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RAV model: Study on urban refined climate environment assessment and ventilation corridors construction

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ABSTRACT

Urban ventilation corridors play a crucial role in regulating urban climate, alleviating urban heat island effect and deterioration of air quality. Considering various factors influencing the city wind environment and based on GIS evaluation methods, we establish a refined assessment model for urban ventilation (RAV model), which provides a reference for the ventilation corridors design. In case of Xi'an, a typical inland city in China, the thermal load index composed of land surface temperature and PM2.5 concentration is introduced to distinguish the urban cold islands and heat islands. The RAV model is calculated according to six influencing factors related to urban spatial morphology, including water body, green land area, road density, average building height, building density, and urban terrain. Furthermore, we have developed ventilation assessment maps with spatial resolutions of 100 and 10 m, which are more refined than the scale of existing studies. On this basis, combined with urban wind environment and the thermal load map, a multi-stage air duct system is generated by using the least-cost path method. As a result, the study area revealed six candidate first-class air ducts, as well as the metropolitan area of Xi'an revealed four candidate second-class air ducts. The evaluation results are more pragmatic than those based on frontal area density. This study provides quantitative reference for urban climate zoning optimization and ventilation corridor control strategies in the process of cost effective and environmentally habitable cities.

1. Introduction

By the end of 2021, China's urban population reached 914.25 million, and the urbanization rate of permanent residents reached 64.72 % (www.stats.gov.cn), indicating that urbanization has entered a stage of high-quality development. With the rapid growth of urban population and limited urban space, urban sprawl shows a trend of high-density development, resulting in a surge of high-rise buildings within built-up areas [1,2]. The growing urban roughness and dense human emissions create particular urban climates, characterized by phenomena such as urban heat islands (UHIs), urban rain islands, and urban turbid islands [3]. It leads to the decrease of urban wind speed, the increase of quiet days and the aggravation of heat island, and affects urban airflow, resulting in urban safety hazards and human health risks [4–8].

The key issue facing urban planning in recent years has been to satisfy the demands of urban growth while mitigating or preventing the negative climate effects caused by construction. Urban ventilation corridors facilitate air exchange between urban areas and the surrounding environment. The majority of studies indicate that constructing urban ventilation corridors is a crucial strategy for improving air quality and mitigating the urban heat island effect [9,10]. By facilitating the flow of cool and moist air from rural areas into cities, these corridors enhance air circulation and help reduce the occurrence of pollution such as haze. In addition, they can improve the thermal comfort of urban residents

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and reduce building energy consumption [11–13]. A few studies have also pointed out that ventilation corridors do not alleviate pollution and could potentially worsen it [14,15]. Additionally, the implementation of ventilation corridors may be ineffective in altering broad-scale air stagnation and other environmental conditions that are not conducive to air circulation [16]. These distinct perspectives have stimulated a debate concerning the quantitative examination of ventilation corridors.

The quantitative construction methods of urban ventilation corridors mainly include wind tunnel experiment, the weather research and forecasting (WRF) model, computational fluid dynamics (CFD), as well as the integration of meteorological data processing with geographic information system (GIS) spatial analysis, and least-cost path (LCP) analysis.

Wind tunnel experiment is a method to simulate the characteristics of urban wind environment by scaling the urban model to the same scale [17,18]. This simulation can provide highly reliable results and is not affected by external conditions [19]. However, practical considerations limit its widespread use, as the collection of data requires large amount of time and resources.

The WRF numerical simulation method is utilized to monitor, simulate, and forecast the real-time meteorological conditions in the urban area [20]. It has been widely applied in urban climate research due to its ability to simulate typical wind environment patterns at the regional scale, making it an effective solution to address the issue of urban ventilation [21]. The WRF model can consider the impact of meteorological factors and seasonal variations on the ventilation corridor, but it requires high-performance computing and a large amount of meteorological data [20,22,23].

The CFD simulation method can simulate wind field ranging from micro scale to local scale, reflecting the impact of urban morphology on the wind field, such as building height, building density, spacing, and orientation [24]. It can identify the urban canopy ventilation corridors and the local ventilation corridors, and provide detailed flow patterns at the community or single building scale [25,26]. However, due to its high computational requirements, it is not suitable for simulating the wind environment of larger areas, such as the whole city [27].

The simulation method based on GIS technology can effectively overcome these algorithm defects, and rapidly quantify the potential impact of urban ventilation by integrating urban morphological parameters [21,28,29]. According to the relevant literature, the urban morphological parameters are identified and summarized, such as frontal area density/frontal area index (FAD/FAI), sky view factor (SVF), building height, and building density [30,31]. Out of all the parameters, the FAD/FAI of buildings is a key roughness indicator for evaluating the surface wind conditions within mesoscale environments, as demonstrated by previous studies [32,33]. The integration of GIS and remote sensing (RS) into meteorology expertise in the development of an overall scheme for urban ventilation corridors (UVCs), introduces a novel strategy for investigating the wind conditions in urban areas [34–36].

The construction of urban ventilation corridors is closely related to climatic conditions, with air pollution and the UHI effect being two of the primary factors affecting urban climate suitability [15].The acceleration of urbanization directly or indirectly leads to the frequent occurrence of urban heat island phenomenon [37], and the optimization of urban wind environment can deliver fresh, cool, and moist air to areas with higher surface temperatures in the city, which can effectively improve the local thermal environment and alleviate discomfort caused by high temperatures [12,38,39]. Based on relevant research, it has been shown that wind speed near the ground in urban areas can profoundly impact the thermal comfort of residents. The higher the wind speed, the higher the thermal comfort, while the area with lower wind speed or urban quiet wind area has higher temperature [40]. Urban ventilation corridors have an important role in dispersing pollutants, and related studies have shown that the wind speed is negatively correlated with pollutant concentration [41].

The urban wind environment is influenced by various spatial morphological factors, and its influence mechanism is often the result of multiple spatial environmental factors. The research on the influence of urban spatial form on wind environment is summarized from different levels, including four categories: urban land cover, land use, building form and road structure [42–45]. Compared with urban land cover types, the diversity of urban land use has a more obvious effect on urban wind environment [42,43]. Buildings are a pivotal determinant in regulating urban ventilation and surface temperature, and higher building density typically results in decreased wind speed [13,46,47]. The layout of roads in a city has an impact on its ventilation system. The distribution of roads affects the speed and volume of wind flow, and the number of road intersections plays a role in determining the direction of wind flow. Optimizing the structure of roads is helpful to improve the overall comfort of residents [45].

At present, the data currently available for meteorological elements such as wind and temperature are typically determined through station observation or numerical simulation at a scale of kilometers or above [39]. It is crucial to combine climatic factors and urban spatial structure parameters in order to carry out a refined assessment of the urban environmental climate within a spatial resolution of 100 m, which is of great importance for the planning of urban ventilation corridors.

Hence, this study effectively merges quantitative and qualitative analytic strategies in the development of urban spatial pattern by applying remote sensing images and geographic data, GIS analysis, and urban characteristics extraction. By incorporating these approaches, the study aims to enhance the overall understanding of urban environments and improve decision-making processes. We investigate the correlation between various spatial structure parameters and urban thermal environment as well as wind environment, in order to evolve a fine-grained climate estimation scheme that integrates diverse spatial structure elements. Additionally, it strategically identifies and effectively utilizes quantifiable main indicators to optimize climatic conditions and design urban air ducts from a practical application standpoint.

Over the past decade, Xi'an has experienced rapid urban sprawl and emerged as one of China's inland cities grappling with the formidable challenges of urban heat island effect and haze pollution [15,48]. This study utilizes Xi'an as a case study and leverages the inversion results from remote sensing images to identify the urban function and compensation areas. After that, using high-resolution urban spatial structure parameters, in conjunction with GIS-based spatial analysis techniques, we construct ventilation potential evaluation maps at both 100-m and 10-m scales. Finally, the LCP process is implemented to dig the ventilation corridors of Xi'an, combining the morphological features, prevailing wind conditions and forward urban development, so as to carry out the construction of multi-level urban ventilation corridor system. This approach of refined urban land data and identifying potential urban ventilation corridors can be widely used in hundreds of cities in China and globally.

