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Nature-based solutions for urban resilience and human health

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Diverse cooling effects of green space on urban heat island in tropical megacities

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Cities in tropical regions are experiencing high heat risks by overlaying the urban heat island (UHI) effect. Urban green space (UGS) can provide local cooling effect and reduce UHI. However, there still lack a comprehensive exploration of the characteristics of UHI and cooling effect of UGS due to high cloud coverage and limited number of available remote sensing observations. In this study, the enhanced spatial and temporal adaptive reflectance data fusion method was employed to develop an enhanced land surface temperature data in winter seasons in three tropical megacities, Dhaka, Kolkata, and Bangkok. The spatiotemporal variations of surface urban heat island (SUHI) were explored from 2000 to 2020 with a 5-years interval. The optimal size of UGS associated with its cooling effects was assessed by using the threshold value of efficiency (TVoE). The relationship between the intensity and range of urban cooling island (UCI) and four landscape metrics of green space patches, total area (P_Area), shape index (P_SI), normalized difference vegetation index (P_NDVI), and land surface temperature (P_LST), were analyzed. The results show that the average SUHI intensity increased by 0.98°C, 1.42°C, and 0.73°C in Dhaka, Kolkata, and Bangkok, respectively, from 2000 to 2020. The maximum intensity of UCI ranges from 4.83°C in Bangkok to 8.07°C in Kolkata, and the maximum range of UCI varies from 300 m in Bangkok to 420 m in Kolkata. The optimal size of green space is 0.37 ha, 0.77 ha, and 0.42 ha in Dhaka, Kolkata, and Bangkok, respectively. The P_NDVI and P_Area had significant positive effects on UCI intensity and range, while the background temperature had significant negative effects. With higher background temperature, the optimal patch size of UGS is larger. This study provides useful information for developing effective heat mitigation and adaptation strategies to enhance climate resilience in tropical cities.

KEYWORDS

urban heat island, green space, threshold value of efficiency, cooling intensity, megacity, sustainable development goals

Introduction

The world has been experiencing an inevitable trend of urbanization (Girardet, 2020). According to the World Urbanization Prospects report (United Nations, 2019), the urban population of the world will continue to rise and 90% of the increase concentrates in Asia and Africa. As cities continue to expand, roads and buildings replace some natural surfaces such as trees, water bodies and soil. The transformation of land use changes biophysical properties of the land surface, which could generate the local warming effect or urban heat island (UHI) effect (Oke, 1973; Arnfield, 2003). The UHI effects and global scale climate change are projected to cause a large number of extreme heat events, thereby contributing to heat-related mortality (Stone et al., 2014). It was estimated that with a 2.0°C increase in temperature, the annual heat-related mortality increased from 32.1 per million people in 1986 to 81.3 per million people in 2005 in China (Wang et al., 2019). Megacities in tropical regions of Asia have dense population density, and were predicted to experience more frequent and intense heatwaves for the next decades (Coleman, 2022). He 11th goal of United Nation's sustainable development goals (SDGs) advocates making cities inclusive, safe, resilient, and sustainable (United Nations, 2015). Exploring the UHI effect and the effectiveness of mitigation measures are crucial for reducing heat risk and enhancing climate resilience in these cities.

Since spaceborne remote sensing can provide timely and objective observations over vast areas, spatiotemporal changes in surface urban heat island (SUHI) at local, regional and global scales were examined by using remotely-sensed land surface temperature (LST) data (Liu et al., 2020b; Weng 2009; Lu et al., 2019). Due to high cloud coverage, the amount of cloud-free and high quality remote sensing data in tropical regions is limited. In order to acquire remote sensing data with both high spatial and temporal resolution, spatiotemporal data fusion methods have been developed (Gao et al., 2006; Zhu et al., 2010). Gao et al. (2006) developed a Spatial and Temporal Adaptive Reflectance Fusion Model (STARFM) to product daily surface reflectance data at a spatial resolution of 30 m. To address landscape heterogeneity, Zhu et al. (2010) further developed the enhanced spatial and temporal adaptive reflectance fusion model data fusion method (ESTARFM) to improve the accuracy of predicted images. The ESTARFM model achieved a satisfied accuracy in generating high spatio-temporal land surface temperature data in previous studies (Liu et al., 2020b).

Urban green space (UGS) including parks, street vegetation, green roofs, and woodlands is a commonly adopted measure to mitigate the UHI effect (Aram et al., 2019). UGS provides cooling effects to their surroundings through several processes such as shading and evapotranspiration. However, the cooling effect of UGS is spatially limited and generally decreases with distance from UGS. Previous studies reported that beyond a certain distance, the cooling effect of UGS patches disappears (Feyisa et al., 2014). To quantify the cooling effect of UGS, Yu et al. (2017) defined the intensity, range and efficiency of urban cooling island (UCI), as well as the threshold value of efficiency (TVoE). The TVoE has been used to acquire the most suitable patch size of urban green space in different study areas (Fan et al., 2019; Yang et al., 2020; Tan et al., 2021). Numerous evidences from field observations and remote sensing data proved that the cooling intensity and range of parks have a positive relationship with their areas (Lin et al., 2015; Algretawee 2022; Vaz Monteiro, 2016). Besides the size of green space, factors such as the composition, configuration, background temperature, neighboring vegetation cover of green space patches also impact their cooling effects (Akbari and Kolokotsa, 2016; Gillner et al., 2015; Yu et al., 2018b; Zhou et al., 2022).

Although the megacities in tropical Asia are vulnerable to extreme heat events, the unavailability of satellite data with both high spatial and temporal resolution hindered the in-depth investigation of urban heat islands and cooling effects in these cities (Giridharan, 2018). Uddin et al. (2022) used the day and night time temperature data provided by MODIS to quantify UHI in Dhaka. They found that the UHI effect was significantly related to population change, urban expansion, and meteorological factors such as cloud cover. Parvin and Abudu (2017) used Landsat data to assess UHI in Dhaka from 2002 to 2014 and reported that the temperature of all types of land cover was rising. Das et al. (2020) used MODIS data to study UHI seasonal changes in Kolkata and the relationship between UHI and vegetation. Halder et al. (2021) investigated the relationship between LST and vegetation and built-up areas using Landsat data and predicted the urban expansion in Kolkata in the next 30 years. Khamchiangta and Dhakal (2019) used Landsat data to study the temperature difference of different land cover types and the relationship between heat island and urban physical structure and non-physical factors in Bangkok. Although the heat island phenomenon has been investigated in previous studies, the analysis based on MODIS data failed to provide sufficient spatial details, while the observation of Landsat was relatively sparse in time. In addition, the regulation capacity of urban green space on thermal environment has barely been explored in these cities.

The megacities located in the tropical and subtropical regions have similar climate background conditions. By adopting standardized analysis methodologies, a comparative analysis of these cities could provide comprehensive information for the design and planning of green space in cities in tropical climate zones. Taking three megacities, Dhaka, Kolkata, and Bangkok, as the study area, the objectives of our study include 1) to generate land surface temperature data with high spatial and temporal resolution in winter season from 2000 to 2020 using data fusion model, 2) to quantify spatiotemporal changes in SUHI from 2000 to 2020 and explore their relationship with land cover using

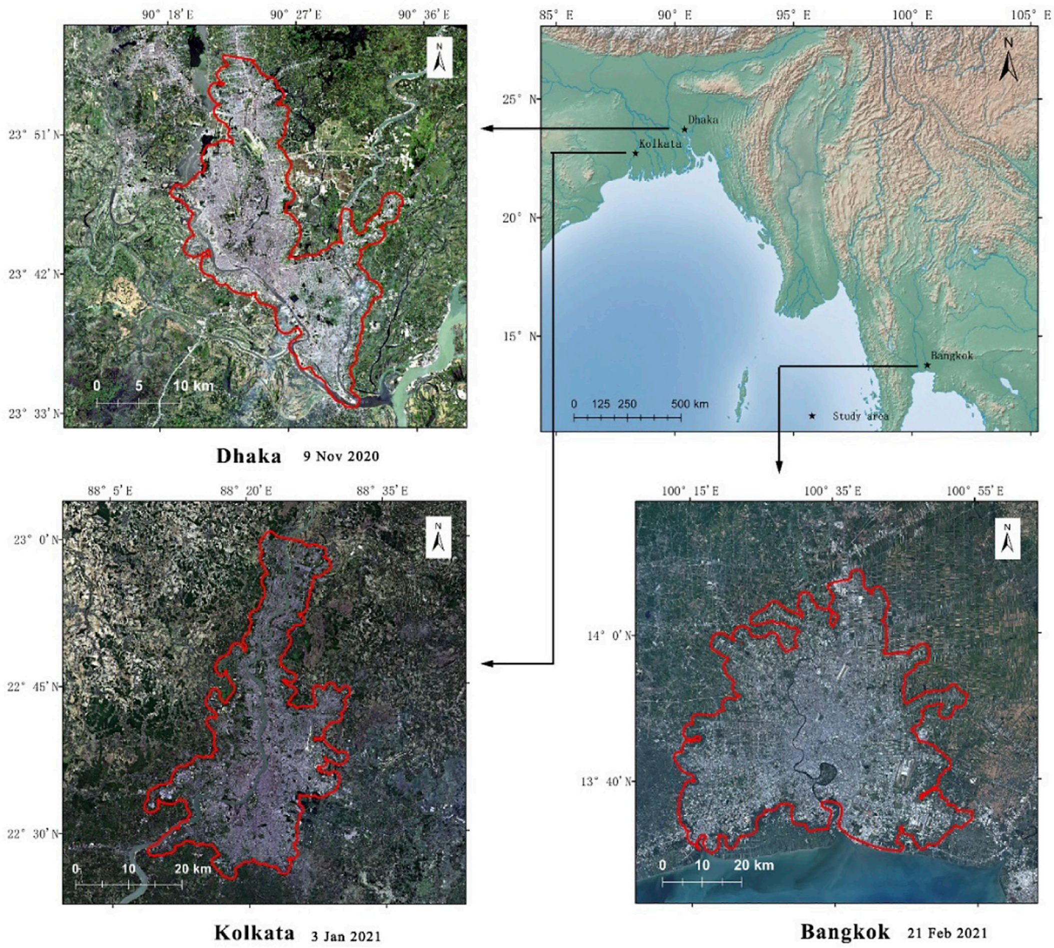

FIGURE 1
The geographic location of the study area. The red polygons represent the urban functional boundary. The underlying satellite images are from Landsat-8 OLI sensor.

the enhanced LST data, and 3) to calculate the threshold value of efficiency (TVoE) of green space and analyze the relationship between their cooling effect and landscape metrics.

Study area and data sets

Study area

The study areas consist of three megacities in Asia: Dhaka, Kolkata, and Bangkok (Figure 1). The three megacities are located in tropical or subtropical regions, and the seasonality of temperature and precipitation in these cities are similar. They are all categorized as tropical savannah (Aw) climate zone in the Köppen-Geiger classification scheme (Beck et al., 2018). Dhaka is the largest city in Bangladesh and one of the major cities in South Asia with a population of over 15 million. Kolkata is the capital of West Bengal and the third largest city in India after Mumbai and New Delhi. In addition, it is the largest trading and commercial center in eastern India which is located 150 km north of the Bay of Bengal above the plains of the Ganges Delta (Nath et al., 2015). As the capital and largest city of Thailand, Bangkok is the second largest city in Southeast Asia. It is the center of politics, economy, trade, transportation, culture, science and technology, education, religion and all aspects of Thailand. Since the study focused on SUHI analysis, urban functional areas of each city were delineated as main study areas.

