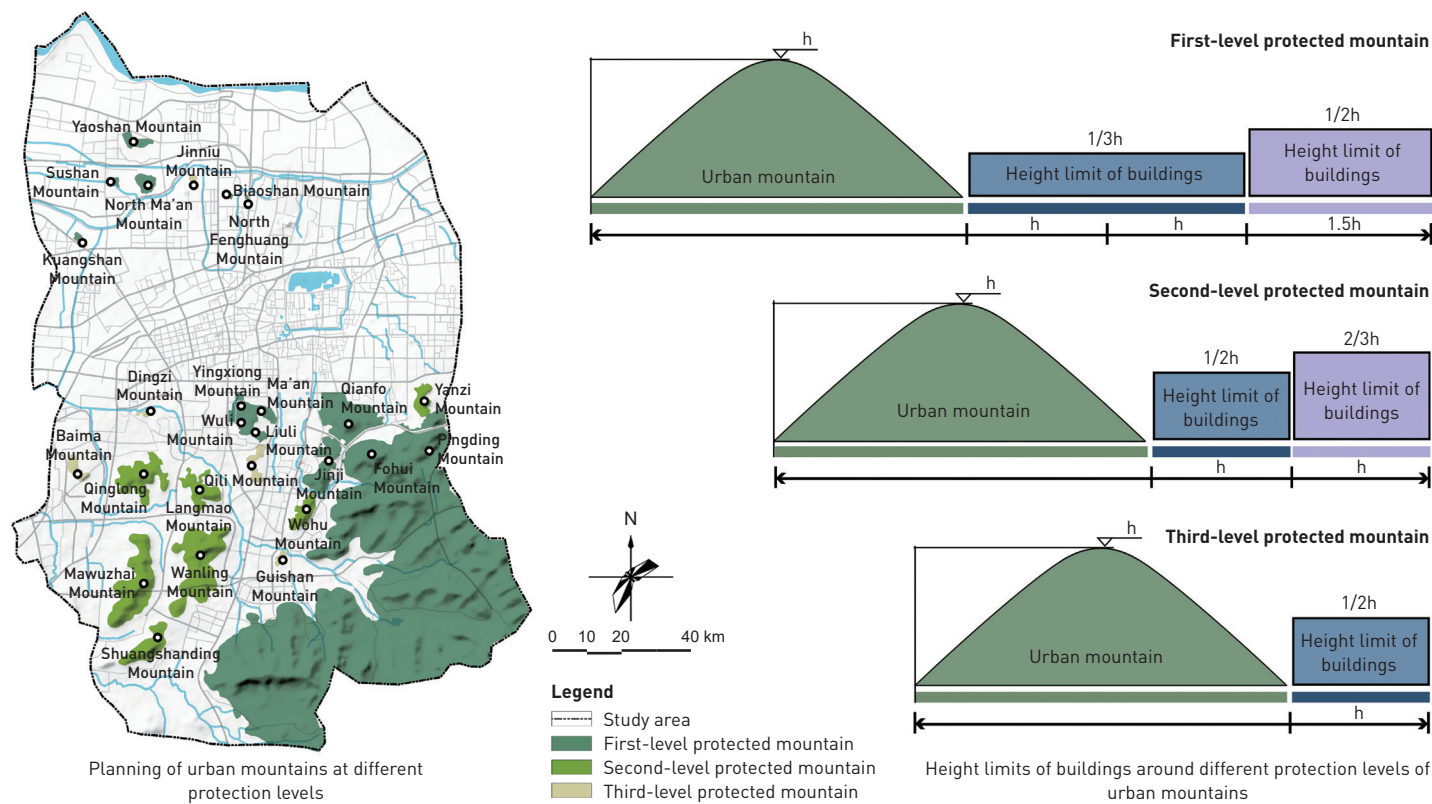
diversity, harmony, openness, and disturbance should be adjusted in line with their level and scale, as well as their cultural, historical, and environmental qualities.

1) For areas with primary or secondary streets and larger blocks, the existing ecological resources and landscape-city spatial pattern should be leveraged, with expressways of high LVAQ (e.g. Jingshi Road and North Xiaoqinghe Road) as the backbone, and so should the edge effect of the interlacing ecological zones formed by mountain patches and urban construction plots. It can help improve the existing fragmented or discontinuous ecological corridors, and create higher-level urban street pedestrian spaces with sound vegetation coverage and visually harmonious landscape at district scale, which would be important to enhance the ecological environment protection and visual landscape resources of the city.

2) For the major neighborhoods and residential areas, natural elements such as mountains should be wisely combined according to local conditions. Based on expressways, arterial roads, and secondary arterial roads (e.g. Yingxiongshan Road and Lvyou Road), a network of slow-traffic system with high vegetation coverage, rich landscape elements, open view, and safer walking environment can be created. At the same time, it should be combined with the

projects such as the remediation of damaged mountains and the construction of mountain parks, to improve the integration of ecological patches; According to specific conditions of mountains, efficient ecological techniques need to be introduced for local damage remediation, to improve the vegetation coverage of mountains and create an urban-mountain interface with a higher visual aesthetic quality.