2. Methods

This study aims to build a **r**efined **a**ssessment model for urban **v**entilation (RAV model) based on GIS wind environment evaluation methods, so as to optimize the planning of urban ventilation corridors and alleviate UHIs and haze. Urban ventilation refers to the process of air exchange between urban areas and their surroundings, introducing fresh air to dilute pollutant concentration and heat. First of all, we select and analyze the factors that affect the circulation of urban wind, and use GIS overlay analysis method to superimpose the single factor influence maps, thus forming a comprehensive evaluation map of ventilation potential. Secondly, based on the refined distribution data of urban **l**and **s**urface **t**emperature (LST) and Particulate Matter 2.5 (PM2.5) retrieved from remote sensing images, the thermal load index is established to ascertain the urban function and compensation areas. Finally, LCP analysis is used to identify potential urban ventilation corridors combined with urban morphology and dominant wind direction.

2.1. Urban climate environmental assessment

2.1.1. Typical method: frontal area density

The sharp edge of the building structure results in form drag acting as the main driving mechanism for its air flow interaction [49]. The frontal area density (FAD) is an important parameter to assess urban ventilation condition, as it indicates the extent to which natural wind affects different regions within the city [33]. The FAD measures the windward building area (A_{proj}) in relation to the area of the horizontal plane (A_T) in wind direction θ [50], as demonstrated in Fig. 1. This study examined the spatial distribution of FAD in Xi'an using grids with resolutions of 100 *m* and 10 *m*, respectively. The FAD can be calculated as follows:

$$\lambda_{f(\theta)} = A_{proj} / A_T$$

where $\lambda_{f(\theta)}$ is the FAD of the study area in wind direction θ, A_{proj} represents the projection area of the buildings on wind direction θ, and A_T refers to the area of the computing grid.

Combined with the characteristics of wind speed and direction in Xi'an, we can calculate the FAD in various directions. Then, the FAD in the study area is obtained by weighting the wind frequency in each direction, as follows:

$$\lambda_f = \sum_{i=1}^{n} \lambda_{f(\theta)} * P_\theta$$

where λ_f is the value of FAD under various wind conditions, $\lambda_{f(\theta)}$ is the FAD in direction of wind (θ) within study region, P_θ is the frequency of wind direction θ, and n denotes the number of selected wind directions, which is set to 16 in this study.

2.1.2. Construction of the RAV model

The physical mechanism of urban ventilation is a complex process involving multiple factors and interactions of thermal driven, urban morphology, topography and meteorology. Firstly, we have compiled a range of data on the driving forces about air circulation. A large number of natural surfaces in the city are occupied by buildings, which leads to the increasing surface roughness and seriously affects the urban ventilation. Typically, large surface roughness makes it more strenuous for the wind to maneuver through the buildings and circulate. We have considered a range of parameters based on both existing urban ventilation studies and the unique geographical characteristics of Xi'an. Six quantitative indicators affecting surface roughness are selected in the RAV model: water body (X_1), vegetation area (X_2), road density (X_3), average building height (X_4), building density (X_5), and city topography (X_6), so as to develop geospatial data sets of the drivers. The definition and computation method of each urban spatial structure indicator is

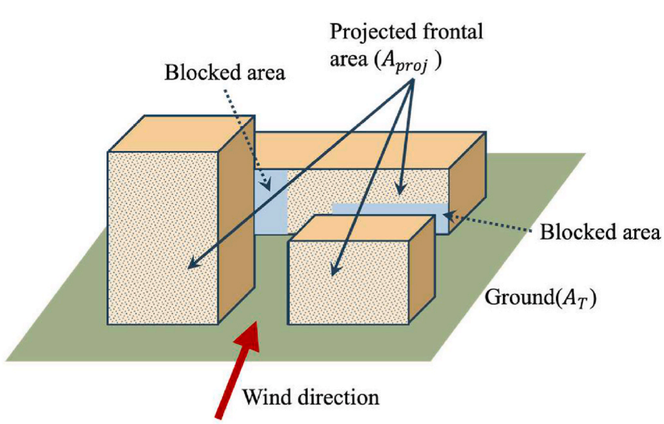

Fig. 1. Computation of frontal area density.

shown in Table 1. Among them, building density, average building height and city topography are all negatively affecting air circulation, while road density, water body density, and vegetation area are positive factors to promote urban air circulation.

Then, the factors are assigned values according to the hierarchical assignment method (**A**nalytic **H**ierarchy **P**rocess, AHP) [51,52]. Since there is no unified outline quantity for each impact factor, it is not comparable and difficult to evaluate. It is necessary to standardize each impact factor. In this paper, we adopt the AHP, which is based on the actual value of the impact factor and assign the value according to the multiple grading standards. Taking into account the features of the six drivers and the modelling performance, we determined 10 levels based on their influence on air circulation. The ventilation score ranges from 0.5 to 5, where a larger value indicates better ventilation capacity.

Expert insights into urban climatology and environmental sciences contribute to the initial weight allocation, and we asked experts from Xi'an Institute of Surveying and Mapping. The weight of each ventilation potential was determined by the Delphi-order relation analysis (ORA) method [53,54]. Based on the expert evaluation, the order of six selected influencing factors is $X_1 > X_2 > X_3 > X_4 > X_5 > X_6$. Their weight relationship is expressed as:

$$r_1 = w_1/w_2 = 1.2,\ r_2 = w_2/w_3 = 1.1,\ r_3 = w_3/w_4 = 1.2,\ r_4 = w_4/w_5 = 1.2,$$
$$r_5 = w_5/w_6 = 1.2$$

Therefore, the calculated weight of the impact factor is $w_1 = 0.2389$, $w_2 = 0.1990$, $w_3 = 0.1809$, $w_4 = 0.1508$, $w_5 = 0.1257$, $w_6 = 0.1047$. The contributing factors and ventilation assessment criteria are detailed in Table 2.

Ultimately, the refined assessment model for urban ventilation was produced:

$$RAV = \sum_{m=1}^{n} F_m \times \omega_m$$

where F_m is the ventilation potential assessment value of the *m*-th influence variable, ω_m is the ventilation weight of the *m*-th variable ($\omega_1 + \omega_2 + \ldots + \omega_n = 1$), n is the number of influence variables, and *RAV* is the overall score of ventilation potential.

The RAV model carries out overlay analysis on the ventilation evaluation results of single driving factor, and eventually produces a fine-grained assessment map showing the potential of urban air circulation.

2.2. Ventilation corridors strategy

2.2.1. Ecological role of urban areas

The urban ventilation system consists of three distinct components: "functional space", "compensative space" and "ventilation corridors" [55]. The functional space is the area that extends in all directions with

Table 1
Urban spatial structure indicator.

Urban spatial structure indicator	Specific description or calculation method
water body	The percentage of water in the unit area can be calculated based on the land cover map
vegetation area	The percentage of vegetation in the unit area can be calculated based on the land cover map
road density	The road density refers the proportion of plots occupied by roads to the study units [35].
average building height	The height weighted average of a building within the unit area, calculated from building data.
building density	The percentage of building in the unit area can be calculated based on the land cover map
urban terrain	Urban terrain reflects surface roughness, which is given by digital elevation model (DEM).

Table 2
Detailed criteria for ventilation assessment of contributing factors.