Datasets and preprocessing

Landsat data of the study area covering five time periods: 2000, 2005, 2010, 2015, and 2020 were acquired in this study. It was obtained from the United States Geological Survey (USGS)

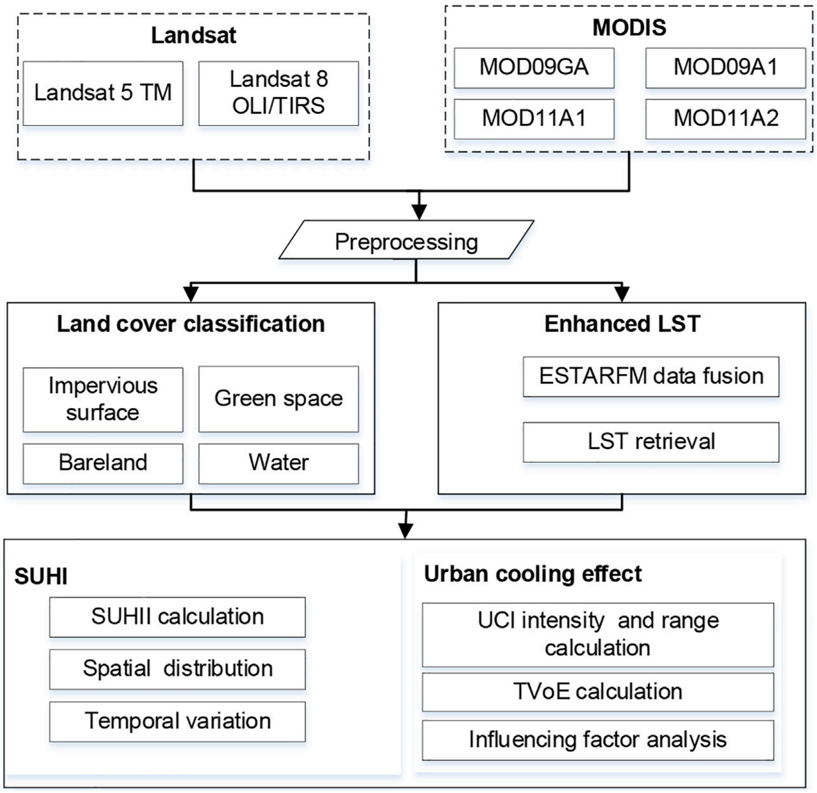

FIGURE 2
The data processing workflow.

TABLE 1 Landsat data used for land cover classification.

Year	City	Sensor	Landsat scene ID	Acquisition time
2000	Dhaka	Landsat 5 TM	LT05_L1TP_137044_20000220_20161216_01_T1	02/20/2000
	Kolkata	Landsat 5 TM	LT05_L1TP_138044_20000126_20161215_01_T1	01/26/2000
	Bangkok	Landsat 5 TM	LT05_L1TP_129051_20001110_20161213_01_T1	11/10/2000
2005	Dhaka	Landsat 5 TM	LT05_L1TP_137044_20040302_20161202_01_T1	03/02/2004
	Kolkata	Landsat 5 TM	LT05_L1TP_138044_20061212_20161117_01_T1	12/12/2006
	Bangkok	Landsat 5 TM	LT05_L1TP_129050_20060127_20161124_01_T1	01/27/2006
2010	Dhaka	Landsat 5 TM	LT05_L1TP_137044_20090228_20161027_01_T1	02/28/2009
	Kolkata	Landsat 5 TM	LT05_L1TP_138044_20100121_20161017_01_T1	01/21/2010
	Bangkok	Landsat 5 TM	LT05_L1TP_129051_20081202_20170111_01_T1	12/02/2008
2015	Dhaka	Landsat 8 OLI/TIRS	LC08_L1TP_137044_20150128_20170413_01_T1	01/28/2015
	Kolkata	Landsat 8 OLI/TIRS	LC08_L1TP_138044_20170108_20170311_01_T1	01/08/2017
	Bangkok	Landsat 8 OLI/TIRS	LC08_L1TP_129051_20150104_20170415_01_T1	01/04/2015
2020	Dhaka	Landsat 8 OLI/TIRS	LO08_L1TP_137044_20201109_20201120_01_T1	11/09/2020
	Kolkata	Landsat 8 OLI/TIRS	LC08_L1TP_138044_20210103_20210309_01_T1	01/03/2021
	Bangkok	Landsat 8 OLI/TIRS	LC08_L1TP_129051_20210221_20210304_01_T1	02/21/2021

TABLE 2 MODIS and Landsat data used for the ESTARFM data fusion.

Year	City	Landsat and daily MODIS (references data)		Daytime MODIS 8-day composites at predicted time (t_p)		
		First pair (t_m)	Second pair (t_n)	December	January	February
2000	Dhaka	02/20/2000	—	—	—	—
	Kolkata	01/26/2000	—	—	—	—
	Bangkok	02/28/2000	12/05/2003	12/18/2000	01/09/2001	02/10/2001
2005	Dhaka	12/13/2003	03/02/2004	12/13/2003	02/10/2004	02/26/2004
	Kolkata	12/03/2006	04/02/2007	12/11/2006	01/17/2007	02/26/2007
	Bangkok	12/07/2004	12/29/2006	12/11/2005	01/09/2006	02/02/2006
2010	Dhaka	04/14/2008	10/26/2009	11/24/2008	01/17/2009	02/18/2009
	Kolkata	05/07/2009	04/12/2010	12/19/2009	01/17/2010	02/26/2010
	Bangkok	02/15/2007	04/25/2009	12/02/2008	01/17/2009	02/10/2009
2015	Dhaka	03/30/2014	11/12/2015	12/03/2014	01/09/2015	02/02/2015
	Kolkata	04/15/2016	04/11/2017	11/16/2016	02/02/2017	03/14/2017
	Bangkok	01/17/2014	02/05/2015	12/11/2014	01/01/2015	—
2020	Dhaka	02/24/2019	12/14/2021	11/24/2020	01/24/2021	02/02/2021
	Kolkata	04/07/2020	04/26/2021	11/24/2020	01/01/2021	02/26/2021
	Bangkok	12/17/2019	02/21/2021	12/02/2020	01/09/2021	—

-Due to image quality, we did not fuse data in part of time.

(https://earthexplorer.usgs.gov/). One Landsat image with good data quality in each time period was selected for land cover classification and two Landsat images were both used for data fusion. The details about Landsat images for land cover classification are listed in Table 1 and the details for data used for fusion are listed in Table 2. Radiometric calibration and atmospheric correction were performed for the preprocessing of the Landsat images. The red, near-infrared, and thermal infrared bands were extracted for data fusion.

MODIS data is provided by the United States National Aeronautics and Space Administration (NASA) (https://ladsweb.modaps.eosdis.nasa.gov/). The MODIS data we used includes surface reflectance data from MOD09GA and MOD09A1 products and daytime land surface temperature data from MOD11A1 and MOD11A2 8-day composite products. Due to the frequent cloud coverage in the study areas, cloud-free remote sensing images in winter months (December to February) were selected to predict the Landsat-like land surface temperature data (Table 2).

The original MODIS data is stored in HDF format. The bands selected from MOD09GA/MOD09A1 are B01 and B02, while Emis_31 and LST_Day_1 km bands were selected from MOD11A1/MOD11A2. Batch data processing codes were used to convert the original MODIS data to geotiff format using MODIS Reprojection Tool. The extracted data bands were converted to surface reflectance by applying the scale factor and offset using the following equation:

$$L_\lambda = \text{Scale Factor} * DN + Offset \quad (1)$$

where L_λ is the surface reflectance of band λ; Scale Factor is the reflection coefficient of band; DN is the integer value of band λ, and Offset is the Offset of band.

The blackbody radiance can be calculated according to Eq. 2:

$$B_\lambda (T_S) = \frac{K_1}{e^{K_2/T_s} - 1} \quad (2)$$

where K_1 and K_2 are Landsat sensor parameters, and T_s is the true reflectance of band LST_Day_1 km.

The radiant brightness in thermal infrared band received by MODIS satellite sensor is calculated using the radiative transfer equation:

$$L_\lambda = \varepsilon_\lambda * B_\lambda (T_S) * \tau_\lambda + L^{\uparrow}_{atm\_\lambda} + (1 - \varepsilon_\lambda) * L^{\downarrow}_{atm\_\lambda} * \tau_\lambda \quad (3)$$

where L_λ is the brightness of thermal infrared radiation with wavelength λ; $B_\lambda (T_S)$ is the blackbody radiation brightness when the surface temperature is T_S; τ_λ is the atmospheric transmittance along the path direction from the target to the sensor; ε_λ is the surface emissivity with wavelength λ; $L^{\uparrow}_{atm\_\lambda}$ and

$L^{\downarrow}_{atm\_\lambda}$ are atmospheric upward radiation and downward radiation. Atmospheric transmittance, atmospheric upward radiation, and atmospheric downward radiation can be calculated using the atmospheric correction parameter calculator provided by NASA. The processed MODIS data were resampled to 30 m with the same resolution as Landsat data. The preprocessing process is automatically performed using IDL scripts.

Methodology

The data processing workflow mainly includes four steps (Figure 2): land cover classification, land surface temperature (LST) retrieval, surface urban heat island (SUHI) analysis and cooling effects analysis for urban green space (UGS).

Land cover classification

Land cover types including impervious surface, bare land, green space and water were classified using Support Vector Machine (SVM) classifier in the study areas for 2000, 2005, 2010, 2015, and 2020. Training and validation samples were randomly collected on Google Earth. The definition criteria issued by the United Nations Human Settlements Programme was used to determine the urban functional boundary (Lu et al., 2022). The urban functional boundary could reflect the urbanization situation in the study area more accurately than the administrative boundary. According to the land cover classification, the pixels with above 50% built-up density was defined as the urban pixel, 25%–50% was defined as the suburban pixel, and less than 25% was defined as the rural pixel. The area within 100 m around the urban or suburban pixels was defined as the urban open space, and the urban, suburban and urban open space pixels were merged. Then, the area of each polygon was expanded by 25% to establish buffer zones. The buffer zone with the largest area is the urban functional area, and its boundary is the functional boundary of the city. The urban functional boundaries of the three study areas were created using the land cover classification results in 2020 (Figure 1).

Land surface temperature retrieval

We used ESTARFM to fuse Landsat and MODIS data in this study (Zhu et al., 2010). Landsat and MODIS images at the time of T_m and T_n were input. The model searched for pixels similar to the center pixel according the window size. The conversion coefficients were determined according to the weights of similar pixels. The predicted images were finally obtained by combing two predicted results.

Among the commonly used land surface retrieval algorithms, the algorithm based on radiative transfer equation has a solid physical basis and high inversion accuracy (Lu et al., 2020; Duan et al., 2021). Radiative transfer equation-based method and the fused Landsat-like data were used to retrieve the LST in our study. The red band and near-infrared band of the fused image were used to calculate the normalized difference vegetation index (NDVI) (Lu et al., 2015; Yuan et al., 2018):

$$\mathrm{NDVI} = \frac{(\mathrm{NIR} - \mathrm{RED})}{(\mathrm{NIR} + \mathrm{RED})} \quad (4)$$

where NIR is the near-infrared band and RED is the red band of the image.

Then, the vegetation coverage P_v was calculated using NDVI:

$$P_v = \frac{\mathrm{NDVI} - \mathrm{NDVI}_{\mathrm{Soil}}}{\mathrm{NDVI}_{\mathrm{Veg}} - \mathrm{NDVI}_{\mathrm{Soil}}} \quad (5)$$

where $\mathrm{NDVI}_{\mathrm{Soil}}$ is the NDVI value of the bare soil or the area without vegetation cover, and $\mathrm{NDVI}_{\mathrm{Veg}}$ is the NDVI value of the pixel completely covered by vegetation. We take the empirical value: $\mathrm{NDVI}_{\mathrm{Veg}} = 0.70$ and $\mathrm{NDVI}_{\mathrm{Soil}} = 0.05$. When the NDVI of a pixel is greater than 0.70, the P_v value is 1. When NDVI is less than 0.05, P_v is set as 0.

The land surface emissivity was then calculated as:

$$\varepsilon = \mathrm{m} * P_v + n \quad (6)$$

by using typical constant values for the emissivity of vegetation and soil, m and n were set as 0.004 and 0.986, respectively (Sobrino et al., 2008).