And 3) in historical and cultural neighborhoods such as Shangbu Commercial Area and Mingfu Historic Area, higher-LVAQ streets (e.g. Jingqi Road, Weisan Road, and Weiba Road) should be used as a landscape resource, which can be combined with the current urban renewal projects on old residential areas and street fronts alongside the city's slow-traffic system, to form higher-LVAQ streets that also meet higher daily walking needs. At the same time, natural landscape elements such as mountains and forests should be integrated by adjusting or adding green spaces and vegetation planting; the configuration of natural or artificial elements that reflect the traditional landscape identities of the city—such as Spring Culture, Qilu Culture, and Literary Culture—can be improved to integrate multi-cultural characteristics and the beauty of the city's traditional inter-connected streets and alleys system.



10. Protection planning and surrounding building height control requirements for urban mountains of different projection levels in the study area

In addition, as mentioned above, the visibility of urban mountains is impacted by the density and height of surrounding buildings. Therefore, the aesthetic experience services based on the visual resources of mountains can be improved by delineating the protection level of urban mountains and the corresponding limitations in building density and height around them^[35]. In order to optimize HVAQUML interfaces, according to the requirements by Jinan Central Urban Mountain Protection and Mountain Periphery Landscape Spatial Control Plan, this paper suggests that Qianfo Mountain, Fohui Mountain, Pingding Mountain, and other mountains in the Buddha Mountain Reflection scenic area with outstanding ecological, cultural, and landscape (high LVAQ) values, or the mountains with peak height above 300 m (DEM) and with a relative attitude above 250 m can be classified as first-level protected mountains. For the surrounding areas of such mountains, it is appropriate to stipulate the construction density of multi-storey buildings no higher than 30%, and 25% for high-rise buildings^[30]; the building height in the distance of 2 and 3.5 times the peak height from its edge should not exceed 1/3 and 1/2 of its height respectively^[30]; In addition, the building height within 200 m of the edge of the main mountain should not exceed 36 m (Fig. 10).

7 Conclusions

Urban streets support citizens' daily commuting, living, social, and leisure and recreation. The study started with viewing the landscape aesthetic visual characteristics of street pedestrian spaces by focusing on the historic downtown of Jinan, and measured and evaluated LVAQ of street pedestrian spaces using panoramic static streetscapes and deep learning method. Based on the evaluation of the aesthetic quality of mountains and viewshed analysis, the visibility of HVAQUML to the streets was evaluated, and then the overall LVAQ evaluation of urban street pedestrian spaces in mountainous cities was realized. Then, informed with the overall LVAQ evaluation results of urban street pedestrian spaces, the paper proposed a series of optimization suggestions of the streets at different levels to improve the harmony with urban mountain landscapes. The study hopes to provide a reference for the creation of mountain-city integration urban landscapes, as well as the healthy and sustainable urban development.

In addition, due to the complexity of factors influencing people's visual perception and the diversity of actual needs, future research that verifies the rationality and credibility of this quantitative method is expected. It should also be combined

with the age and identity characteristics of different users and corresponding usage needs to propose more targeted strategies for optimizing the visual aesthetics of urban street pedestrian spaces.

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山城一体背景下街道步行空间景观视觉美学质量测度、评价与优化——以山东省济南市旧城片区为例

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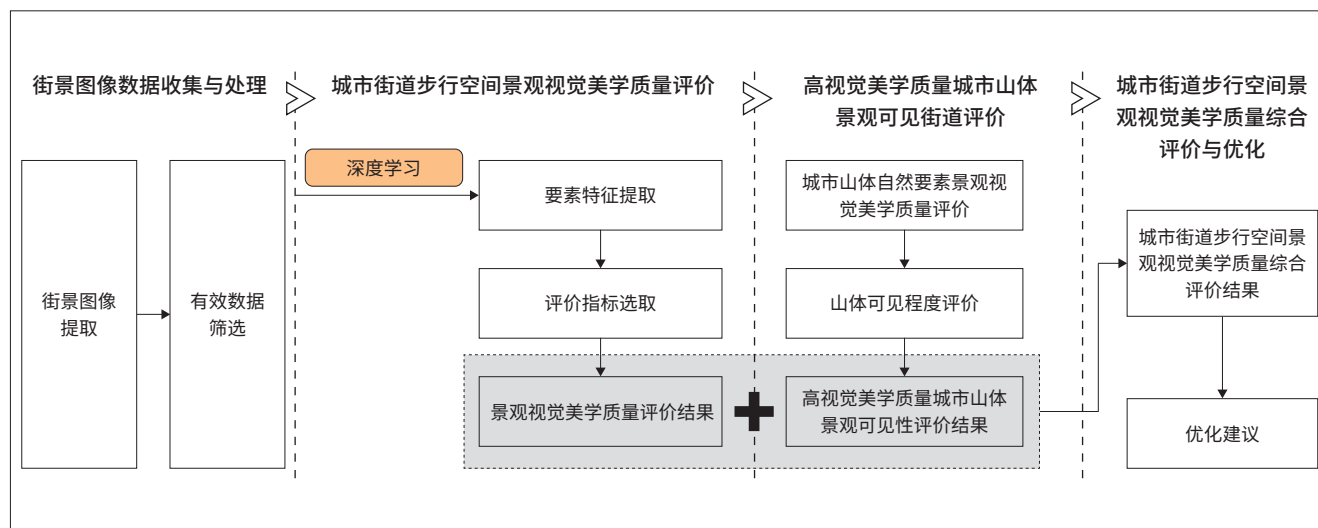
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图文摘要