	Contributing factors						Score
	Water body (%)	Vegetation area (%)	Road density (%)	Average building height (m)	Building density (%)	City topography (m)	
Grading criteria	1	1	1	>72	>40	>1000	0.5
	5	5	5	72	40	1000	1
	10	10	10	36	35	900	1.5
	15	15	15	27	30	800	2
	20	20	20	21	25	700	2.5
	25	25	25	15	20	600	3
	30	30	30	9	15	500	3.5
	35	45	35	6	10	450	4
	40	60	40	3	5	400	4.5
	>40	>60	>40	1	1	350	5
Weight	0.2389	0.1990	0.1809	0.1508	0.1257	0.1047	–

the core of the city as the center. This area is deeply urbanized, with dense building, pedestrian and vehicular traffic, and frequent social activities, which makes it difficult to circulate the air with serious anthropogenic heat emission. The compensative space provides fresh, cool air to the inner city. According to the theory of local circulation, the compensation area is grouped into two categories. One is to stimulate the air circulation in the functional space, mainly to ensure the supply of fresh air. The other is the compensation area for reducing pollution, which acts to clean the inflow air. The ventilation corridor connects these two components, and makes use of the temperature difference effect and the fluid characteristics of wind to import fresh air from the rural area into the metropolitan area. Simultaneously, the wind dilutes the polluted air in the city, thus lessening the UHI effects and urban haze.

Many factors influence how urban functional and compensative spaces are allocated. It is essential to take into account not only the air pollution, the urban thermal environment and the hot pressure gradient, but also the green space system and the composition of the underlying surface. We use the land surface temperature and air pollutant concentrations (PM2.5) to calculate the thermal load index, so as to identify the urban function and compensation areas, and roughly characterize the air flow pathway.

$$TL = Norm(T_S) \times Norm(PM2.5)$$

where *TL* is the thermal load, *Norm* is normalized operation, T_S is the land surface temperature, and PM2.5 is the concentration of PM2.5.

2.2.2. LCP analysis

The Least Cost Path (LCP) is designed to calculate the lowest specific cost path from the beginning to the ending point, and it is often used in urban traffic accessibility analysis, urban ecological corridor simulation, greenway alignment simulation, etc. The paths indicate the most likely routes with sufficient ventilation and good connectivity. By estimating the resistance of urban morphological parameters to wind, the easiest path of urban air flow can be obtained. Several investigations have effectively employed FAI as the cost layer for approximating the path of minimum resistance. The LCP can be calculated as follows:

$$LCP = F_{min} \sum_{i=m}^{j=n} (d_{ij} * r_i)$$

where *LCP* is the minimum cumulative cost; d_{ij} stands for the weight of cost component *i* in grid *j*; r_i denotes the cost value for the movement of component *i*; *m* and *n* represent the number of sources and cost components; and F_{min} represents the relationship between the minimum cumulative cost and urban ventilation, with a normal distribution.

In order to guarantee that the wind entirely covers the metropolitan area of Xi'an, we have defined enough source points and target points to make them coincide with wind directions in various periods of the year.

In order to ensure that the urban wind covers the whole urban area of Xi'an, we have defined enough source points and target points to make them consistent with the wind directions in different seasons. In this paper, the comprehensive ventilation potential evaluation grid is used as the cost grid, and the trajectory generated by the LCP method can reflect the path with the lowest air flow resistance in the city, that is, the potential ventilation corridor. We extracted the ventilation corridor of Xi'an by LCP method in ArcGIS.

3. Study area and data sources

3.1. Study area

3.1.1. Geography and climate characteristics

Xi'an is located in the Guanzhong Basin (33.42°N-34.45°N, 107.40°E−109.49°E), with a total area of 10,108 square kilometers and a resident population of 13, 163, 000 (Fig. 2). Xi'an has a wide range of altitudes, the urban area is built on the secondary terraces of the Weihe Plain at an altitude of about 400 *m*–700 *m*, and the southern Qinling Mountains at an altitude of 2,000 *m*–2,800 *m*. By the end of 2019, the built-up area of Xi'an had reached 729.14 km^2, compared with 13.2 square kilometers in 1949, which increased 55 times in 70 years.

Xi'an has a warm temperate semi-humid continental monsoon climate with four pronounced seasons. The northeast wind prevails in Xi'an, with an average annual wind speed of 1.8 m/s and a still wind frequency of about 30 %. The urban heat island effect is obvious in summer, and Xi'an has suffered a large-scaled lasting fog and haze for the past ten years in winter. Xi'an is one of the top 10 furnace cities in China. In 2022, Xi 'an experienced the hottest June since records began in 1951, with 20 days exceeding 35 °C. The average concentration of PM2.5 in 2021 was 43 μg/m^3, and that of PM10 was 96 μg/m^3, which were 0.23 times and 0.37 times higher than China National Ambient Air Quality Level II Standard, respectively.

Xi'an is prone to smog weather in winter, and its geographical location plays a significant role, mainly in Qinling Mountains and Weibei Plateau. In winter, the Qinling Mountains block the cold air from going south and form an inversion layer near the ground, just like a natural dome over the city. Its own geography hinders the vertical diffusion of air pollutants in Xi 'an. When there is no wind or little wind in winter, air pollutants can only be found in the limited space in the urban area, which aggravates the rapid accumulation of local and regional pollutants and causes serious air pollution and smog.

3.1.2. Urban morphology

As the imperial capital of 13 dynasties, the urban morphology of Xi'an was deeply influenced by the ancient Chinese concept of axial symmetry. Nowadays, Xi'an is centered on the square city of the Ming Dynasty City Wall, inheriting, and developing the characteristics of Chang'an City with its grid type urban traffic network and symmetrical axes layout, forming a structural model in which the new district

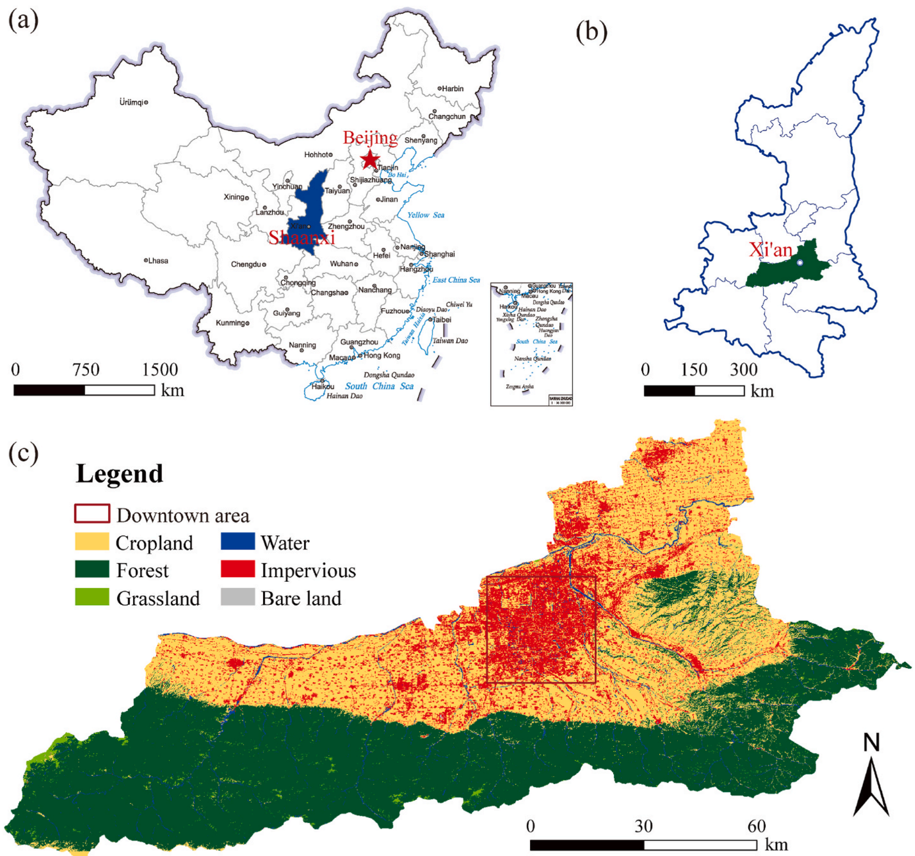

Fig. 2. Study area and its land cover type. (a) Map of China; (b) Map of Shaanxi Province; and (c) Land cover map in Xi'an, the red boxed area represents the main urban area of the study. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

develops around the old city. In the past 20 years, the urban land use in Xi'an has grown rapidly, and the spatial structure has undergone drastic changes. With the Bell Tower as the center, Xi'an has gradually expanded outwards in a concentric circle. Urban sprawl has caused problems such as dense population, traffic jams, and environmental pollution, prompting Xi'an to revise its Urban Master Plan (2021–2035) in 2022. The new plan breaks away from the "City Wall" and for the first time introduces the pattern of "Xi'an Metropolitan Area", adopting a spatial development model of "multi-axis, multi-center, and multi-group".