The blackbody radiance was calculated using the radiative transfer equation:

$$B_\lambda(T_S) = \frac{L_\lambda - L^{\uparrow}_{atm_\lambda} - (1-\varepsilon_\lambda) * L^{\downarrow}_{atm\_\lambda} * \tau_\lambda}{\varepsilon_\lambda * \tau_\lambda} \quad (7)$$

The land surface temperature was calculated as:

$$T_s = \frac{K_2}{ln(K_1/B_\lambda(T_s)+1)} \quad (8)$$

The temperature, T_s, was converted to degrees Celsius. The LST retrieval was performed automatically using IDL scripts.

Surface urban heat island analysis

The surface urban heat island intensity (SUHII) can be defined as the difference between the surface temperature of built-up area and green space (Estoque and Murayama, 2017; Bechtel et al., 2019). At each built-up area pixel, the SUHII was calculated using the following equation:

$$SUHII = T_{urban} - \overline{T_{rural}} \quad (9)$$

where T_{urban} is LST at pixel i and $\overline{T_{\text{rural}}}$ is the land surface average temperature of green space pixels. The average temperature of dense vegetation with NDVI greater than 0.55 in green patch within urban functional boundary was taken as the average temperature of green space.

The SUHII of the study area was further divided into five levels as: very low level (SUHII <μ-std), low level (μ-std≤ SUHII <μ-0.5*std), moderate level (μ-0.5*std≤ SUHII <μ+0.5*std), high level (μ+0.5*std≤ SUHII <μ+std), and very high level (SUHII ≥μ+std). The average of the annual SUHII in the urban functional area (excluding water area) was calculated as:

$$SUHII_{cj} = \frac{\sum_{i=1}^{n} SUHII_{cij}}{\sum i} \quad (10)$$

where SUHII_{cj} represents the average SUHII of city C in the jth year (j = 2000, 2005, 2010, 2015, and 2020), i is the pixel i, and SUHII_{cij} represents the value of SUHII of city c at pixel i in the jth year.

Quantifying the urban cooling effect

UGS patches were manually selected using Google Earth for each study area. Due to the complex composition of green space, only green space patches with dense trees were selected in order to control the influencing variables and dense trees are recognised as having strong cooling effects. The selection of green space patches follows several rules: select green patches that are primarily covered by trees, green patches that have no internal water spots and are more than 300 m away from other green spaces or water bodies to avoid interaction between samples, and green patches smaller than 900 m^2 (30 m*30 m) were removed. Based on these rules, 73, 90, and 107 green space patches were delineated in Dhaka, Kolkata and Bangkok, respectively.

The intensity and range of urban cooling island (UCI) were used to quantify the cooling effect of green space patches in our study. The intensity of UCI was calculated as the temperature difference between the temperature of the green patch and the peak temperature at the first turning point when the temperature decreased (Yu et al., 2018b). The cooling range is the distance from the edge of the patch to the first turning point on the temperature curve (Yu et al., 2017). In order to study UGS cooling effect, we used Arcpy scripts to create 18 buffers for each green patch. Since the image resolution is 30 m, the buffer distance is set to 30 m, and then the average LST of each buffer was calculated. According to previous studies (Fan et al., 2019), 540 m (18*30 m) could cover far more of the cooling range that a green space patch can produce. Then, the UCI intensity and range of each green space patch were calculated. The patches which LST dropped at the beginning were treated as abnormal patches and removed in our analysis.

Yu et al. (2017) defined the threshold value of efficiency (TVoE) to find the optimal patch size of urban green space in different study areas. UCI intensity increases rapidly in the first half of the period with the increase of patch area, while the change of UCI intensity is no longer obvious after exceeding a certain value (Yu et al., 2018a; Yu et al., 2018b; Fan et al., 2019). The log function is used to fit the change in UCI intensity according to Eq. 11:

$$y = a * \ln x + b \quad (11)$$

where a is the coefficient of the log function; b is the constant of the log function. The critical point where the slope of the log function is equal to one is defined as TVoE. The UCI intensity increases significantly with the increase in patch size before the TVoE, and increase insignificantly after exceeding the TVoE. The logarithmic regression was used to extract the TVoE or optimal green space patch size in each city.

Statistical analysis

Following previous studies (Sun and Chen, 2017; Fan et al., 2019; Yu et al., 2020; Shah et al., 2021; Tan et al., 2021), four dominant factors, namely normalized difference vegetation index (P_NDVI), land surface temperature (P_LST), shape index (P_SI) and area (P_Area) of UGS patches were selected to explore their influence on the cooling intensity and range of UGS. The shape index represents the complexity of patch shape. The larger the value of the shape index, the more complex the shape is. The four metrics, their definition and description are listed in Table 3.

Pearson correlation was used to examine the relationship between the UCI effect and relevant landscape metrics. In specific, The UCI effect includes cooling intensity and cooling range and landscape metrics include P_NDVI, P_LST, P_SI, and P_Area. Pearson correlation coefficients were calculated to represent the magnitude of the correlation between UCI effect and relevant landscape metrics. Landscape metrics can affect UCI effect independently as well as interactively. Due to the possible correlation between landscape metrics, partial correlation analysis was performed to exclude the interaction between the landscape metrics.

Landscape metrics were used as independent variables, and the intensity and range of UCI effect were used as dependent variables. For landscape metrics with significant correlation relationship with UCI, regression analysis was conducted to analyze their effects on cooling effects. Because the relationship between the two is not necessarily a simple linear relationship, multiple functions were used to find the optimal regression. The R^2 represents the degree to which the dependent variable can be explained by the model. The coefficient reflects the expected change in the dependent variable for every unit

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TABLE 3 Landscape metrics of the urban green space patches.

Metric	Definition	Description
P_NDVI	$P\_NDVI = \sum_{i=1}^{n} NDVI_i/n$	P_NDVI is the average NDVI of the patch. $NDVI_i$ is the NDVI of pixel i, n is the number of pixels in the patch
P_LST	$P\_LST = \sum_{i=1}^{n} LST_i/n$	P_LST is the average LST of the patch. LST_i is the LST of pixel i, n is the number of pixels in the patch
P_SI	$P\_SI = a/2*\sqrt{\pi * b}$	P_SI is the shape index of the patch. A is the patch perimeter and b is the patch area
P_Area	—	P_Area is the area of the patch

change in the associated independent variable. The ordinary least squares (OLS) regression was performed using SPSS25.0 software.

Results

Land cover changes

Table 4 shows the validation results of land cover maps for these three Asian megacities in five time periods. The overall accuracies range from 85.75% to 91.78%, and the Kappa coefficients range from 0.82 to 0.88. For Dhaka and Kolkata, low overall accuracies were obtained in 2000. It might be caused by the relatively low image quality.

The three cities have experienced significant urban development from 2000 to 2020. The urban areas have continuously expanded and green space has shrunk (Figure 3). The land cover changes in the three cities experienced similar changing trajectories. From 2000 to 2020, the green space of the three cities decreased by 1138.69 ha, 13894.52 ha, and 14416.24 ha respectively. Bare land decreased by 15257.98 ha, 20315.92 ha, and 109164.43 ha, respectively. The area of water bodies changed slightly in Dhaka and Kolkata. The impervious surface of each city expanded rapidly and increased by 16062.34 ha, 34707.11 ha, and 112698.38 ha respectively. The built-up areas in the three cities are rapidly expanding outward. The green space and bare land areas were mainly converted into impervious surface areas.

Spatiotemporal variation of surface urban heat island

According to previous studies (Weng et al., 2014; Liu et al., 2020b), the observed Landsat data can be used to evaluate the accuracy of prediction results. The LST data obtained from the Landsat image on 13 December 2003 was used to estimate the accuracy of the LST from the predicted image. At the significance level of 0.01, MAD and RMSE between the two datasets were 0.26°C and 2.02°C, respectively, and Pearson's value was 0.99. These results indicated that there was a strong correlation between predicted and observed LST (Figure 4).

Figure 5 shows the spatial pattern changes of SUHII in the three cities from 2000 to 2020. The High Level and Very High Level areas in all three cities continue to extend outward. The high level areas are concentrated in the city center in 2000, while they spread to the whole functional area of the city in 2020. The SHUII in the three cities show different spatial patterns. Multiple high intensity areas were observed in Dhaka in 2020. Some marginal areas even have higher heat island intensity than the central areas, and most high-intensity areas are concentrated in the central and northwest of the city. The SUHI in Kolkata sprawls in all directions from the city center. In Bangkok, the SUHI gradually spreads to the east and west from 2000 to 2020. Compared with the land cover map, it is obvious that the spatial evolution of SUHI corresponds well with the spatial pattern of urban expansion.

The temporal variations of SUHII and LST differences in the three cities were analyzed from 2000 to 2020 (Figure 6). The intensity of SUHI showed a monotonic increasing trends, and experienced a fluctuation in 2010 only in Bangkok. The changing slope of SUHII indicated that all three cities has been experiencing intensified SUHI effect. The continuous rise of SUHII is related with the increase of the difference between urban temperature and background temperature. The increase of urban surface temperature is significantly faster than that of background temperature. From 2000 to 2020, the urban surface temperature in three cities increased by 4.03°C, 8.39°C, and 4.47°C respectively, and the background temperature increased by 3.05°C, 6.97°C, and 3.74°C respectively.

Urban cooling effects

Figure 7 shows the logarithmic regression analysis results in each city. Based on the fitted logarithmic regression models, the TVoE values were estimated. The p-value of each city is less than 0.01, indicating that the relationship is significant. The TVoE is 0.37 ha ($R^2 = 0.08$), 0.77 ha ($R^2 = 0.31$) and 0.42 ha ($R^2 = 0.12$) in Dhaka, Kolkata and Bangkok, respectively.

Table 5 shows the statistics of landscape metrics and UCI intensity in the study areas. The mean patch size of greens space is larger in Kolkata and Bangkok than Dhaka. The shape index of green patches is largest in Bangkok. The average NDVI and LST of UGS are higher in Kolkata than the other two cities. The

TABLE 4 Accuracy of classified land cover maps.

City	2000		2005		2010		2015		2020	
	Overall Accuracy (%)	Kappa Coefficient	Overall Accuracy (%)	Kappa Coefficient	Overall Accuracy (%)	Kappa Coefficient	Overall Accuracy (%)	Kappa Coefficient	Overall Accuracy (%)	Kappa Coefficient
Dhaka	85.75%	0.82	87.36%	0.85	89.47%	0.87	91.11%	0.88	88.98%	0.85
Kolkata	86.66%	0.82	90.27%	0.87	87.65%	0.84	89.62%	0.87	91.78%	0.88
Bangkok	90.23%	0.87	91.28%	0.88	89.39%	0.87	88.66%	0.85	89.21%	0.86

maximum UCI intensity ranges from 4.83°C in Bangkok to 8.07°C in Kolkata. The mean UCI intensity is highest in Kolkata and lowest in Dhaka. The maximum UCI range varies from 300 m in Bangkok to 420 m in Kolkata. The mean UCI range varies from 67 m in Bangkok to 81 m in Dhaka.

The correlation between landscape metrics and cooling effects in the megacities was also analyzed (Table 6). Among the four metrics, P_NDVI has a significant positive correlation with UCI intensity in Kolkata and Bangkok, but only has a significant positive correlation with UCI range in Bangkok. P_LST has a strong influence on UCI intensity and UCI range in all the cities, and the absolute values of Pearson correlation coefficients are greater than 0.50 on UCI intensity. For P_SI index, although correlation is negative on UCI intensity, the relationship is no significant. P_Area has a strong influence on UCI intensity and UCI range in the study areas.