文章亮点

- 基于街景数据测度了步行环境下的城市街道景观视觉美学质量
- 基于视域分析方法评价了高视觉美学质量山体可见街道
- 结合实例提出山城一体背景下的街道步行空间景观视觉美学质量优化建议

摘要

城市街道步行空间承载了居民日常通勤、交往和游憩等重要活动, 其景观视觉资源是城市景观风貌的重要组成部分, 也是提升街道空间品质和活力、引导城市健康可持续发展的重要载体。同时, 作为城市空间架构的重要生态载体与自然要素, 山体在打造“山城一体”的城市空间结构与景观风貌特征中起着重要作用。

本研究以具有典型山城空间特色的济南市旧城片区为例, 在分析街道步行空间景观视觉审美表现特征——自然性、多样性、开阔性、协调性和干扰性——的基础上, 基于街景图像数据对街道步行空间景观视觉美学质量进行了测度, 同时对高视觉美学质量城市山体景观可见街道进行了识别; 最后, 根据街道步行空间景观视觉美学质量综合评价结果, 提出了针对不同等级城市道路结合山体风貌协调的步行空间景观视觉美学质量优化建议, 以期为打造“山城一体、城景相融”的城市景观风貌和引导城市健康可持续发展提供借鉴。

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关键词

山城一体; 街道步行空间; 景观视觉美学质量; 高视觉美学质量城市山体景观可见度; 定量评价; 城市街景

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1 引言

随着城市建设对土地需求的不断增长,中国城镇正逐渐由人口过于稠密的平原地区向山地区域扩张^[1]。关于“山—城”的研究多从“山水城市”的概念延伸而来,提倡以山水为代表的自然环境与以城市为代表的人工环境相融合的人类聚居环境建设^[2]。以“山水城市”聚居环境研究为基础,已有许多专家学者分别从城市特色和文化塑造的角度探讨了城市山水的重要性与格局构建方法^{[3]-[5]}。作为城市空间架构的重要生态载体与自然要素,城市山体在一定程度上能够决定城市空间结构、布局及城市景观风貌,特别是在山地城市中。“山城一体”^{[2][6][7]}模式是指在城市尺度上以山体格局为重要的结构性要素,引导构成不同城市空间形态;其在街区尺度上表现为建成区向山体蔓延的空间关系^[2]。

城市街道承载了居民日常通勤、休闲游憩、文化交流和生态环境保护等功能,其中街道步行空间景观对居民的景观视觉审美感知有决定性影响^[8]。景观视觉审美感知行为强调人们在视觉层面与景观发生反馈与交互^[9]。目前,城市街道的景观视觉美学质量测度与评价研究日益增多,量化指标常以城市建筑、道路、构筑物等人工景观要素,以及植被、天空等自然景观要素在城市空间中的构成为主^{[9]-[11]}。然而,这些评价研究多聚焦于人眼可视距离较为有限的城市街道,而对山城一体发展背景下,综合人眼可视距离内相对较远的城市山体的景观视觉美学质量评价探讨较少。因此,本文基于山城一体空间架构,在新数据环境下分析大量街景图像等开源数据,继而运用精细化评价方法综合评价具有典型山城空间特色的城市街道步行空间景观视觉美学质量,并以此探究山城一体城市街道步行空间品质优化的途径。

2 城市街道步行空间景观视觉美学质量评价途径

2.1 城市景观视觉审美表现特征

作为生态系统文化服务的重要组成部分,景观审美体验服务意指人类通过视觉、听觉、嗅觉等感官能力从环境中获取的非物质获益,通常表现为感官上的愉悦感或精神上的舒适感^[12]。受空间审美感受和自然文化环境影响,城市景观视觉审美具有自然性、多样性、开阔性、协调性、干扰性等表现特征^[13],且各项特征间存在复杂的相互关系。针对不同类型与尺度的城市公共空间,尽管使用者视觉审美特征偏好略有不同,但总体上倾向于自然性、多样性及开阔性较高,协调性较好、干扰性较低的视觉景观空间^{[14]-[16]}。此外,视觉美学质量良好的山体作为山城一体城市空间优质景观风貌的重要构成载体,使用者可通过一定视域范围内山体自然景观参照物(林地、灌丛等)和山体周边人工景观参照物(城市建筑等)形成的丰富视觉关系,获取具有独特视觉景观特色的审美感受,从而获得审美体验服务。