In recent years, the unprecedented urbanization and population growth in Xi'an have led to a significant increase in the roughness of the urban surface, resulting in frequent occurrences of still or weak wind in the main urban area. This alarming phenomenon has contributed to the deterioration of urban air quality, thus highlighting the urgent need for strategic construction of scientific urban ventilation corridors aimed at promoting air circulation and mitigating the adverse implications on public health. In this study, the boundary of Xi 'an administrative district is taken as the research scope of city-scale ventilation corridor, focusing on the area in Fig. 2(c) (hereinafter referred to as "main urban area").

3.2. Data

As shown in Table 3, study data have been collected from diverse sources. All these data are in the China Geodetic Coordinate System 2000 (CGCS2000) projection format. The ventilation potential of Xi'an was analyzed with 100 *m* resolution for the whole area and 10 *m* resolution for the main urban area.

Based on the land cover extraction product, we can calculate the building density, water body, green land area and other information of Xi'an with 10-m and 100-m resolution by using the method proposed by Dong, Fang [58]. The road data came from OpenStreetMap. Information on the position of buildings and the height of floors was derived from Xi'an Institute of Surveying and Mapping. The Geospatial Data Cloud was used to obtain DEM data.

Table 3
Data sources and descriptions.

Data	Data Source
Meteorological data (wind speed and wind direction)	Meteoblue (https://www.meteoblue.com)
Land surface temperature	MOD11A1.061 Terra Land Surface Temperature and Emissivity Daily Global 1 km (https://developers.google.cn/earth-engine/datasets/catalog/MODIS_061_MOD11A1)
PM 2.5	ChinaHighPM2.5 [56,57]
Land cover product	High-Resolution Land Cover Mapping Through Learning With Noise Correction [58]
Landsat 8	United States Geological Survey (USGS) (https://earthexplorer.usgs.gov/)
MODIS	Moderate-resolution Imaging Spectroradiometer (MODIS) (https://modis.gsfc.nasa.gov/)
Building information	Xi'an Institute of Surveying and Mapping
Road data	Open Street Map (https://www.openstreetmap.org/)
DEM	ASTER GDEM V2 (http://www.gscloud.cn)

The data sets used to assess the thermal load came from remote sensing images. Two types were considered: PM2.5 and LST. On the basis of the existing PM2.5 data (ChinaHighPM2.5) and surface temperature data (MOD11A1.061 Terra Land Surface Temperature and Emissivity Daily Global 1 km), as well as MODIS images and Landsat-8 images, this study used a super-resolution method based on deep learning to obtain the refined PM2.5 data and LST data. We achieved this by applying bicubic sampling to the 250 *m* resolution MODIS data, resulting in downsampled MODIS data at 1 km resolution (MODIS_DS). The MODIS_DS data and ChinaHighPM2.5 data are put into the Random Forest model. After training the model using the 1 km resolution sample data, we applied the model to the 250 *m* resolution MODIS imagery, assuming scale invariance, in order to generate a higher-resolution PM2.5 concentration distribution. The 250 *m* spatial resolution PM2.5 data and 30 *m* spatial resolution LANDSAT-8 image were utilized to redo the previous actions to generate the 30 *m* spatial resolution PM2.5 concentration map of Xi'an in winter. We evaluated the quality of the super-resolution results using two metrics, Mean Absolute Error (MAE) and Root Mean Square Error (RMSE). The existing ChinaHighPM2.5 data and the data from 13 observation sites in Xi'an were compared with the simulation results. The mean PM2.5 concentration at 250 *m* resolution was 64.4 mg/m3, MAE = 7.5 mg/m3 and RMSE = 13.4 mg/m3. These results were comparable to those of a study by Wei et al. [56] during the same period.

The wind direction and speed of the city determine the design of air ducts. Among them, the prevailing wind direction, i.e., the wind direction with the most observation times, serves as the foundation for the construction of urban air ducts. Wind speed and direction data come from Meteoblue, based on 30 years of hourly weather simulations. We generate wind rose maps for both summer and winter (Fig. 3).

4. Results

4.1. Urban thermal load index and regional roles in urban ventilation

The result of the LST retrieval in the summer of 2021 is shown in Fig. 4(a). An overview indicates that the Xi'an surface temperature tend to be higher on the north side and lower on the south side. Regions with high temperature mostly clustered in the metropolitan area of Xi'an (Beilin District, Xincheng District, Lianhu District, Weiyang District and Yanta District). The UHI effect is significant in the downtown area where the density of built-up land is high. However, there is no obvious high-temperature area in rivers and dense vegetation coverage, such as Han Great Wall Heritage Park and Daming Palace National Heritage Park, and cold islands emerge in the Qinling mountains.

Fig. 4(b) shows the distribution of PM2.5 concentration in the winter of 2021. The distribution of PM2.5 concentrations and LST is roughly the same, but the difference between urban and suburban is more significant. Air pollution is most server in urban centers, especially in areas with heavy traffic and industry. These areas are affected by sources such as vehicle exhaust, coal-fired pollution and industrial emissions, resulting in high PM2.5 concentration. The mountainous areas around the cities are relatively fresh and the concentration PM2.5 is low.

Based on the LST and PM2.5 distributions, a composite thermal load map of the city is ultimately developed (Fig. 5), from which the allocation of functional and compensative spaces in Xi'an UVC system is obtained. The compensative spaces in Xi'an consist of green spaces and water bodies, and the functional spaces mainly consist of impervious construction land. The green spaces include heritage sites such as the Han Great Wall Heritage Park and the Daming Palace National Heritage Park, and parks such as Park of Xingqing Palace and Tang Paradise (marked by blue circles in Fig. 5). Xi'an has long been known as "Eight Rivers Surrounding Chang'an" (a reference to the city's ancient name). The major water bodies include the Weihe River, Bahe River, and Chanhe River, all of which are potential wind sources of good ventilation for the urban area.

4.2. Geospatial distribution of ventilation capability

Wind direction frequencies in 16 directions were acquired from Meteoblue to produce the density map of windward area within the research region. Fig. 6 illustrates the spatial distribution of FAD in Xi'an. The larger the windward area of the building, the greater the obstruction to the wind. That is, as the FAD value of the area increases, the ventilation decreases. Regions with higher FAD value mostly lie to the south

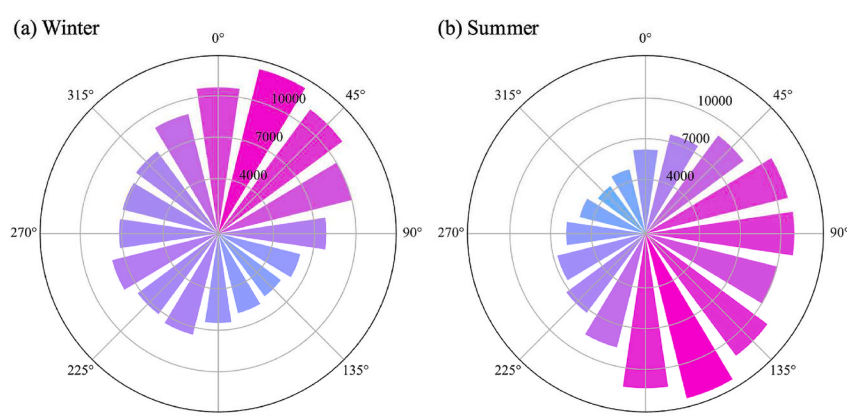

Fig. 3. The wind rose for Xi'an: (a) wind rose map in summer; and (b) wind rose map in winter.