For the significant correlations, the effects of landscape metrics were further analyzed using OLS regression (Table 7). The increase in NDVI leads to increase of UCI intensity in Kolkata (coefficient = 8.37) and Bangkok (coefficients = 4.83) and increase of UCI range in Bangkok (coefficient = 201.99). An increase in average LST is significantly associated with the decrease of UCI intensity and range in all the megacities. The effect of LST on UCI intensity in strongest in Kolkata, and its effect on UCI range is most significant in Dhaka. In addition, the increase of patch area is significantly associated with the increase of UCI intensity and range in all the megacities.

Discussion

Spatiotemporal variation of surface urban heat island

The study areas have a tropical monsoon climate, which is cloudy and rainy almost all year round. These lead to the difficulty in obtaining continuous gap-free remote sensing images. The blending of MODIS and Landsat data produced LST data with high spatio-temporal resolution. Since MODIS data have a spatial resolution of 1 km, narrow rivers and small-sized land features cannot be identified from the LST images. Compared with Hassan et al. (2021) which used MODIS data to explore SUHI effect, our data captured more detailed information (Figure 5). The overall land cover change results are similar to previous studies (Estoque et al., 2017; Si et al., 2022). The comparison between the land cover and SUHI map indicates that the expansion of urban impervious surface areas affects the variations of heat island. Due to the different physical properties of visible band and thermal infrared band, the visible bands and thermal infrared bands were fused separately, which effectively improved the accuracy of data fusion. The data fusion methods and processing framework have been developed to improve the efficiency and accuracy of data fusion. Since data gaps often exist in MODIS data, Liu et al. (2020b) used a mean filter or

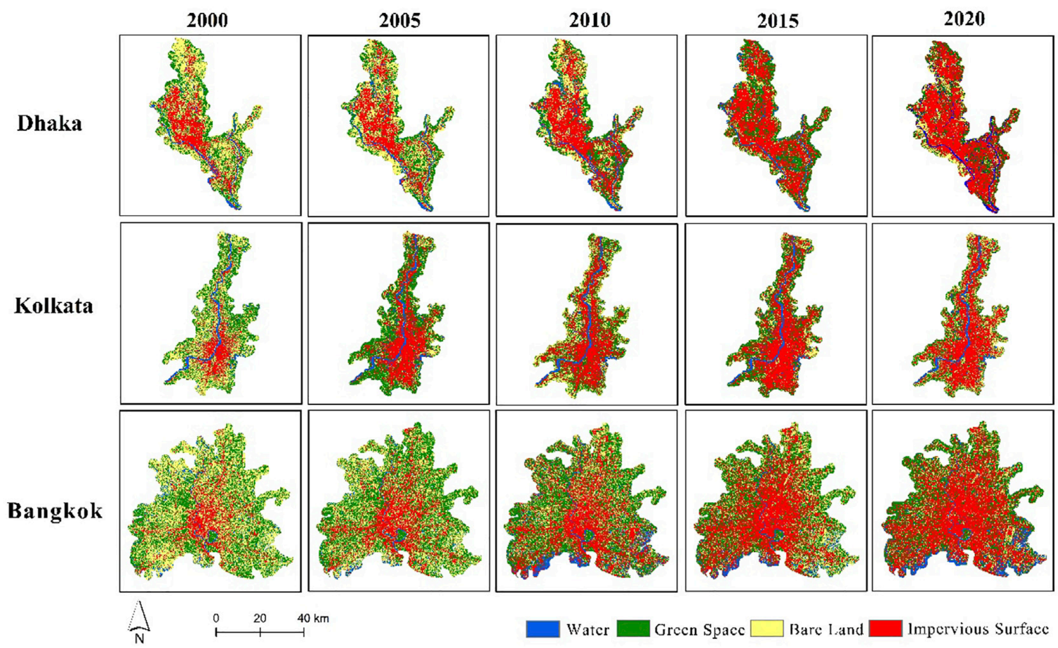

FIGURE 3
Land cover maps of the three megacities in 2000, 2005, 2010, 2015, and 2020.

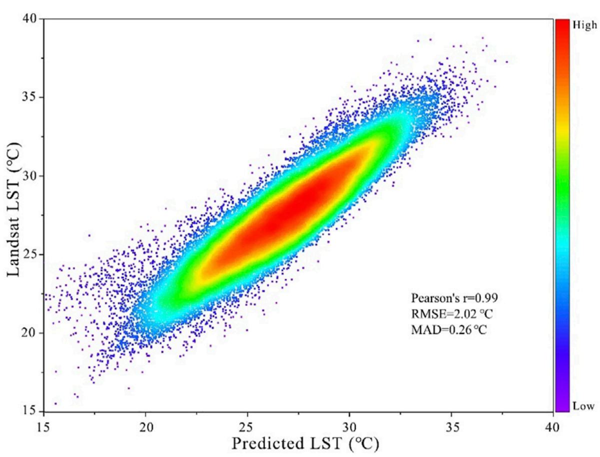

FIGURE 4
Scatter plot between the estimated and the observed land surface temperature.

linear regression to fill the missing pixels, which enhanced data availability and provided richer information for fusion. Since the moving window of ESTARFM model has a fixed size, Liu et al. (2020a) used surface heterogeneity information to develop a new spatiotemporal data fusion algorithm which could automatically adjust the size of the moving window. These methods can be tested and applied to improve the accuracy of fused LST data in future studies. Based on the multi-temporal land cover and SUHII maps, the variations of land cover and urban thermal environment from 2000 to 2020 was captured clearly in the study areas.

Urban cooling effects and policy implications

The maximum intensity of UCI was found to range from 4.83°C to 8.07°C, and the maximum range of UCI varies from 300 m to 420 m in the three megacities. Our result show that the largest park in Kolkata (39 ha) provided a maximum cooling island effect with an intensity of 8.07°C and range of 420 m. Surveys in different seasons, times of day, and measuring methods indicated that the maximum cooling of large-sized parks could reach 5°C–8°C (Aram et al., 2019; Yin et al., 2022). The average night-time cooling range of Kensington Gardens (111 ha) in London was found to vary between 20 and 440 m (Doick et al., 2014). The Heiwa Park (147 ha), Nagoya had a cooling distance of 200–300 m during night and 300–500 m during daytime (Aram e al., 2019). The mean cooling range and intensity of blue-green space are 150 m and 2.47°C in summer in Copenhagen (Yang et al., 2020). Different TVoE values to provide the optimal green space patch area were obtained for each megacity. Our study shows that the TVoE is 0.37 ha, 0.77 ha, and 0.42 ha in Dhaka, Kolkata and Bangkok, respectively. Geng et al. (2022) applied the TVoE method to 207 urban parks in 27 cities in East China with four

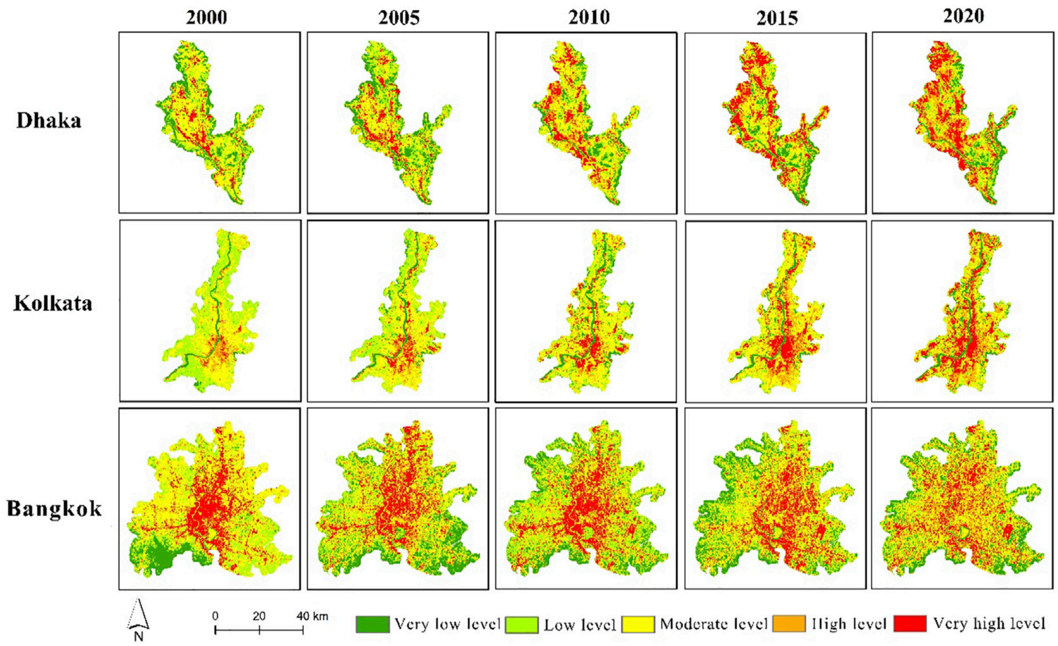

FIGURE 5
SUHII in the three megacities in 2000, 2005, 2010, 2015, and 2020.

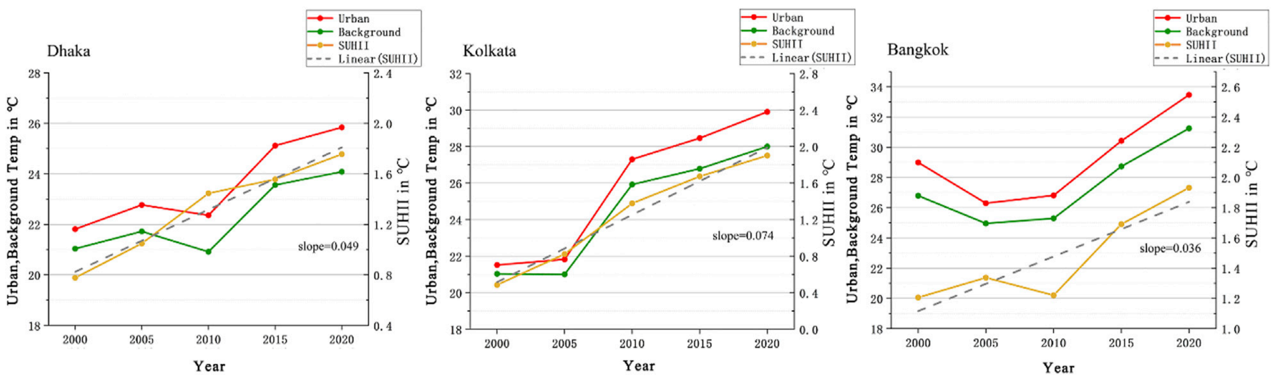

FIGURE 6
Temporal variation of SUHII in the three megacities from 2000 to 2020.

different local background climates, including warm temperate sub-humid monsoon, northern subtropical sub-humid monsoon, northern subtropical humid monsoon, and middle subtropical humid monsoon climate, and found that the TVoE was significantly affected by the background climate. Fan et al. (2019) found that the TVoE was about 0.6–0.62 ha in Hong Kong, Jakarta, Mumbai, and Singapore, and 0.92–0.96 ha in Kaohsiung, Kuala Lumpur, and Taiwan. Tan et al. (2021) found that the TVoE of three-based green spaces was about 0.31 ha in Nanning, China. The TVoE was found to be 4.55 ha in Fuzhou (Yu, et al., 2017). According to Fan et al. (2019), the TVoE was influenced by the background temperature and NDVI of green patches in the seven hot humid Asian cities. With higher background temperature, the optimal size of green space will be larger. This agrees well with our study.