2.2 城市街道景观视觉美学质量定量评价方法

审美体验是较易被感知的生态系统文化服务产品功能类型^[16],但由于其难以以货币价值量化,因此相关研究多借助可描述的景观视觉审美特征要素,并选取相关指标定量评价不同景观类型的审美体验服务能力^[12]。

1) 自然性:自然性对景观视觉审美体验的影响较为公认,通常空间内景观的自然性越高,给人们带来的视觉审美体验感受越好。该特征可通过街景图像内植被等自然景观要素的占比反映,并通常与植被覆盖率呈正相关^[17];

2) 多样性:多样性主要受景观要素的复杂性影响,当空间的景观要素构成丰富时,人们通常能在该空间中获得较好的视觉审美体验。韩君伟等人的研究证实视觉熵与景观要素呈复杂性呈显著正相关^[11],可以作为反映街道景观多样性的量化指标;

3) 协调性:协调性关注由景观空间各构成要素间的搭配所营造的整体视觉审美感受,可通过搭配合理程度来衡量。本研究参考吴建生等人的相关研究结论^[13],以城市中自然与人工景观的面积比例量化反映该指标;

4) 开阔性:开阔性主要指使用者在街道步行空间中通过视觉感知到的空间范围;当视野较为开阔时,人们的视觉审美感受通常较好。李雪莹等人通过测量以人眼平视视角采集的街景图像中天空面积占比进行开阔性评价,发现天空所占面积越大,其所对应街道的开阔性及视觉美学质量越高^[18]。

5) 干扰性:街道审美体验和步行活动易受街道环境安全感受干扰,且较少的非机动车有助于提高街道景观的恢复能力^[19]。在唐婧娴等人的研究中,街道机动化程度可通过车行道路和机动车图像面积占比与人行道图像面积比重的差值进行量化评价^[20]。

分析居民对山体高品质自然景观的可见程度是衡量山体景观视觉美学质量的有效方式^[21]。既有研究常运用美景度评价法(Scenic Beauty Estimation Method)并借助GIS等技术手段,多考虑山体植被覆盖情况与影响山体景观获取视线的山体周边建筑高度控制情况等因素。其中,陈梓茹等人通过问卷分析居民偏好,发现大多数受访者认同山体形态和景观质地的变化能影响山体美学质量的高低^[22];作为影响山体立面形态和表面质地的重要方面,植被生长状态及植被覆盖度常采取归一化植被指数(NDVI)等指标进行测算^[23]。与此同时,部分城市工程建设等人工活动造成的局部地形、地貌、植被等突变而成的山体裸露空隙可见区域同样属于街道步行空间中居民视觉感知的敏感区,裸露山体可见面积越大、与周围自然环境视觉反差越明显,造成的视觉冲击及污染程度越高^[24];对于山体裸露部分造成的视觉美学质量影响,可综合所在山体周边交通环境、裸露面积及裸露部分可见情况进行量化^[24]。相较于建筑单体而言,针对城市山体的可见程度控制更应考虑街道可见范围中的建筑

群体与被观赏山体间的视觉关系，对相关可见性控制要素则可通过视廊视域分析方法进行量化^[25]。

此外，城市规划、景观设计学和建筑学等学科借助不断发展的计算机视觉领域和机器学习算法，已开始应对城市人居环境问题。其中，使用机器学习算法的卷积神经网络工具对图像进行语义分割以提取街景图片要素特征的研究方法，已被大量运用在街道绿化和城市风貌评价等景观视觉美学质量研究领域。利用深度学习分析方法计算通过谷歌、百度等开放数据平台获取的大量街景图像数据，不仅改善了以往街道基础数据获取难、处理量大、耗时长等问题，同时也为城市街道要素特征与视觉美学质量的大规模、精细化评价提供了技术支撑^{[26][27]}。

3 研究区域与研究方法

3.1 研究区域

本研究选取山东省济南市旧城片区（该市人口和路网最为集中的地区）作为研究区域，整体面积约203.51km²，包括1 300余条街道^[28]（图1）。研究区域中泰山余脉山体分布众多，多为山体公园和城市型风景名胜^[29]。2017年开始，济南市政府逐步开展了破损山体整治和山体公园建设等工作，本文的研究区域作为济南“山水融城”格局的典型代表，面临着如何有机更新并提升以街道步行空间为重要组成部分的城市慢生活空间品质的挑战。本研究利用海量街景图像数据和深度学习方法，结合高视觉美学质量城市山体景观可见性的叠加分析，旨在实现大样本、高效率的多特征城市街道步行空间景观视觉美学质量综合评价，以为提升山城一体城市景观风貌提供参考^[30]。