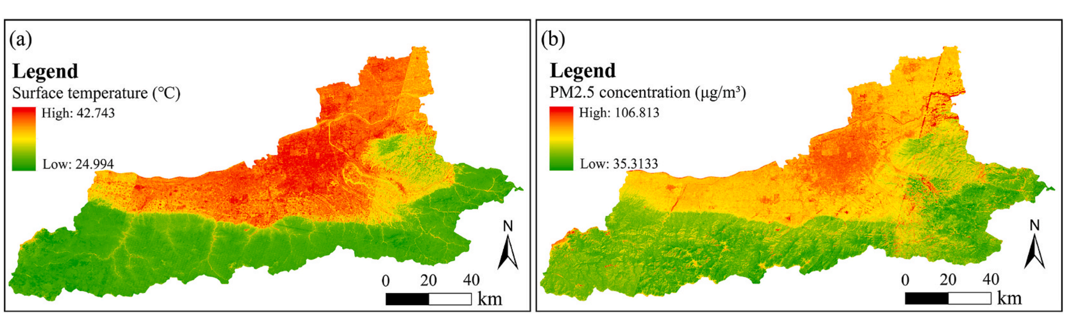

Fig. 4. Land surface temperature and PM2.5 concentration in Xi'an.

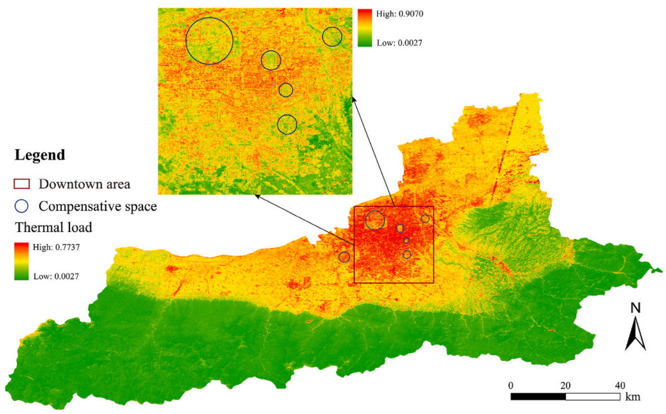

Fig. 5. The thermal load map of Xi'an.

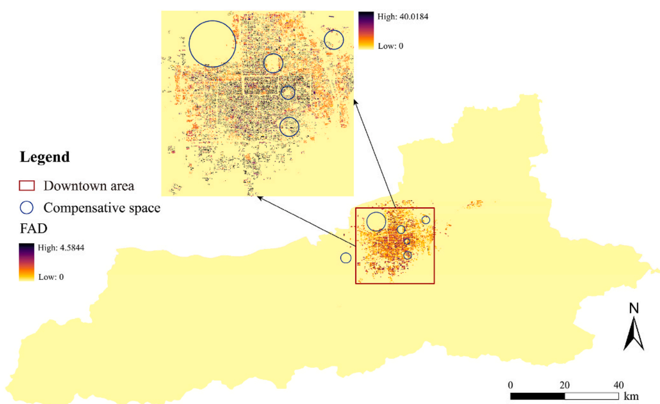

Fig. 6. Geographical distribution of the FAD in Xi'an.

of Xi'an. Hotspots tend to be situated in core locations with a dense concentration of tall buildings, such as the old city districts of Beilin District, Lianhu District and Xincheng District, and Yanta District and Gaoxin District in the south-east. These areas are the commercial, cultural, and technological centers of Xi'an, and have a higher concentration of population and traffic. However, the FAD values of Weiyang District and Lintong District, which are located in the north and west, are relatively lower. These areas are mainly agricultural and industrial land, with a more dispersed population and traffic.

Fig. 7 shows a series of single-factor ventilation potential evaluation maps. The RAV model is used to perform hierarchical evaluation, reclassification and spatial overlay analysis in ArcGIS, so as to generate the integrated influence map of UVCs in Xi'an (Fig. 8). As shown in Fig. 8, the greener the color, the greater the ventilation potential, the more conducive to urban wind circulation; and the redder the color, the more unfavorable the urban wind. The suburbs of Xi'an have good ventilation potential. The surface cover of the areas with strong ventilation capacity is ecological space such as green space and water. Buildings are the main types of surface cover in areas of poor ventilation potential. Compared to the First Ring Road within Ming City Wall, the Second Ring Road and the Third Ring Road have a lower building density, and there are a number of green spaces and water bodies. Large green areas such as the Daming Palace National Heritage Park and Park of Xingqing Palace are located within the Second Ring Road. Large water areas within the Third Ring include the Bahe River and Qujiang Pool, and green areas include the Xi'an Botanical Garden, the Tang Paradise and the Wild Goose Pagoda. All these sites act as ecological compensation spaces providing good ventilation for the surrounding area. The farmland outside the Third Ring Road also plays an important role in the ventilation of the city.

To verify the effectiveness of the impact factors, Pearson correlation coefficient (r) and Coefficient of determination (R^2) were used to analyze the correlation between the impact factor and ventilation

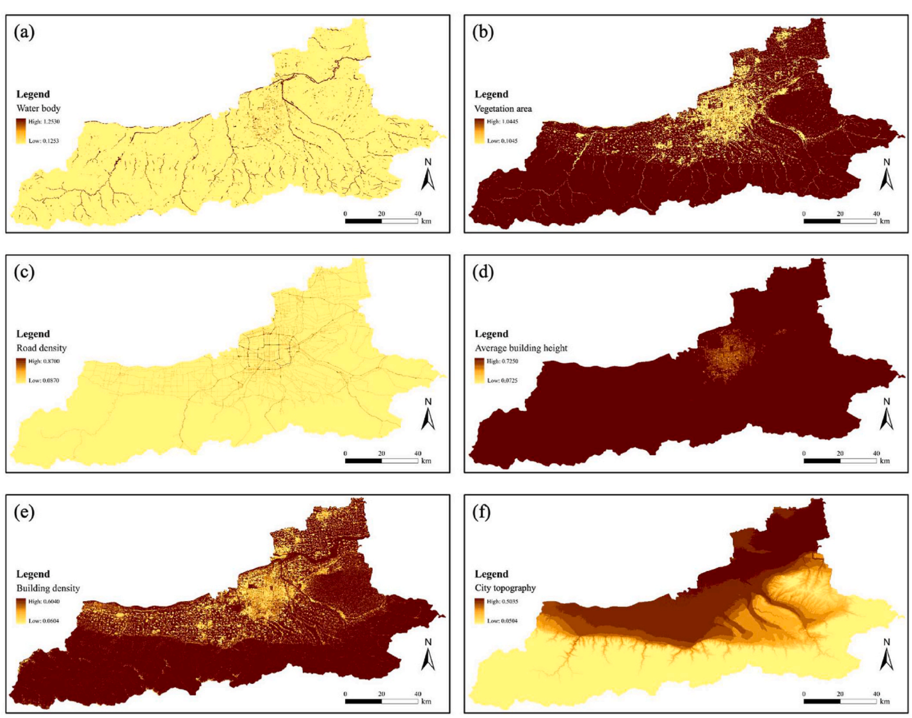

Fig. 7. Spatial distribution of single-factor ventilation potential: (a) Water body, (b) Vegetation area, (c) Road density, (d) Average building height, (e) Building density, and (f) City topography.