Our results indicate that UCI intensity is correlated negatively with P_LST and positively with P_NDVI and P_Area, while UCI

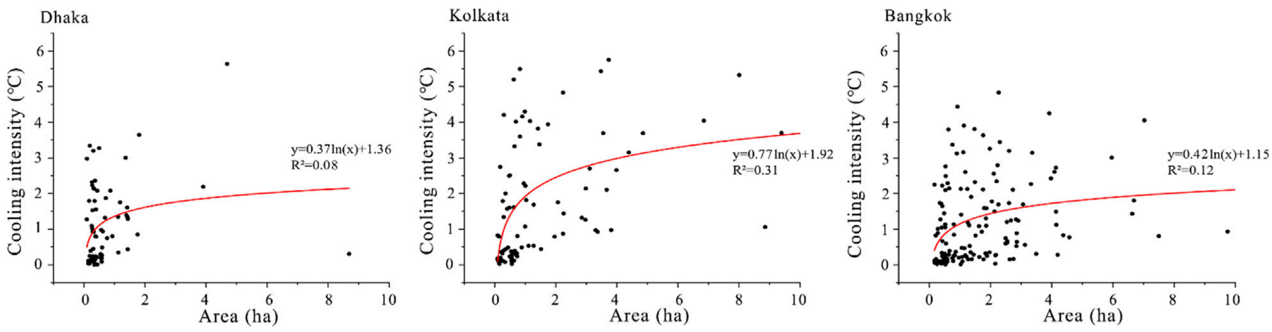

FIGURE 7
Logarithmic regression analysis results in the three megacities.

TABLE 5 Statistics of landscape metrics, UCI intensity and range in the three megacities.

City	P_Area		P_SI		P_NDVI		P_LST		UCI intensity		UCI range	
	Range (ha)	Mean (ha)	Range	Mean	Range	Mean	Range (°C)	Mean (°C)	Range (°C)	Mean (°C)	Range (m)	Mean (m)
Dhaka	0.09–8.68	0.75	1.08–2.23	1.38	0.17–0.73	0.42	28.75–35.14	31.93	0.0006–5.64	1.08	30–390	81
Kolkata	0.09–39.42	2.55	1.06–1.87	1.32	0.25–0.82	0.55	38.07–46.03	41.98	0.021–8.07	1.90	30–420	70
Bangkok	0.28–22.46	2.55	1.11–2.72	1.44	0.30–0.60	0.41	32.02–37.70	34.47	0.008–4.83	1.33	30–300	67

TABLE 6 Pearson correlation coefficients between the cooling effect and landscape metrics.

Landscape metrics	UCI intensity			UCI range		
	Dhaka	Kolkata	Bangkok	Dhaka	Kolkata	Bangkok
NDVI	0.11	0.43**	0.23*	0.06	0.18	0.23*
LST	−0.58**	−0.80**	−0.68**	−0.46**	−0.44**	−0.32**
SI	−0.00	−0.04	−0.00	0.10	−0.06	−0.18
Area	0.28*	0.39**	0.26*	0.25*	0.34**	0.22*

*Correlation is significant at the 0.05 level.
**Correlation is significant at the 0.01 level.

TABLE 7 Regression analysis between the cooling effect and landscape metrics.

Landscape metrics	UCI intensity						UCI range					
	Dhaka		Kolkata		Bangkok		Dhaka		Kolkata		Bangkok	
	R^2	Coefficients	R^2	Coefficients	R^2	Coefficients	R^2	Coefficients	R^2	Coefficients	R^2	Coefficients
NDVI	—	—	0.20	8.37	0.08	4.83	—	—	—	—	0.09	201.99
LST	0.38	−0.62	0.70	−0.86	0.52	−0.75	0.19	−9.45	0.15	−12.62	0.17	−17.58
Area	0.30	0.37	0.30	0.80	0.17	0.62	0.10	5.65	0.10	4.32	0.09	4.11

range is correlated negatively with P_LST and positively with P_Area. Since dense vegetation can increase the NDVI value and UCI intensity, the planting of woody vegetation is suggested to be increased in urban green space. The results also show that patch shape index has insignificant relationship with UCI intensity and range. Thus, city planners should choose the most convenient and economic way to plan green patches in terms of green space shapes. The effective method to enhance UCI intensity and range include increasing the area and biomass of green space, and lowering its background temperature. However, different results have been reported in previous studies. Some studies found that the correlation between P_Area, P_NDVI, P_SI, and UCI was insignificant (Shashua-Bar and Hoffman, 2000; Derkzen et al., 2017). The cooling effect of UGS is a huge and complex system (Murakawa et al., 1991). It is not only related to these landscape metrics, but also to other factors such as local climate background (Oliveira et al., 2011), geographical location (Hathway and Sharples, 2012), detailed landscape components (Zhao et al., 2014), humidity and evaporation (Vaz Monteiro et al., 2016; Zhou et al., 2017). In addition, ordinary linear regression (OLS) was used in our study. The OLS assumes that a linear relationship exists between the dependent and the independent variables. It also assumes error terms are independent and normally distributed. Spatial regression models such as spatial lag model, spatial error model and geographically weighted regression can be applied in order to account for spatial dependencies in the relationship between characteristic of UGS and intensity and range of UCI (Bartesaghi-Koc., 2022; Baqa et al., 2022).

Urban ecology is a huge system, and any environmental factors are likely to affect urban cool effects (Yu et al., 2017). The proposed methods can be adopted in other tropical cities to obtain more generalizable findings about the effects of urban greening characteristics on cooling effects in tropical climates (Bartesaghi-Koc et al., 2018). The physical characteristics of trees, the patterns of planting, and arrangement can also influence the air temperature and cooling effects of green infrastructures (Hami et al., 2019). The effects of these factors can be investigated by using more precise and comprehensive approaches in future studies. Moreover, the cooling effect of city parks varies in different seasons (Yang et al., 2020). The investigation of cooling effect of urban green spaces in different seasons can provide more information for the design of UGS patches. Urban morphology/geometry parameters such as sky view factor, aspect ratio, building and tree height, vegetation structure or stratification, orientation, altitude may also influence the thermal environment in cities (Irger, 2014; Morakinyo et al., 2020). They affect air circulation, heat dissipation, and thermal energy absorption in open spaces and urban canyons (Morakinyo et al., 2017; Ahmadi Venhari et al., 2019; Bartesaghi-Koc et al., 2022). A comprehensive investigation of urban and green space characteristics on urban thermal environment will be helpful to the planning of urban spaces to mitigate heat and improve thermal environment of cities in future studies.

Conclusion

In this study, ESTARFM data fusion method was applied to produce enhanced LST data for SUHI analysis the tropical megacities. Impervious surface has increased by 30%–40% and bare land and green space have decreased by 20%–40% in the megacities from 2000 to 2020. The average SUHI intensity increased by 0.98°C, 1.42°C, and 0.73°C in Dhaka, Kolkata, and Bangkok, respectively in last 2 decades. The urban cooling effects analysis results indicate that the maximum intensity of urban cooling island ranges from 4.83°C in Bangkok to 8.07°C in Kolkata, and the maximum range of urban cooling island varies from 300 m in Bangkok to 420 m in Kolkata. The optimal patch size of green space is 0.37 ha, 0.77 ha, and 0.42 ha in Dhaka, Kolkata and Bangkok, respectively. UCI intensity is negatively correlated with P_LST and positively correlated with P_NDVI and P_Area, while UCI range was correlated negatively with P_LST and positively correlated with P_Area. The optimal size of green space patches is larger in cities with higher background temperature. These results provide valuable information for the scientific planning of urban green space to produce effective cooling effects. Comprehensive investigation of urban characteristics on thermal environment can be performed for heat mitigation and adaptation in future studies.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The reviewer XS declared a shared affiliation with the authors except for ZF to the handling editor at the time of review.

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Research progress and application prospect of nature-based solutions in China

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In recent years, Nature-based Solutions (NbS) have become an important concept in the field of climate change and sustainable development. The study screens academic journals relevant NbS researches using China National Knowledge Infrastructure (CNKI) and Web of Science database to explore different perspectives for Nature-based Solutions research through qualitative analysis. This study reviews the existing research on NbS, summarizes what research ideas are covered by Nature-based Solutions, as well as the relationship between previous relevant studies, focuses on different perspectives of refining the implementation of Nature-based Solutions in various studies and practices, and explains them with typical cases. The research shows that existing Nature-based Solutions researches mostly prefer to determine schemes by objects, with insufficient emphasis on subjects and goals. On this basis, the specific operational framework of promoting Nature-based Solutions in China is considered to promote the development of indigenous application of Nature-based Solutions in China. This study reveals the diversified ideas in the research and implementation of Nature-based Solutions at home and abroad, which is of practical significance to promote the localization of Nature-based Solutions in China.

KEYWORDS

nature-based solutions (nbs), research progress, ecological restoration, localization of NbS, application prospect

1 Introduction

Cities are facing challenges of sustainable development, such as climate change, biodiversity loss, flood, drought, extreme high temperature. The sustainable development of urban and rural areas has become a recognized global wicked problem (Xiang, 2013). In order to solve a series of challenges faced by urban and rural areas, such as resource consumption, environmental pollution and ecosystem degradation, more and more scholars call for natural and ecosystem based methods to transform urban and rural areas to increase ecosystem resilience (Scott and Lennon, 2016; Lafortezza et al., 2017). China's urban and rural areas have different development levels and characteristics, so its sustainable development also faces a series of challenges. Although there is no clear solution, respecting nature has become a consensus concept in land use and ecological restoration (Wang and Yuan, 2019). At the same time, scholars' research also focuses on how to implement these "natural concepts" (Wang et al., 2020a). Nature-based solutions (NbS) provide a collaborative governance idea for addressing such challenges.

The World Bank first presented NbS in its 2008 report named *Biodiversity, Climate Change and Adaptation: Nature-Based Solutions in World Bank Investments*, and described it as "a more systematic understanding of the relationship between people and nature", pointed out that NbS should protect biodiversity and improve sustainable livelihoods while mitigating and adapting to the impacts of climate change (The Word Bank, 2008). The International Union for Conservation of Nature (IUCN) has defined NbS as: actions that effectively and adaptively address social challenges and provide benefits to human wellbeing and biodiversity through the conservation, sustainable management and restoration of natural or man-made ecosystems. It also suggested tackling climate change by NbS (IUCN, 2016). Over the past decade, it has blended this concept into about 100 investment projects, such as the support of Colombo wetland in Sri Lanka for urban flood control, and mangrove restoration in Vietnam. NbS includes a series of umbrella concepts based on ecosystem approach, such as natural climate solutions (NCS), ecosystem based adaptation (EbA), ecosystem based disaster risk reduction (Eco DRR), green infrastructure (GI), it plays an important role in addressing a number of major social challenges, including climate change mitigation and adaptation, disaster prevention and reduction, economic and social development, human health, food security, water security, ecological environment degradation and biodiversity loss (IUCN, 2020).

NbS is the development and integration of previous concepts (Lin and Sun, 2020), such as green infrastructure, natural capital (Sarukhan et al., 2005), ecological design and design ecology (Wang, 2017), ecosystem approach and other related concepts (Campbell et al., 2008), and has similar connotation with the recent concept of "natural idea" in China. The recent research on NbS is mainly concentrated in developed countries in European and American area, and has accumulated some experience and lessons, such as the NbS Roadmap for America, the EU Biodiversity Strategy for 2030, and The Post-2020 Global Biodiversity Framework. From ancient times some of planning and design, practice of ecological protection and restoration in China are also closely related to NbS. In order to effectively learn from the related experience at home and abroad, the study reviewed the existing research and analyzed the research progress of NbS. On this basis, it looks forward to promoting the specific application and operation framework of NbS in China and promoting the localization development of NbS in China.

2 Data sources and research methods

2.1 Data sources

The main subject of this article is the NbS. The literature studies that the author has studied are papers in the web of science and CNKI database. The survey was conducted in October 2022, mainly searching the papers of the last 10 years. The "search terms" procedure was designed according to the application field of NbS, by reading the title, abstract and conclusion of the paper, search terms irrelevant to NbS were eliminated. The results of literature retrieval influenced our decision to use these terms. The author set the search terms as NbS, ecological conservation and restoration, ecosystem, climate change, biodiversity, natural financing. The index results showed that 324 articles studied the NbS from journals in the web of science database, 183 papers related to the theme of NbS in the CNKI database. The author removed the articles from the first online journals and other volumes that were not part of the research papers. Eventually, 126 relevant literature studies including reviews and articles were pitched to analyze and study.