3.2 研究路径与方法

本研究主要包含街景图像数据收集与处理、城市街道步行空间景观视觉美学质量评价、高视觉美学质量城市山体景观可见街道评价，以及城市街道步行空间景观视觉美学质量综合评价与优化4个阶段（图2）。

3.2.1 街景图像数据收集与处理

研究基于开源地图数据获取研究区域城市街道信息，数据采集时间为2019年5月，四级街道（快速路、主干路、次干路和支路）的数量分别为24、81、237与1 043条，并在ArcGIS 10.4软件平台协助下逐条提取各级城市街道拐点及间隔100m的节点坐标；基于Python 3.5与PyCharm平台访问百度地图API，抓取各提取坐标点位置的1 024×512像素的街道全景静态图，为模拟使用者视角的视觉感知程度，将其垂直角度设置为0°、水平角度设置为360°；在剔除高架、隧道等无步行环境的无效街景数据后，为消除街景图片采集车对识别结果的干扰，批量裁剪去除图像数据

中采集车部分，最终获取研究区域内1 024×290像素的城市街景图片共20 847张（图3）。

3.2.2 城市街道步行空间景观视觉美学质量评价

研究采用由谷歌团队开发的语义分割工具DeepLab v3+进行街景图像特征提取，该工具结合了DenseCRFs概率图模型和深度卷积神经网络（Diffusion-Convolutional Neural Networks, DCNNs），在Cityscapes数据集上的均交并比（Mean Intersection over Union, MIoU）为82.1%^[31]，对图像分割的精度较高，并已有相关研究将该数据集应用于中国城市街道的研究^[32]。因此，研究基于Python 3.5平台，使用谷歌开发的深度学习开源库Tensorflow人工智能学习系统，建立DeepLab v3+开源图像语义分割深度学习模型，在Cityscapes精细图像集基础上，对处理后的街道全景静态图进行要素解译，识别各要素在图像中所占像素点比例。在此基础上，参考城市街道景观审美特征，并依据各指标量化方法计算评价结果，借助ArcGIS软件展示城市街道景观视觉美学质量评价空间分布结果。

3.2.3 高视觉美学质量城市山体景观可见街道评价

在本研究中，高视觉美学质量城市山体景观可见街道，主要指居民在其中进行步行活动时可通过视觉感知到城市山体且感知到的山体获得较高景观美学质量评价的城市街道。高视觉美学质量城市山体景观可见街道空间评价建立在山体景观视觉美学质量评价与山体可见程度评价的基础上。根据前文中对影响居民感知城市山体视觉审美的相关要素分析，选取山体植被覆盖程度与山体裸露程度分别量化，并叠加获取山体自然要素景观视觉美学质量评价结果，计算山体美学质量评价等级。基于视域分析衡量城市山体在各街道采样点的可见程度，叠加山体美学质量等级，取各采样点乘积均值并赋值于每条街道，由此评价高视觉美学质量城市山体景观可见街道。

3.2.4 城市街道步行空间景观视觉美学质量综合评价与优化策略

根据上述城市街道步行空间景观视觉美学质量与高视觉美学质量城市山体景观可见街道评价结果，加权叠加最终获取城市街道步行空间景观视觉美学质量综合评价结果，并通过分析不同等级街道的景观视觉美学质量特征，针对性地提出优化策略。

4 城市街道景观视觉美学质量评价

4.1 基于街景数据与深度学习的城市街道景观视觉美学质量测度

根据研究区域内街道全景静态图的要素识别结果，在排除样本量较少或意义较小的要素类别后，共获取植物、建筑、天空、人行道、车行

道等共计18类要素^[33] (图4)。研究将自然性、多样性、协调性、开阔性与干扰性这五个城市街道景观审美特征作为城市街道步行空间景观视觉美学质量评价指标,并分别进行测度(表1)。

其中,车行环境要素包括车行道、小汽车、货车、公交车、摩托车、自行车和骑行者;人行环境要素包括人行道和行人;自然要素包括植物、天空和被低矮灌木与草本植物覆盖的地表;人工要素包括建筑、人行道、车行道、围栏、墙体、柱体、交通信号灯、道路标识。自然要素视觉熵计算公式如下:

$$H = - \sum_{i=1}^n p_i \ln p_i \quad (1)$$

式中, H 为街景图片自然要素视觉熵值, p_i 为第*i*项自然要素出现的概率($i=1,2,3,\dots,n$, n 为研究对象总数),当 $p_i=0$ 时, $\lim_{p_i \rightarrow 0} p_i \ln p_i = 0$ 。