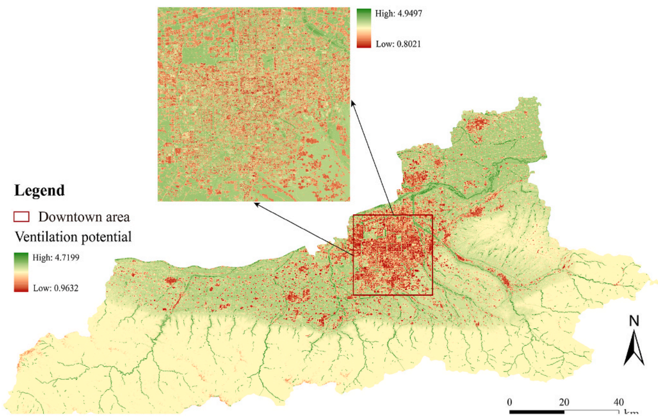

Fig. 8. Fine-grained assessment of ventilation potential in Xi'an and its spatial distribution.

potential. The regression analysis of UVP on potential contributors for urban ventilation are shown in Fig. 9. The results indicate that UVP tends to increase as the values of Water body, Vegetation area and Road density increase, and the values of Average building height, Building density and DEM decrease. Among them, Water body, Vegetation area and Building density all contribute more than 70 % individually to the UVP variation, which has a significant impact on the potential of urban surface ventilation. Therefore, these three factors could be taken as the major guideline parameters of ventilation control in Xi'an urban planning.

4.3. Potential ventilation corridors

The prevailing wind direction is southeast in summer and northeast in winter. The sources and sinks of local airflow movement are identified based on the prevailing wind direction. For example, in winter, with the source location to the north-east and the sink location to the south-west, we set up 20 points along the north-east and south-west sides of the research area respectively. Taking the comprehensive evaluation of ventilation potential as the cost value of wind circulation, we use LCP analysis to calculate the minimum cumulative cost path of fresh air in suburbs from source location to sink location. The least cost path is used to represent the best trajectory of wind movement, so as to construct the urban air duct. The LCP method based on RAV model is used to calculate the ventilation corridors for the whole city of Xi'an as shown in Fig. 10 and for the main city as shown in Fig. 11.

The potential urban ventilation corridors constructed by LCP method are mainly through the ecological compensative spaces, such as water surfaces, trunk roads, parks, etc. The structures of these potential air ducts are complex. Considering the ventilation efficiency and the cost of planning and construction, it is necessary to optimize the potential ventilation efficiency. Using a combination of qualitative and quantitative analysis, we can obtain the optimized spatial structure of urban ventilation corridors in Xi'an (Fig. 12) and the ventilation corridors in main urban area (Fig. 13).

As shown in Fig. 13(a), there are three first-class air ducts in the main urban area in winter, which are generally northeast-southwest.

(1) Bahe River - Daming Palace National Heritage Park - Xi'an Xi Railway Station – Yuhuazhai,

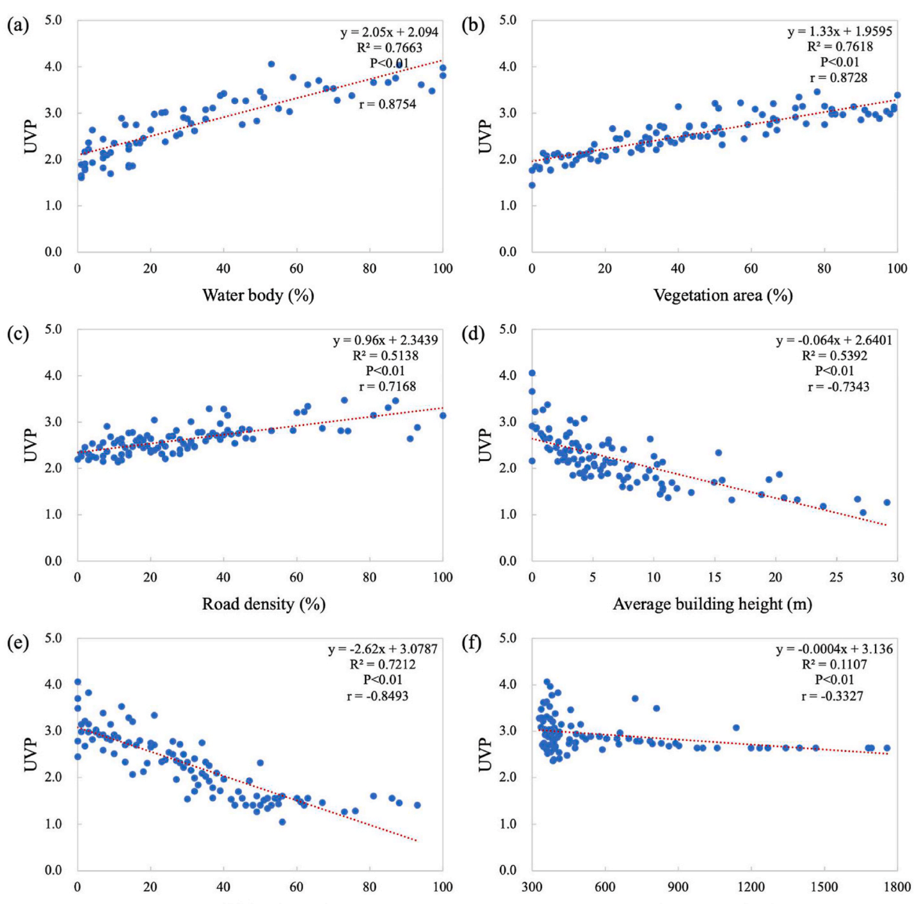

Fig. 9. Scatter plots and fitting regression models between urban ventilation potential (UVP) and spatial landscape parameters for Xi'an ($P < 0.01$ donates statistical significance at the 99 % confidence level.).

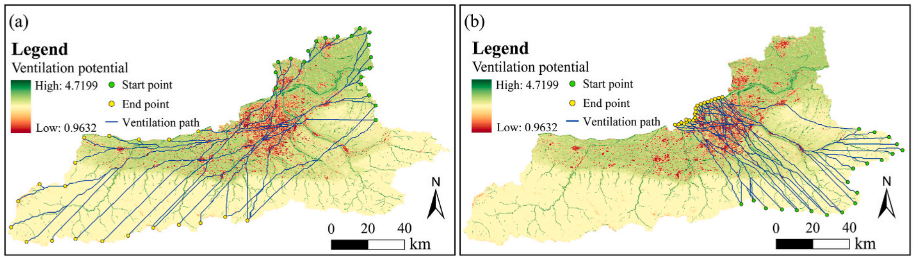

Fig. 10. Ventilation corridors of Xi'an obtained through the RAV model: (a) the northeast-southwest direction in winter and (b) the southeast-northwest direction in summer.

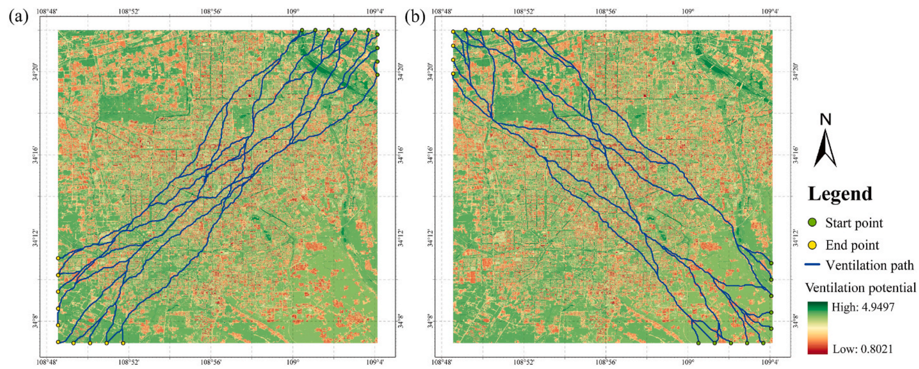

Fig. 11. Ventilation corridors in the main urban area of Xi'an obtained through the RAV model: (a) the northeast-southwest direction in winter and (b) the southeast-northwest direction in summer.