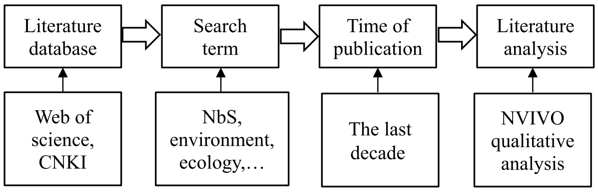

FIGURE 1
A flow chart of Nvivo-Qualitative Data Analysis in NbS.

2.2 Research methodology

The study mainly uses qualitative research methods to summarize various research perspectives on NbS at home and abroad. First, the preliminary reading of the text data, in order to grasp the overall framework and main content; Then Nvivo12 software is used to encode the initial text data to get the corresponding child nodes; Finally, the parent node is further refined from the child node, which is the research perspective of NbS (Figure 1). With the perspective of NbS as the focus for the study, the perspective and keywords of the collected literature was labeled by NVIVO qualitative analysis software (Pan and Tang, 2020); Extracting the whole paragraph content related to the core research perspective for subsequent text analysis materials, using the method of text analysis, the pattern rules between topics or features in the literature were summarized and analyzed. The keywords of each article are classified into unsupervised classification (algorithm direct classification) and supervised classification (manual classification). The words with similar connotation are classified into one category based on the two classification results, summarize the patterning rules between the themes or features hidden in the literature, so as to systematically refine various research perspectives of NbS. Finally, it explains the research perspective and significance of the literature to form a clear research viewpoint.

3 Research hotspots and evolution trends

3.1 Research hotspots

The key words or subject terms in the literature can reflect the core content and research hotpots of the study. The authors

TABLE 1 Top ten high-frequency emergent words.

Number	Keywords	Frequency
1	Climate change	37
2	Ecosystem services	31
3	Green infrastructure	28
4	Sustainable development	23
5	Climate resilience	19
6	Biodiversity	16
7	Urban green space	14
8	Ecological restoration	11
9	Landscape management	9
10	Stakeholder engagement	7

analyzed the high-frequency keyword co-occurrence and summarized the hot spots of the research of NbS in each literature. These keywords include climate change adaptation, ecosystem services, green infrastructure, sustainable development, climate resilience, urban green space, climate-change adaptation and mitigation, landscape management, stakeholder engagement (Table 1). In summary, they focus on ecological conservation and restoration, urban waterlogging mitigation, climate change response, biodiversity conservation, challenges of sustainable development, urban water management, economic transformation and ecosystem carbon sink, reflecting the research hotspots of NbS in the recent years.

3.2 Evolution trends

In the 1990s, the term "NbS" was first proposed in the field of biodiversity, and then was cited in agricultural development, land use planning and industrial design (Wang and Hou, 2021). Now it is widely used in climate change, urbanization, food security, water supply, and disaster risk. (Chen and Lin, 2019). In the field of environmental and natural protection, NbS is a "sustainable and cost-effective solution to social challenges such as global warming, water management and human health and promote the development and management of urban ecosystems, while enhancing biodiversity" (Eggermont et al., 2015). The NbS covers a range of ecosystem related measures. IUCN puts forward a classification system of measures according to the purpose, effectiveness and orientation (Cohen-shacham et al., 2016), NbS approaches including policies, management systems, plans, measures, projects, formulated for an ecosystem or specific problems (Table 2).

Internationally, IUCN, the World Bank, the European Union, UNESCO and other institutions have formed project support for special research related to NbS, especially in water resource management, flood control and other aspects. In 2012, the World Bank prepared a research report on the application of NbS to water resources protection in East Asia, and supported 60 countries to implement about 100 projects related to NbS; In 2015, the European Commission included NbS in the "Horizon 2020" research plan (Church, 2015); In 2018, UNESCO, together with other relevant international institutions, released the United Nations World Water Development Report on the theme of "nature based solutions for water" at the 8th World Water Forum; IUCN released the global standard of NbS, trying to unify a series of different methods from different fields into one operational framework, expand its implementation scope, and improve its influence in relieving the pressure of challenges that the world needs to solve urgently (IUCN, 2019).

3.3 Main research content

Based on the analysis of the occurrence time and frequency of keywords, the main research contents of NbS were divided into four aspects (Table 3).

1) Implementation objects of NbS

The research on the implementation objects of NbS is mainly in three aspects. First, in terms of infrastructure, it emphasizes the connectivity of green infrastructure and corridors from the perspective of landscape elements, such as the green belt around London in the United Kingdom (Davies et al., 2015) and the gray infrastructure greening in Philadelphia in the United States (Wang and Lin, 2015); The second is to implement nature based ecological restoration solutions for different ecosystems. For example, China has launched a pilot ecological restoration project of "mountains, rivers, forests, farmlands, lakes, grasslands and sandy lands" to repair areas with severely damaged ecosystems, and promote ecological protection and restoration. In addition, river ecosystems (Boelee et al., 2017), forest ecosystems (Ordóñez, 2019), urban

TABLE 2 Categories and examples of NbS approaches.

Categories of NbS approaches	Examples
Ecosystem restoration methods	Ecological restoration; Ecological engineering; Forest landscape restoration
Ecosystem related approaches to specific problems	Ecosystem-based adaptation; Ecosystem-based mitigation; Climate adaptation services; Ecosystem-based disaster risk reduction
Infrastructure related approaches	Natural infrastructure; Green infrastructure
Ecosystem based management approach	Integrated coastal zone management; Integrated water resources management
Measures for ecosystem protection	Area-based approaches to conservation, including reserve management

TABLE 3 The main research contents of NbS.

Aspects	Related content
Objects	Green infrastructure, ecosystem, Social challenges
Subject	The relation between human and nature, Ecological restoration type
Goals	Ecosystem services, Sustainable development objectives
Approach	Landscape Design, Ecological restoration, Climate change, water resources crisis

and cultural ecosystems (Engstrom et al., 2018; Frantzeskaki et al., 2020) were taken as the research objects to study corresponding methods of ecological protection and restoration; Third, apply NbS to address social challenges, mainly including water security, climate change, public health and welfare, or to address natural disasters, ecological recovery and other challenges and problems faced by urban development. The social challenges facing cities include climate change, biodiversity, water security, food security, economic and social development. Some of these social challenges are universal and some are local. Taking climate change as an example, some scholars believe that various schemes for mitigating climate change depend on the synergy of each ecosystem, such as forests, grasslands, farmland, wetlands, oceans, and cities (Zhang et al., 2020). It requires comprehensive application of ecology, geography, management and other disciplines to achieve complementary effects (Klink et al., 2016; Siegner, 2018).

2) Implementation subject of NbS

In terms of the research on the implementation subject of NbS, the role of human and nature in NbS was mainly discussed. According to the relationship between nature and human, types of ecological protection and restoration approaches were divided (Swart et al., 2001), and views on the balance between ecosystem and human activities were put forward (Yaffee, 1999). Another perspective of the implementation subject research is to explore the role of stakeholders and decision-makers in the implementation of NbS, such as the definition of the responsibilities of the government and enterprises in ecological restoration, and the obligation of enterprises to carry out ecological restoration if the ecosystem is damaged in the process of resource development and utilization (Li and Liu, 2022); When the responsible party for ecological restoration is unclear, the government takes the lead in carrying out restoration projects for the damaged ecological environment. The ecosystems of NbS can be divided into forest, grassland, farmland, wetland, ocean and city. The traditional environmental policy instruments were applied to group the policy instruments of NbS in command-and-control regulations, incentive policies, and voluntary participation (An et al., 2021). NbS plays an important role in coping with climate change as well as conserving biodiversity, and it also has great potential in the co-governance. China has made sort of achievements in the co-governance of cope with climate change and biodiversity conservation. The idea of NbS is embodied in policies such as the ecological protection red line system, which was also considered as the bottom line of national and regional ecological security, delineated a strict management-control boundary for areas such as important ecological functional areas, eco-environmental sensitive areas and fragile areas. The administrative mechanism of nature reserve network dominated by national park, the establishment of priority areas for biodiversity conservation and the implementation of major ecological conservation and restoration projects (Zhang and Yin, 2022).

3) Implementation goals of NbS

The implementation goals of NbS mainly focus on two aspects: ecological protection and restoration and ecosystem services. For example, river ecological restoration considers each element as a life community and determines the ecological restoration goals of river courses. The expected function of ecosystem services is the ultimate goal of many NbS studies abroad, which emphasize how to build a bridge between NbS and ecosystem services, so as to realize the trade-offs and synergies of ecosystem services in different spaces and practical scales (Almenar et al., 2021; Calliari et al., 2019). In addition, the concept of nature's contribution to people (NCP) is similar to ecosystem services. The NCP was divided into three categories: intrinsic value, instrumental value and relational value (Pascual et al., 2017). How to realize the sustainable development of ecosystem through NbS is also a major focus of recent research (Wendling et al., 2018). NbS can cope with the closely related challenges such as ecosystem degradation, biodiversity reduction, human welfare and climate change (Cassin et al., 2021). Access to safe water is the most basic human need for health and wellbeing. Demand for water is rising owing to rapid population growth, urbanization and increasing water needs from agriculture, industry, and energy sectors. While realizing water security, NbS can help achieve multiple other SDGs sub-goals, such as “poverty eradication” (SDGs-1, the role of water on livelihoods), “zero hunger” (SDGs-2, and NbS provides sustainable water for agriculture) and other goals (SDGs-3, Good Health and Wellbeing; SDGs-6, Clean Water and Sanitation; SDGs-11, Sustainable Cities and Communities; SDGs-13, Climate Action) (Bremer et al., 2021). Sustainable city construction advocates the return of urban areas to nature and provides habitats for plants and animals, the urban heat island effect can be improved by planting trees, and the construction of roof gardens, campus green space and large urban parks can reduce the energy required for the environment. (Raffaele and Giovanni, 2019). In addition, NbS provides natural guarantee and mitigation measures for extreme natural disasters, among which the most typical case is the construction of natural catchment to avoid flooding of farmland (Marianne et al., 2021), and the catchment can also solve the problem of water shortage in extremely arid climate (Areeja et al., 2022).

4) Implementation approach of NbS

Aiming at specific ecosystem or social challenges, the NbS program focuses on the degree of damage to the ecosystem, and proposes different ideas for ecological protection and restoration, such as repairing the ecological disaster area, restoring the ecosystem with damaged functions, improving protected natural areas and elevating semi-natural landscapes (Hobbs and Norton, 1996). Some scholars put forward concepts related to ecological protection and restoration of different degrees: ecological restoration, ecological rehabilitation, ecological reconstruction, ecological replacement (Chen, 2019). The Sustainable Sites Initiative (SITES) in the United States creates sustainable and resilient land development projects directly based on site characteristics. The initiative is generally divided into four categories of development and design: conserve, manage, restore, and regenerate (Danielle et al., 2017). NbS schemes for single social challenges are also research hotspots, such as water-related challenges (Boelee et al., 2017), biodiversity conservation and food security crises (Wang et al., 2020b). NbS is regarded as an important part of climate change mitigation and adaptation strategy (IUCN, 2016). The Nature Conservancy (TNC) has put forward a set of Natural Climate Solutions (NCS), the forests, wetlands, agriculture and grasslands are the most important paths which have attracted much attention (Griscom et al., 2017). Many domestic and foreign researchers have conducted detailed research and exploration on climate change (Chausson et al., 2020; Seddon et al., 2021), and further proposed various natural solutions to climate change (Tian et al., 2021).