研究使用ArcGIS空间连接功能,以街道采样点各指标均值为该街道景观视觉美学质量赋值;进而采用自然断点法分级,获得各级城市道路景观视觉美学质量评价可视化结果(图5)。研究结果显示,研究区域内自然性水平较高的城市街道占比达17%,主要分布于研究区域东南部的旅游路以北区域,以及研究区域中部和南部的小清河以南的各级城市道路;多样性水平较高的城市街道占比达7%,主要包括位于研究区域中心的道路及部分城市快速路和主干路;协调性水平较高的城市街道占比达5%,主要包括研究区域东南的旅游路、二环南路和北部的二环北路;开阔性水平较高的城市街道占比达61%,主要为研究区域城市快速路和主干路;干扰性水平较低的城市街道占比达70%,在研究区域各级道路中均占比较高。

4.2 城市街道步行空间景观视觉美学质量评价

熵值法是一种客观赋权方法,相较专家打分和层次分析等方法,更能够弱化主观因素的干扰^[34]。研究采用熵值法计算各指标权重进行叠加,主要包括数据标准化、指标信息熵计算,以及指标权重确定三个部分。数据标准化公式为:

$$S_{ij} = (x_{ij} - x_{min.i}) / (x_{max.i} - x_{min.i}) \quad (2)$$

$$S_{ij} = (x_{max.i} - x_{ij}) / (x_{max.i} - x_{min.i}) \quad (3)$$

当评价对象总数为 m ,指标数量为 n 时,式中 S_{ij} 为第*j*个评价对象的第*i*个指标标准化值, x_{ij} 表示第*j*个评价对象的第*i*个指标值, $x_{max.i}$ 和 $x_{min.i}$ 分别为第*i*项指标的最大值和最小值。其中, $i=1,2,3,\dots,n$, $j=1,2,3,\dots,m$ 。其中,指标指向为正向时选用式2,指标指向为负向时选用式3。

指标信息熵计算公式为:

$$p_{ij} = S_{ij} / \sum_{j=1}^m S_{ij} \quad (4)$$

$$e_i = -(1/\ln m) \sum_{j=1}^m p_{ij} \ln p_{ij} \quad (5)$$

式4、5式中, p_{ij} 为第*i*个指标下第*j*个评价对象的贡献度, e_i 为第*i*项指标信息熵值。对于第*i*项指标,指标值 S_{ij} 的差异越大,对评价对象评价的作用越大,熵值越小。因此,指标权重计算公式为:

$$w_i = (1 - e_i) / \sum_{i=1}^n (1 - e_i) \quad (6)$$

式中, $(1 - e_i)$ 表示第*i*项指标的差异系数, $(1 - e_i)$ 越大指标越重要; w_i 表示各指标权重, $i=1,2,3,\dots,n$ 。

根据熵值法计算结果,各指标权重计算结果分别为:0.17(自然性),0.07(多样性),0.51(协调性),0.05(开阔性)和0.2(干扰性)。基于ArcGIS叠加分析功能计算各街道景观视觉美学质量评价结果,采用自然断点法进行分级,获取研究区域内城市街道景观视觉美学质量评价空间分布(图6)。

评价结果显示,研究区域内街道步行空间整体景观视觉美学质量较高,其中较高和高美学质量道路390条,占比约28%,各级道路较其总数而言所占比例较为均等;中等美学质量道路511条,占比约37%,分布较广,以城市快速路、主干路和次干路为主;低和较低美学质量道路484条,占比约35%,以城市支路为主。

表1:步行环境下城市街道景观视觉审美质量评价指标

测度指标	指标指向	指标内容
自然性	正向	植物要素像素数占比
多样性	正向	自然要素视觉熵
协调性	正向	自然要素占比与人工要素占比比值
开阔性	正向	天空要素像素数占比
干扰性	负向	车行环境要素比重减去人行环境要素占比

5 城市街道步行空间景观视觉美学质量综合评价

5.1 高视觉美学质量城市山体景观可见街道评价

5.1.1 城市山体自然要素景观视觉美学质量评价

城市山体自然要素景观视觉美学质量评价指标（表2）由两部分构成。研究首先基于DEM数据确定研究区域内的山顶点，并结合等高线确定各山体具体范围。在ENVI遥感图像处理平台支持下，计算各城市山体的NDVI均值，表征现状城市山体植被覆盖程度。通过最大似然法对基于影像数据获取的可分离性较好训练样本进行监督分类，获取现状城市山体裸地空间分布并计算其面积占比，表征山体破损程度。

采用熵值法计算各指标权重进行叠加，获取山体景观视觉美学质量评价等级，发现研究区域内的26处山体中，较高和高品质山体12处，包括千佛山、金鸡岭、英雄山、马鞍山、五里山、六里山、金牛山、北凤凰山、药山、匡山、栗山和青龙山；中等品质山体6处，包括丁字山、郎茂山、七里山、卧虎山、龟山和燕子山；低和较低品质山体8处，包括北马鞍山、标山、白马山、马武寨山、万灵山、双山顶、佛慧山和平顶山。