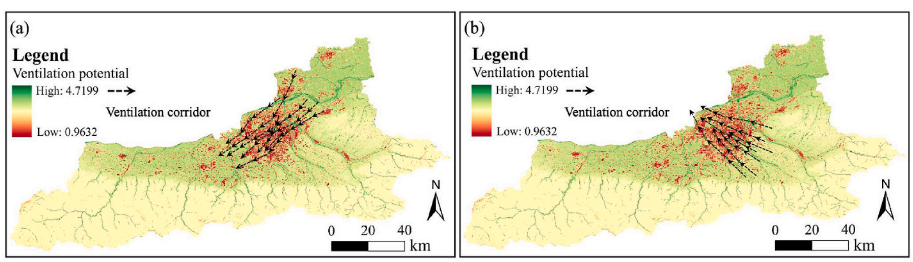

Fig. 12. Optimized ventilation corridors in Xi'an: (a) the northeast-southwest direction in winter and (b) the southeast-northwest direction in summer.

(2) Xi'an Expo Park - Daming Palace National Heritage Park - Bell Tower - Fengqing Park - Xihu Road, and
(3) Lanzhou-Lianyungang Railway corridor - Yangjiawan Village - Park of Xingqing Palace - Wild Goose Pagoda - Qingliangshan Forest Park - Xifeng Road.

The second-class air ducts are distributed around the first-class air ducts. The paths are as follows.

(1) Bahe River - Xi'an Administrative Center - Han Great Wall Heritage Park, and
(2) Daming Palace National Heritage Park - Youyi West Road - Taibai South Road.

The southeast wind vents are mainly distributed in Yanming Lake, Xi'an Botanical Garden, Chanhe River, Duling Mausoleum, and Shaolingyuan. As shown in Fig. 13(b), there are three first-class air ducts in the main urban area in summer, which are generally southeast-northwest.

(1) Xi'an Botanical Garden - Qinglong Temple - Bell Tower,
(2) Duling Mausoleum - Tang Paradise - Wild Goose Pagoda - Chang'an North Road - Han Great Wall Heritage Park, and
(3) Shaolingyuan - Xi'an International Exhibition Conference Center - Fengqing Park.

There are also two second-class air channels.

(1) Chanhe River - Daming Palace National Heritage Park, and
(2) Yanming Lake - Changming Road Interchange - Park of Xingqing Palace.

The spatial orientation of these ventilation corridors is consistent with the dominant wind direction in Xi'an. They connect the Bahe River, Chanhe River and other water systems as well as open spaces such as Tang Paradise and Han Great Wall Heritage Park together, which can effectively improve the ventilation environment within the city.

5. Discussion

Ventilation corridors are a key means of mitigating the UHI effect and air pollution. Incorporating climate and environmental information into urban planning and establishing a refined quantitative assessment process can help ensure that multiple ventilation corridors are provided to urban areas where they are most needed [34,59]. Incorporating the ventilation design into the development of urban areas at a lower cost is

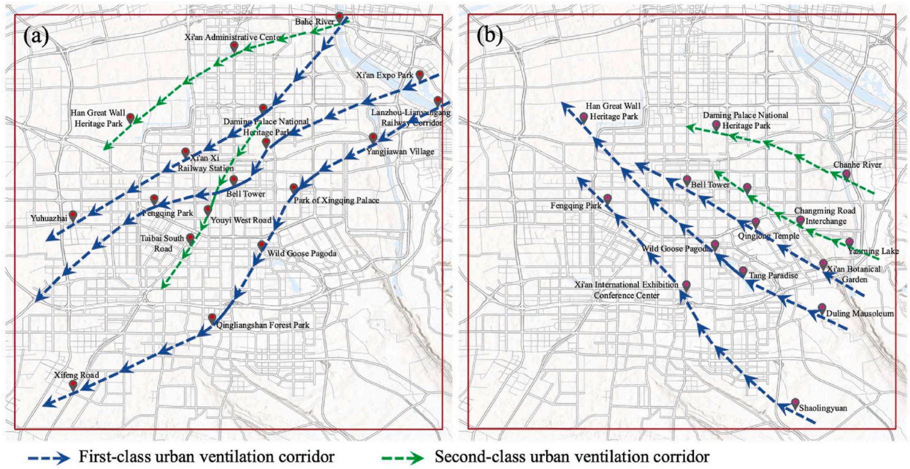

Fig. 13. Optimized ventilation corridors in Xi'an main urban area: (a) the northeast-southwest direction in winter and (b) the southeast-northwest direction in summer.

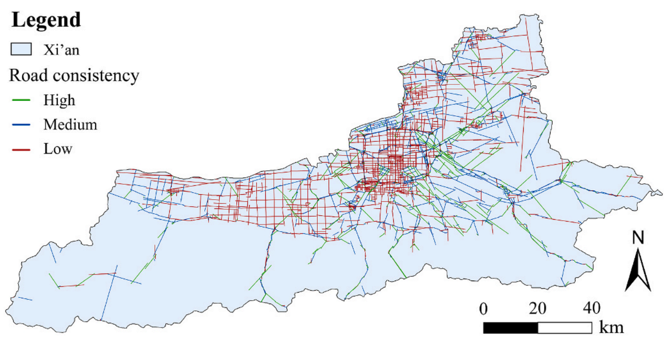

Fig. 14. Spatial distribution of road consistency with dominant wind direction.

of great importance to improve the air quality of cities and the thermal comfort of residents. In this study, we investigate climatic and environmental conditions and urban spatial morphology, quantitatively analyze the influence of each factor on urban ventilation, assess the wind environment of Xi'an. The RAV model for the comprehensive assessment of potential ventilation corridors is constructed by combining GIS with LCP analysis.

The main contribution of this study is the integration with urban morphology information, remote sensing data and meteorology data into the design of ventilation corridors and carry out the refined assessment, which has significantly improved in spatial resolution and the granularity of impact factors. Existing studies on urban ventilation on the basis of spatial morphology have a relatively coarse grid division. For example, Liu, Huang [35] developed the IAVA method and used the 1 km × 1 km grid to investigate the urban wind environment of Shenzhen. Fang and Zhao [60] and Han, Zhao [15] both used the 500 m × 500 *m* grid to assess the ventilation conditions in the research area. However, we use high-resolution land cover classification data and refined building information of Xi'an to assess the whole area of Xi'an at the 100-m level and the downtown area at the 10-m level, which is more refined than previous studies.

The planned construction type and distribution of the underlying surface are static factors reflecting the basic ventilation situation of the city. The changes of surface thermal environment, especially in summer and winter when ventilation demand is strong, are dynamic factors reflecting the pattern of air flow near the surface. Balancing these two aspects - thermal stress mitigation and air quality improvement - throughout the year is a complex challenge. During winter, the main concerns focus on air pollution and the need for ventilation to clean the air. Whereas in summer, the emphasis may shift to alleviating the thermal stress, and ventilation corridors can assist in bringing cool air into metropolitan areas, reducing the UHI effect. Therefore, the design and planning of ventilation corridors need to be adapted to the specific needs of each season. Based on the superposition analysis of static and dynamic factors, combined with the measured data of multiple years, can provide a more objective classification and spatial distribution of the urban comprehensive ventilation potential.

This paper introduces the thermal load indicator consisting of land surface temperature and PM2.5 concentration distribution to determine the functional space and compensative space, aiming at alleviating the UHI effect and haze. The compensative space plays a key role in urban ventilation by providing clean air in winter and cool air in summer for the central city. Regarding the idea that ventilation exacerbates air pollution, as mentioned in some studies, we assert that the assessment of air quality should be an integral part of corridor design, especially in winter when the potential for exacerbating air pollution exists. It is necessary to utilize the air quality data to accurately forecast the geographical distribution of harmful substances, so as to estimate whether the compensation space is able to offer cool and fresh air to the downtown area. Without assessing the purity of cool air, ventilation systems may not enhance the air quality. In fact, they may exacerbate air pollution, worsening the urban climatic conditions and posing a significant threat to public health, as mentioned in Refs. [14,16].