4 Research conclusions and application prospect

4.1 Conclusion of the study

The study tries to estimate the research progress of NbS by analyzing the research hotspot, research content, and the evolution trend of research direction using literature analysis software. The result shows that the research frequency of NbS is on the rise, and the number of articles has gradually increased in recent years, and the high-frequency co-occurring words with NbS mainly involve climate change, biodiversity, ecological conservation and restoration, resilient city, urban sustainability and sustainable development, reflecting the research hotspot in different fields. In addition, the main content includes the localization of NbS, carbon neutrality, economic transformation, sponge city, and water management. Last, from the perspective of the evolution trend of research content, the research content gradually changes from theoretical research to engineering practice and policy formulation of NbS. This study lacks a comprehensive understanding of the NbS theory, and fails to put forward effective countermeasures for the obstacles faced by the practice of NbS localization. It is necessary to research localized results based on the characteristics of different regions and the problems to be solved in China.

4.2 Application prospect

As NbS is increasingly proving to be a hot topic in the field of natural resource management and ecological conservation, its concepts and technical approaches are increasingly being discussed and practiced. Based on the analysis of the current predicament and research progress of NbS, the authors assume that more attention should be paid to the following area:

1) Promoting the co-governance of cope with climate change and biodiversity conservation. NbS plays an important role in coping with climate change as well as conserving biodiversity, and it also has great potential in the co-governance. The NbS can effectively mitigate and adapt to climate change, improve climate resilience, and bring benefits to human welfare and biodiversity conservation by protecting, repairing and sustainably managing ecosystems, improving ecosystem service functions, and increasing carbon sinks. It has become an important link and bridge to address climate change and biodiversity conservation synergies. It is recommended to mainstream NbS in responding to climate change, from three aspects-theoretical and scientific research, policy formulation, and supervision-to to promote capacity-building and the willingness to participate.
2) Enhance ecosystem carbon sink, reduce carbon emissions. "Carbon peak in 2030 and carbon neutralization in 2060" has been established as one of the important strategic goals of China's economic and social development. To enhance the carbon sink capacity of Chinese terrestrial ecosystems, it is necessary to implement some important ecological protection and ecological restoration projects at large scale. To maximize NbS in China, NbS should be included in nationally determined contributions and quantitative goals should be proposed at the next stage. China will scale up its intended nationally determined contributions by adopting more vigorous polices and measures. China aim to have carbon dioxide emissions peak before 2030 and achieve carbon neutrality before 2060.
3) Strengthen city resilience and advance urban sustainability. Under the context of global warming and rapid urbanization, cities worldwide are increasingly facing problems of environmental pollution and ecosystem degradation, one of the grand challenges in achieving Sustainable Development Goals. Such challenges call for new frameworks and approaches for improved urban ecosystem management. NbS has now been increasingly recognized as an effective means to mitigate ecological risks, strengthen city resilience and advance urban sustainability. The potentials of applying NbS on climate adaptation to enhance urban resilience, like stormwater management *via* restoration of natural water body, utilization of rainwater and optimization of urban landscape. NbS plays an important role not only in flood control, but also in biodiversity conservation. Building urban resilience through "green recovery" will certainly promote global sustainable development.

4) Localization of NbS in ecological conservation and restoration. The transformation and absorption of NbS by the Ministry of Natural Resources has made NbS mainstream in China's ecological protection and restoration work. However, NbS is still immature in the world, and the research mainly focuses on the natural disaster prevention and the urban level, most of which ignores the ecological space as an important component. To incorporate NbS into the national policy system and bring the idea into the vital ecological space supervision and evaluation index system. China should incorporate biodiversity conservation into its climate policy system, focus on incorporating NbS into national development strategies such as urbanization and rural revitalization.

The raw data supporting the conclusions of this manuscript will be made available by the authors, without undue reservation, to any qualified researcher.

Author contributions

XH was in charge of designing the experiments and writing the manuscript. XH, HW, and SL were in charge of revising the manuscript. HW was in charge of project administration.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The evaluation and optimization method of major events-driven polluted coastal zone renewal: a case of the polluted coastal zone in the Dalian Barracuda Bay Stadium Area

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Introduction: Coastal zone pollution leads directly to a series of local ecological, economic, and social damages. The renewal of polluted coastal zones is a comprehensive challenge that includes the degeneration of ecological services, the decrease in urban livability, and the increase in maintenance costs. Since current ecological management pays more attention to relevant technologies and investments, it plays a limited role in effectively and quickly executing the renewal of polluted coastal zones. Nature-based solutions (NbS) aim to improve regional ecological restoration and renewal by balancing multiple interests such as ecology, economy, and society. Therefore, NbS is an effective way to address this comprehensive challenge. Current studies on NbS are actively exploring the theoretical framework and practice process of solving complex social challenges through an ecological approach.

Methods: As an implanted production process, major events could provide robust policy support and continuous economic backing, which makes this an effective solution for challenges such as a lack of support and ineffective guarantees. This paper was centered around the goal of NbS theory, which is achieving comprehensive benefits, and establishing the Social-Economic-Ecological Systems framework (SEESs) that is driven by major events to achieve the renewal of polluted coastal zones.

Results: The main objective of this study was to investigate the renewal-driving potential of major events in facilitating the restoration (renewal) of coastal ecosystems from the perspective of NbS. Specifically, it aimed to explore how major events promote the renewal of polluted coastal zones, thereby fostering local socioeconomic advancements and enabling regional sustainable development. Driven by hosting the 2023 China Asian Cup, the renewal of the polluted coastal zone in the area around Dalian Barracuda Bay Stadium was studied. Three subsystems and 12 indexes were selected as evaluation indexes of polluted coastal zone renewal driven by major events. Furthermore, using the entropy weight method, we constructed an evaluation system of polluted coastal zone renewal benefits driven by major events, then verified the synergistic effect of the major event on the social, economic, and ecological recovery of the polluted coastal zone. Moreover, we evaluated the change in the comprehensive scores of the polluted coastal zone from 2018 to 2021 under the impact of the 2023 Asian Cup. The spatial and temporal patterns of each subsystem and index were also discussed.

Discussion: Finally, we proposed methods for the optimization of the renewal of urban coastal zone pollution driven by major events and provide solutions to cope with the negative impact of epidemics, strikes, and war throughout the process.

KEYWORDS

polluted coastal zone renewal, major event, nature-based solutions, Asian Cup, Dalian Barracuda Bay Stadium

1 Introduction

A large amount of evidence and many scientific studies have proven that coastal zone pollution has long-term and immeasurable negative impacts on social, economic, and ecological benefits, including damaging ecosystems, limiting the development of the marine economy, and reducing social well-being (Feng et al., 2021). Once the damage occurs, recovery requires significant financial and social resources, which are often time-consuming and ineffective. Jones and Schmitz reviewed 236 case studies on polluted coastal zone renewal and found that because of the comprehensive nature of the challenge, two-thirds of the cases were not adequately restored (Jones and Schmitz, 2009). In the past decade, China's coastal areas have had serious conflicts in human activities, tidal land resource utilization, waste disposal, etc., which have resulted in various pollution problems. Moreover, coupled with the cumulative effects of pollution, the social, economic, and ecological impacts will persist (Chen et al., 2017). Nature-based solutions (NbS) are natural resource management methods that resolve problems and challenges in the development of human society by effectively intervening in the ecological system. In the 1990s, the term 'NbS' was first proposed in biodiversity and then cited in agricultural development, land use planning, and industrial design (Wang and Hou, 2021). It is currently widely employed in urbanization, coastal development, tourism economy, water supply, and disaster risk (Chen and Lin, 2019; Jean et al., 2022), with a focus on climate change, urban sustainable development, and addressing ecological and social challenges. NbS focuses on synergistic benefits and could function as a comprehensive approach for compound social-economic-ecological challenges (Yu et al., 2022). However, many theoretical studies and applications that are based on NbS tend to focus on ecological resilience, which could easily get stuck because of a lack of motive force and the difficulty in safeguarding the results. Therefore, traditional approaches are not suitable for solving problems such as the degeneration of ecological services, the decrease in urban livability, and the increase in maintenance costs (McPhearson et al., 2022; Egusquiza et al., 2021).

Represented by major sporting games, major events could provide opportunities for the practice of NbS. Specifically, NbS could support ecological governance and restoration, as well as provide a sustainable safeguard in many aspects, such as policy, finance, and management. As a type of critical strategy, major sporting games could boost urban improvement and have far-reaching impacts on local and national politics, economy, culture, and society (Buwen, 2013). This top-down approach could coordinate the social, economic, and ecological benefits and achieve synergistic progress in multiple aspects (Liu and Gratton, 2010; Lopez et al., 2022). Major sporting games play an active part in boosting local economic development, improving national or local images, stimulating urban renewal, and restoring the ecosystem (Black, 2007; Cornelissen, 2004; Cornelissen and Swart, 2006; Horne and Manzenreiter, 2006). As the driving force, major events could rapidly, effectively, and constantly improve the renewal and utilization of ecological resources. In the 1980s, the general public started to realize the positive effects of hosting major sporting games (Fainstein, 2008; Orueta and Fainstein, 2008), including quickly and effectively developing and recovering brownfields and less-developed regions (Deyi et al., 2015). For example, in 1988, by hosting Seoul Olympics, the local infrastructure was improved and further contributed to the economic growth of South Korea. In 1992, the Barcelona Olympics changed the city development framework and reconstructed the old industrial zone to a modernized area on the waterfront. In 2000, the Sydney Olympic Park industrial area was rehabilitated into a green Olympic village (Davidson, 2013). Such transformations bring eco-friendly activity spaces into the community. In 2012, London Olympic Park rehabilitated polluted land and rivers, which drove local economic development (Daothong and Stubbs, 2014).

However, most existing studies have focused on analyzing the social, economic, or ecological impacts of major sporting events (Makropoulou, 2017). For instance, Ying Gu, Deyi Hou, and Uribe-Castañeda discussed the impact of sports field construction on urban space regeneration (Gu and Zhang, 2015), sustainable development (Deyi et al., 2015), and ecosystem restoration (Uribe-Castañeda et al., 2018). First, evaluation of the synergistic and integrated impacts on social, economic, and ecological aspects is still lacking. Second, as a special land type, the renewal of coastal polluted zones has not been sufficiently discussed in this context. Finally, most of the study methods were either theoretical analysis before a major event or the evaluation of effects afterward. Thus, there is a gap in the spatial and temporal analysis of the renewal process driven by major events. The present study is based on the viewpoint of NbS theory and focuses on the sustainable development of polluted coastal zones driven by major events, as well as the social-economic development brought about by ecological restoration. This study concentrates on how major events, specifically major sporting events, influence the social-economic-ecological renewal-driving potential of polluted coastal zones. The study case was the renewal of the polluted coastal zone in the area around Dalian Barracuda Bay Stadium driven by the Asian Cup. The entropy weight method was applied to evaluate the benefit

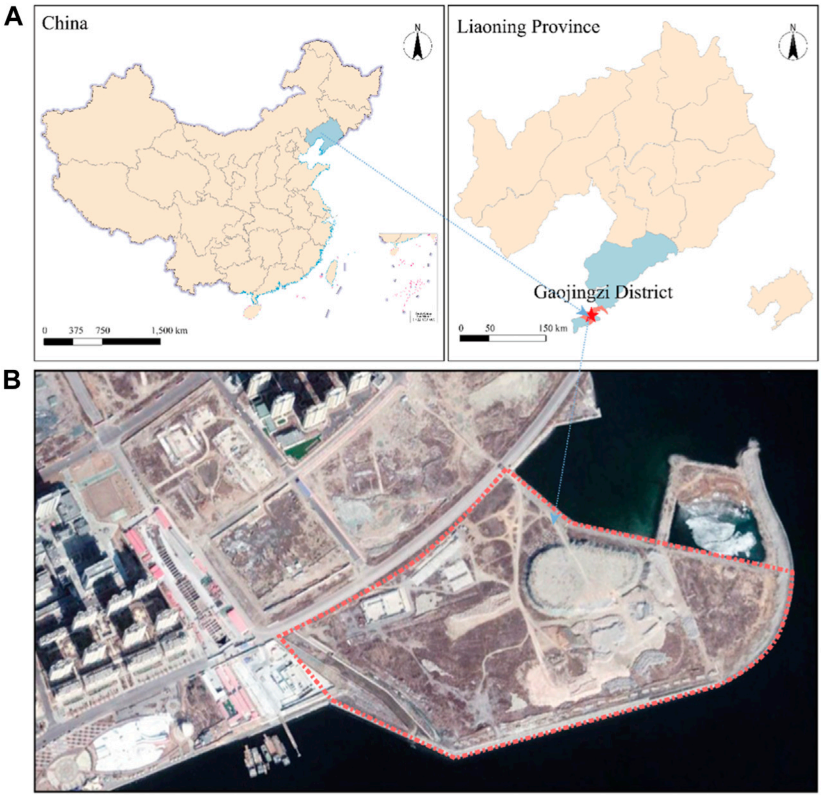

FIGURE 1
Location map of the polluted coastal zone of Dalian Barracuda Bay Stadium and its condition in 2018. Picture **(A)**—Author. Orthophoto **(B)**—GoogleEarth (2018).