5.1.2 高视觉美学质量城市山体景观可见街道评价

以研究区域内山体山脊线上每隔40m取点，基于ArcScene构建的研究区域现状建筑与地形三维模型进行视域分析，衡量各山体在各采样点上的可见程度。根据计算结果，以青龙山、郎茂山、千佛山、佛慧山、平顶山、万灵山和马武寨山为主的山体可见范围广、可见程度高，其中，由千佛山、佛慧山和平顶山构成的“佛山倒影”的山体区域是研究区域内可见程度最高的山体（图7）。

研究将各山体于街道采样点上的可见程度评价结果与各山体景观视觉美学质量评价等级结果（作为系数）相乘，以街景采样点为单位获取高美学质量城市山体景观可见程度评价结果；然后采用ArcGIS空间连接方法，计算各街道采样点高美学质量城市山体景观可见程度评价结果均值，并对该街道赋值，进而通过自然断点法对高品质山体可见街道进行评价（图8）。评价结果显示，研究区域中北部的小清河以南和经十路以北范围内城市街道的高视觉美学质量城市山体景观可见程度较低，约占道路总数的66%。此外，各级城市街道高视觉美学质量城市山体景观可

见程度以低和中等为主。高视觉美学质量城市山体景观可见程度低和较低的道路共计1 083条，占比约78%，以城市主干路和支路为主；高视觉美学质量城市山体景观可见程度中等水平道路222条，占比约16%，主要为研究区域北部及南部的城市快速路和次干路；高视觉美学质量城市山体景观可见程度较高和高水平道路80条，占比约6%，主要包括研究区域北部及南部的少数支路和个别次干路。

5.2 城市街道步行空间景观视觉美学质量综合评价

研究叠加城市街道景观视觉美学质量评价与高视觉美学质量城市山体景观可见街道评价结果，分析研究区域内街道步行空间综合景观视觉美学质量（图9）。叠加结果显示，研究区域内街道步行空间综合景观视觉美学质量较高。其中，综合景观视觉美学质量较高至高的道路共622条，占比约45%，以城市主干路为主，主要分布在研究区域西北的药山片区南部、研究区域南部的二环南路两侧部分区域，和研究区域中部的经十路商埠、明府城路段；综合景观视觉美学质量中等的道路390条，占比约28%，其中多数为城市快速路，并集中分布于研究区域中心地带；综合景观视觉美学质量低和较低的道路373条，占比约27%，散布于研究区域内，以城市支路为主。

研究区域内街道步行空间景观视觉美学质量综合评价结果显示，具有自然性和多样性水平较高、协调性和开阔性水平较好、干扰性水平与高品质山体可见程度适中特点的城市街道^①，主要包括研究区域中部以经十路为主，南部以二环南路、英雄山路、旅游路为主和北部以小清河北路为主的城市快速路，以及研究区域中心的以经七路、纬三路、纬八路为主的传统街坊社区道路。

结合实地调研过程中在街道步行空间中的实际视觉体验，与量化分析结果中综合景观视觉美学质量中等和高的街道对比发现（图9），以二环南路、小清河北路、经十路、英雄山路、旅游路、经七路为主的城市快速路和主干路的步行空间，实际视觉感知到的开阔性、自然性水平较高，干扰性水平适中，于街道内视野开敞处的高美学质量城市山体景观可见程度较好。此外，由于该类街道尺度较大，街道两侧虽具有较大体量的建筑，但协调性和整体多样性较好。而在机动化程度较低的城市次干路和支路，特别是位于传统街坊社区内部的纬三路、纬八路等街道，整体植被覆盖率高，因此在实际视觉体验过程中，可感知到的街道步行

表 2：山体自然要素景观视觉美学质量评价指标

测度指标	指标指向	指标内容
植被覆盖程度	正向	城市山体归一化植被指数均值
山体破损程度	负向	城市山体裸地面积占比

^① 分析结果显示，研究区域内几乎不存在自然性和多样性水平较高、协调性和开阔性水平较好、干扰性水平较低，且高美学质量城市山体景观可见程度较高的街道。结合实地调研情况，研究团队认为整体表现较好的街道呈现出自然性和多样性水平较高、协调性和开阔性水平较好、干扰性水平与高美学质量城市山体景观可见程度适中的特点。

空间自然性水平高，开阔性适中；尽管沿街界面商铺及建筑较多，但由于对城市建筑高度及体量的限制，整体协调性和多样性较高；同时，由于该类街道具备面积占比较高且较为连续的人行道路空间，因此整体干扰性水平较低。然而，由于其地处高密度的城市建成区内部，该空间内的城市山体体量较小，可见界面较少，因此在实际调研过程中对高视觉美学质量城市山体景观的可见程度较低。