Roads are an important part of urban ventilation corridors and should be oriented as closely as feasible along the dominant wind direction. We used the "linear directional mean" tool in the GIS statistical analysis module to calculate the angle between the road and the compass angle (clockwise from due North). This assisted in examining the spatial relationship between the road and the prevailing wind direction. As shown in Fig. 14, the old urban area within the Xi'an city wall is a grid pattern of Chang'an City in the Tang Dynasty, which has a low consistency with the dominant wind direction. While outside the old urban area to the ring expressway is a circular radial road network, which has a medium consistency with the dominant wind direction. The statistical results show that the road directions in Xi'an are consistent with the dominant wind direction at high, medium and low levels, accounting for 17.8 %, 32.7 % and 49.5 % respectively. Roads parallel to the dominant wind direction should be retained and the width of these should be increased. At the same time, the density and height of streetside buildings ought to be restricted. Relevant studies have shown that while urban roads offer wide access for urban ventilation, the composition and orientation of roads can exacerbate the urban heat island effect to a certain degree [61–63]. The use of pavement materials with lower thermal conductivity is therefore essential (Ren et al., 2018).

The FAD provides a convenient method for assessing the urban wind

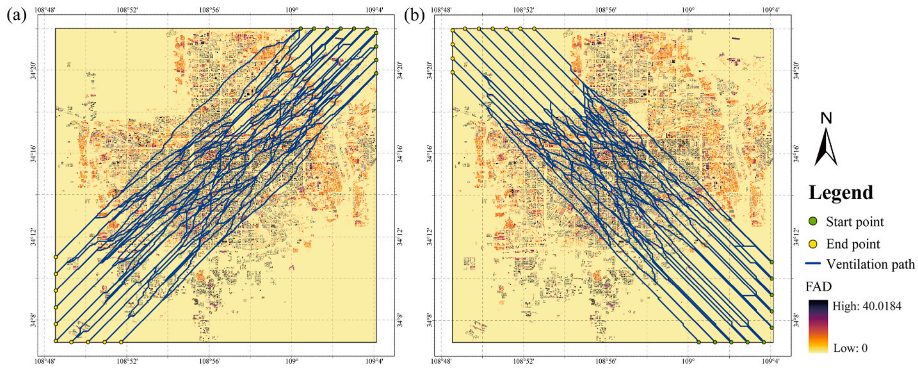

Fig. 15. Ventilation corridors generated by FAD in (a) the NE-SW direction and (b) SE-NW direction.

conditions and can assist in calculating the cost of ventilation corridors [39,64]. Most studies focus on exploring the relationship between FAD and other climate metrics, including building density, building height, surface temperature, and normalized difference vegetation index (NDVI) [35,46]. Ventilation corridors generated by the LCP method utilizing the FAD with the dominant wind direction, and the results are displayed in Fig. 15. This method only provides the ventilation path from the perspective of minimum FAD cost, without considering the reduction of urban heat island effect and air pollution in functional areas. Therefore, the ventilation corridor does not pass through the functional area and cannot improve the wind environment of the functional area. Although the orientation of the ventilation corridors based on FAD and RAV is similar, the ventilation corridors based on RAV are closer to the local terrain and urban morphology.

Finally, the study area revealed six candidate first-class air ducts, as well as the metropolitan area of Xi'an revealed four candidate second-class air ducts. We suggest that Xi'an adopt the "ventilation corridor + scenic area" construction model, combining urban ventilation with scenic spots. This model can not only find an effective breakthrough for the construction of urban ventilation corridors, but also make the city more livable.

According to the position correlation and functional fit of existing scenic spots, parks and green spaces in Xi'an, the scenic spots of ventilation corridors are preliminarily classified into three categories.

I First-class scenic spot of ventilation corridor. Most are located in the draught of the city or the key position on the main air duct. These are usually large, long spans, dominated by rivers, lakes and green areas, and have a significant ecological role. For example, the Chanba National Wetland Park, the Xi'an Expo Park, etc.

II Second-class scenic spot of ventilation corridor. Most of the sites are located along or adjacent to the air duct, with small scale and short span. These scenic spots are less capable of delivering wind over long distances, but they have a more significant role in generating wind and air convection, and at the same time carry more leisure and recreational functions. Such as Xi'an City Sports Park, Big Wild Goose Pagoda, the Muta Temple Park, and the Xingqing Palace Park, etc.

III The potential ventilation corridor scenic spot. Most of them are the current lack of development and construction, outdated appearance, poor sanitary environment, inconvenient location and transportation, and chaotic surrounding land. However, their location and land scale play an important role in ventilation, ecological perception, and landscape display. These places mainly include: Happy Forest Belt, Epang Palace Site, Kunming Pool, and Cangjie Word-making Platform, etc.

This study has constructed the urban ventilation corridors from a multi-scale perspective, which can not only provide new ideas and methods for the urban ventilation corridor planning in Xi'an, but also provide reference for the planning and construction of other cities in the future. However, there are some areas for improvement. Due to the limitation of the current data, the refined spatial pattern of building density can only be obtained in the downtown area, but it cannot fully reflect the ventilation potential of the whole urban area of Xi'an. The complexity of the urban space affects the fineness of the urban microclimate simulation results. Therefore, in order to obtain the urban wind field environment that is infinitely close to the actual situation, more complex parameter schemes and long time series of uninterrupted simulations are required, which we will further explore in our subsequent research.

6. Conclusion

Urban ventilation corridors can bring suburban ecological cooling sources into the inner city, promote urban airflow exchange, alleviate the UHI effect to a certain extent, reduce the frequency of pollution such as haze, and enhance the comfort of urban residents in terms of wind-heat perception.

Using Xi'an, a city with severe smog pollution and frequent heatwaves in the summer in northwestern China as an example, this study aims to construct the RAV model, a refined GIS-based wind environment assessment method, to assist in optimizing the design of air ducts and mitigating UHIs and haze. The thermal load index composed of land surface temperature and PM2.5 concentration and the ventilation potential index calculated from urban spatial morphology are introduced respectively to establish the ventilation assessment maps with spatial resolution at the 100 *m* and 10 *m* levels. On this basis, we construct a multi-stage air duct system by integrating the topographic features of the city with the background wind environment, providing a quantitative reference basis for urban climate zoning optimization and ventilation corridor control strategy.

Taking into account the analysis of various factors affecting urban air circulation, six influence factors are finally selected for analysis and calculation in this study: water body, green land area, road density, average building height, building density, and urban terrain. By combining the ordinal relationship method with Delphi method, the weight of each ventilation potential is determined. The potential urban ventilation corridors are determined by combining the characteristics of urban functional space and compensation space, ventilation potential map and urban dominant wind direction. Finally, the study area revealed six candidate first-class air ducts, as well as the metropolitan area of Xi'an revealed four candidate second-class air ducts. We have used highly accurate land cover classification data and refined building information of Xi'an to assess the whole area of Xi'an at the 100-m level and the downtown area at the 10-m level. The grid scale in this study is more refined compared to existing studies.

We propose a more rational and detailed ventilation scheme, the evaluation results are more pragmatic than those based on FAD. The results of the study offer a basis for scientific assessment of urban air circulation and support local urban spatial management. However, the complexity of the urban space affects the fineness of the urban microclimate simulation results. Therefore, more complex parameter schemes and long time series of uninterrupted simulations are required to obtain an urban wind field environment that is infinitely close to the actual situation, which we will explore in depth in subsequent studies.

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CRediT authorship contribution statement

Qingmei Li: Writing – original draft, Validation, Methodology. **Juepeng Zheng:** Writing – review & editing, Methodology. **Shuai Yuan:** Resources, Data curation. **Lixian Zhang:** Investigation. **Runmin Dong:** Project administration. **Haohuan Fu:** Supervision, Funding acquisition.

Declaration of competing interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled.

Data availability

Data will be made available on request.

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