6 研究区域街道步行空间景观视觉审美体验优化策略

在“山城一体”空间架构下，景观视觉美学质量较高的城市街道步行空间，不仅需为城市居民提供视觉审美享受和慢生活空间，同时还需强调与城市山体等自然要素的串联衔接，以此向城市山体，特别是高视觉美学质量城市山体景观因时因地借景。不同等级与尺度的城市街道空间对步行活动的友好程度不同，影响其景观视觉审美体验的具体构成要素也存在一定差异。因此，针对城市街道步行空间的景观视觉审美优化策略的制定，本文认为应根据城市道路等级、尺度，结合其所在的特定文化、历史与自然环境，调整并优化与自然性、多样性、协调性、开阔性和干扰性5个景观视觉审美特征指标相关的街道环境构成要素。

1) 针对研究区域内道路等级较高、街区尺度较大的区域，应依托现有景观生态资源与城市山水格局，以景观视觉美学质量较高的经十路、小清河北路等城市快速路为骨架，充分利用山体生态斑块与城市建设用地交错形成的生态交错带的边缘效应，完善被割裂或不连续的现状景观生态廊道，构建街道级别较高、植被覆盖率较高且视觉景观协调的片区尺度城市街道步行空间，发挥对市域生态环境保护和景观视觉资源提升的重要作用。

2) 针对研究区域各主要组团内部，因地制宜结合城市山体等自然景观要素，以英雄山路、旅游路等城市快速路、主干路及次干路为基础，打造植被覆盖率高、景观要素丰富、视野开阔和步行环境较为安全的城市慢行系统网络；同时结合济南市破损山体整治和山体公园建设行动整合破碎生态斑块，根据实际情况有针对性地对山体破损面采取高效生态修复技术手段，提升山体植被覆盖率，打造视觉美学质量较优的城市山体界面。

3) 在以商埠区和明府城为代表的研究区域历史文化街区，依托经七路、纬三路和纬八路为主的景观视觉美学质量较高的街道，协同现有城市慢行支路两侧现状改造旧住区和旧院区沿街界面，形成满足周边社区居民高频次日常步行活动需求、景观视觉美学质量较高的街道；同时协同山体、林地等自然景观要素，调整、增设部分绿地和植被种植，结合体现济南泉水文化、齐鲁文化和名士文化等具有济南传统风貌特征的自然或人工景观要素的合理配置，营造多文化融合且兼具经纬坊巷特色美

感的城市景观。

此外，如前文所述，城市山体可见程度受周边建筑密度和高度影响较大。因此，为提升以山体视觉资源为主的审美体验服务还可通过划定城市山体保护级别，并提出相应的山体周边建筑密度与建筑高度控制要求等方法来实现^[35]。为优化高视觉美学质量城市山体景观可见界面，结合《济南市中心城山体保护及山体周边景观空间控制规划》中的相关要求，宜将千佛山、佛慧山、平顶山等济南市“佛山倒影”区域内具备重要生态、人文和景观价值（高景观视觉美学质量），或主峰海拔高度300m以上且相对海拔高度250m以上的城市山体，划分为一级保护山体。针对该类山体，宜规定其周边多层建筑建筑密度不超过30%、高层建筑建筑密度不超过25%^[30]；同时在其山体主体边缘2倍、3.5倍山体高度范围内，设置建筑高度分别不超过1/3和1/2山体高度的上限参考值^[30]；此外，山体主体边缘200m范围内建筑高度不宜超过36m（图10）。

7 结语

城市街道是承载居民日常通勤、生活、交往、游憩等活动的重要空间载体。研究从街道步行空间景观视觉审美表现特征入手，以济南市旧城片区为例，采用街道全景静态图数据和深度学习方法，对街道步行空间景观视觉美学质量进行了测度与评价，并基于山体美学质量评价和视域分析方法，识别了高视觉美学质量城市山体景观可见街道，实现了对山城一体城市街道步行空间景观视觉美学质量的综合评价。其次，根据街道步行空间景观视觉美学质量综合评价结果，本文提出了针对不同等级城市道路结合山体风貌协调的步行空间景观视觉美学质量优化建议，以期期为打造“山城一体、城景相融”的城市景观风貌和引导城市健康可持续发展提供借鉴。

此外，由于影响居民视觉感知因素的复杂性与居民实际需求的多样性，未来研究应进一步加强检验该量化方法的合理性与可信度；还应结合不同使用者年龄、身份特征及其对应的具体使用需求，提出更具有针对性的城市街道步行空间景观视觉审美优化策略。

图 1. 研究区域及城市街道与山体空间分布

图 2. 研究路径

图 3. 研究区域内街景静态图采样点数据抓取示意图

图 4. 研究区域内街道全景静态图爬取及语义识别结果

图 5. 研究区域内城市街道各项景观视觉美学质量评价指标计算结果

图 6. 研究区域内城市街道景观视觉审美评价空间分布结果

图 7. 研究区域内三维模型及“佛山倒影”山体空间区域景观视觉效果

图 8. 研究区域内山体审美质量等级与高品质山体可见空间评价结果

图 9. 研究区域内街道步行空间景观视觉审美综合评价结果与部分位置街道实景图

图 10. 研究区域内各类城市山体分级保护规划及周边建筑高度控制要求