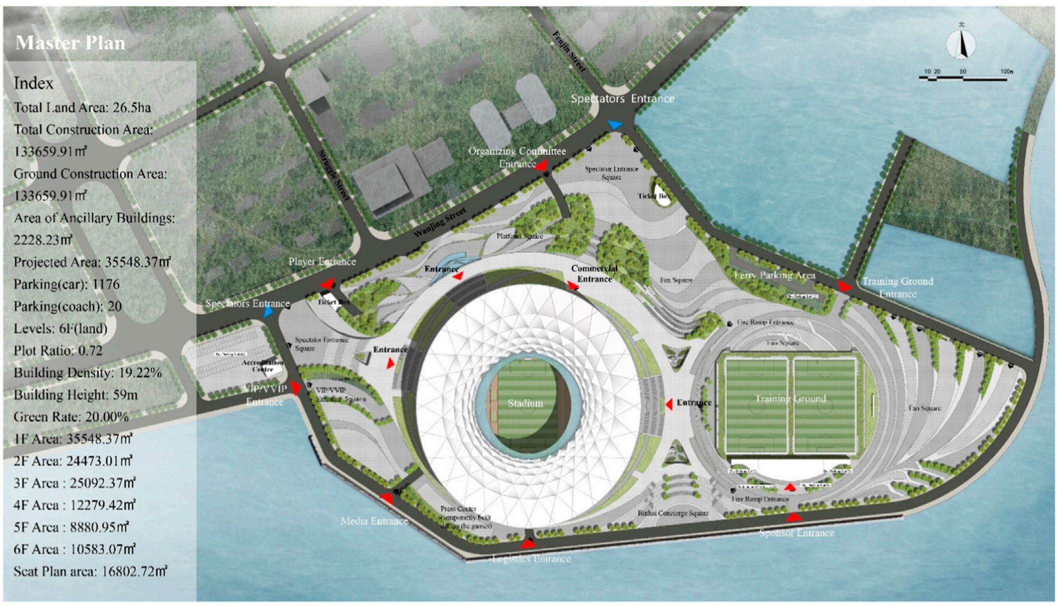

FIGURE 2
Overall layout of the polluted coastal zone of Dalian Barracuda Bay Stadium. Source: Author.

FIGURE 3
Renewal progress of the polluted coastal zone. Source: Author.

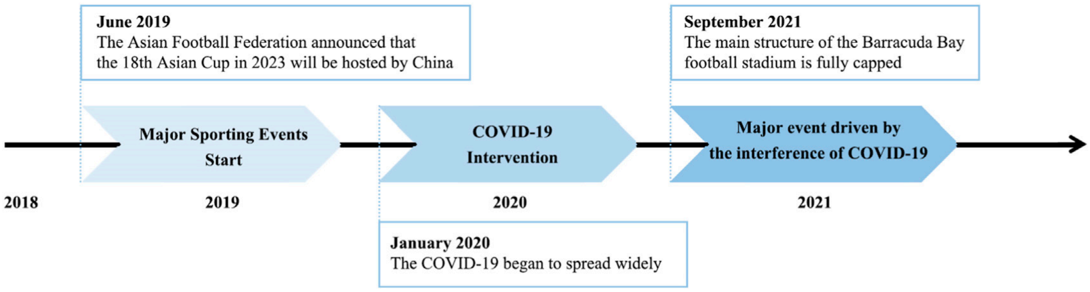

FIGURE 4
Timeline of polluted coastal zone renewal. Source: Author.

of the polluted coastal zone renewal and provide optimization methods for the renewal of the polluted coastal zone in the Dalian Barracuda Bay Stadium area, which is still in process. Such optimization methods directly help engineering practice by applying the research conclusion.

2 Overview of the research area

As shown in Figure 1, the Dalian Barracuda Bay Stadium is located in the polluted coastal zone in Ganzijing District, Dalian City, Liaoning Province, China. This polluted coastal zone is a land reclamation area built in 2000. Since then, chemical, steel, and shipbuilding industries have occupied the coastline area. The traditional industries severely hindered the city's coastal view, leaving much land deserted, undeveloped, and of low economic value. Because the reclaimed land included industrial waste, the soil and groundwater were heavily polluted. In addition, the accessibility and the continuity of the close water shoreline were cut off, and residents' requirements for the close water shoreline were not met. With the opportunity of hosting the 2023 Asian Cup in China, the polluted coastal zone of Barracuda Bay Football Stadium was renewed and renovated. By 2021, the local social, economic, and ecological value was effectively improved, as shown in Figures 2, 3.

The renewal of the polluted Dalian Barracuda Bay Stadium coastal zone had characteristics typical of other renewal cases driven by major sporting events. For example, the approach was top-down, and the renewal had a synergistic boosting effect on the social, economic, and ecological benefits. Studying the mechanism of this case could provide a universal solution for polluted coastal zone renewal cases driven by major events. However, this case was also unique: the progress of renewal has encountered the global pandemic, as shown in Figure 4. Therefore, by studying this case, we could further analyze how major event-driven region renewal reacts under negative outside influences. Moreover, we can further understand its potential to resist risk and provide solutions for potential black swan events during the renewal process, such as pandemics, wars, or strikes.

3 Methodology

3.1 Building the major event-driven SEESs

In 2015, a multidisciplinary team of experts led by the European Commission defined NbS as "nature-based and nature-dependent solutions that address diverse challenges in a resource-efficient and adaptive manner while ensuring economic, social, and ecological benefits" (Wang et al., 2022). This team emphasized that the goal of NbS is to achieve integrated economic, social, and ecological benefits. However, current research on the application of NbS to the resilience of coastal areas still focuses on the exploration of techniques for ecological restoration, such as coastal renewal (Liu et al., 2021) and adaptation to climate change (Donatti et al., 2022), and lacks research on the NbS goal of achieving integrated social, economic, and ecological benefits with rapid, effective, and durable

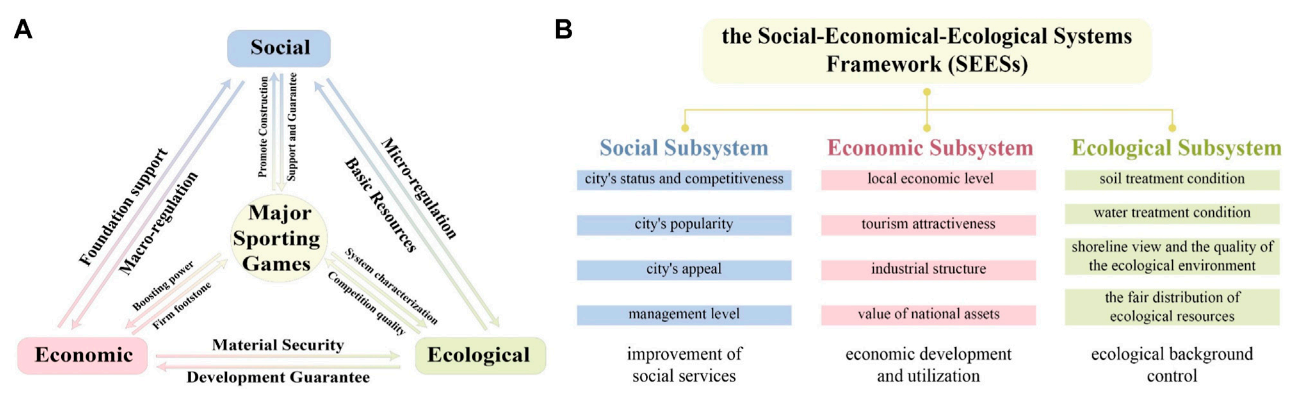

FIGURE 5
Social-Economical-Ecological Systems Framework (SEESs). Source: Author. **(A)** Driving mechanism of the SEESs. **(B)** Influential factors of the SEESs.

NbS implementation methods and safeguard measures. While defining the three criteria of NbS, namely, achieving social, economic, and ecological benefits, Alber proposed that the NbS framework should be continuously improved and iterated by integrating economics and sociology (Albert et al., 2017). Therefore, the present paper was centered around achieving comprehensive benefits through NbS theory and establishing a Social-Economic-Ecological Systems Framework (SEESs) for polluted coastal zone renewal driven by major events. Additionally, this study aimed to enhance the synergistic improvement of social, economic, and ecological benefits, as well as urban renewal, in the process of ecological restoration in coastal polluted zones. It did so by introducing major events with an obvious driving focus on social policies, support for circular economy practices, urban space reconstruction, and improving environmental quality. Moreover, this study explored and addressed the practical challenges in the application of NbS, specifically insufficient support and ineffective performance guarantees. This study refined and updated the theoretical framework and practice process of NbS. Meanwhile, based on the theoretical framework of social-ecological systems (SESs) (Epstein, 2013), we incorporated the economic subsystem since major events always bring substantial economic benefits to form the SEESs. Finally, by evaluating the synergistic benefits of the social, economic, and ecological aspects, we proposed an evaluation index for the polluted coastal zone renewal driven by major events. The entropy weight method was applied to calculate the weights of the social, economic, and ecological subsystems and clarify their interaction relationships. By doing so, we uncovered the driving mechanisms behind social, ecological, and economic renewal in coastal zones within the context of major sports events, and discovered the key factors for coastal renewal.

The SEES framework is divided into three subsystems: social, economic, and ecological. Figure 5A reflects the interactions between these three subsystems and with major sporting games. First, the government regulates and supports major sporting games; thus, social development is beneficial for securing the bid and hosting major sporting events (Zhang et al., 2015). Meanwhile, hosting games could also reversely drive social development (Solberg and Preuss, 2007). Second, one of the necessary conditions for a successful major sporting event is sustained economic growth in the hosting city. Third, major sporting events can boost urban space reconfiguration, enhance ecological restoration, and improve the environmental quality in polluted coastal zones. The local environment would have a direct impact on the quality of the event. In conclusion, at the social level, the government promulgates policies and systems to macro-regulate the market economy and micro-regulate the ecological environment. The joint force pushes local industry transformation and boosts the sustainable development of the economy and environment. At the economic level, economic growth is the foundation of social progress since it could support ecological compensation and restoration. At the ecological level, a good ecological environment provides essential natural resources for a society to progress and protects the sustainable development of the economy.

We show the Social-Economical-Ecological Systems framework (SEESs) in Figure 5B. For the social subsystem, the impact of the major sporting game reflects the city's status, competitiveness, popularity, appeal, and management level. For the economic subsystem, the impact of the major sporting game reflects the local economic level, the attractiveness for tourism, the industrial structure, and the value of national assets. For the ecological subsystem, the impact of the major sporting game reflects the soil and water treatment condition, the shoreline view, the quality of the ecological environment, and the fair distribution of ecological resources.

3.2 Selecting the evaluation index for major event-driven coastal renewal

Based on the SEES framework, we proposed a coastal renewal evaluation system under the impact of major sporting events. This evaluation system included three subsystems and 12 indexes. Among those indexes, soil contamination and groundwater contamination were negative indexes, while the others were positive.

The social subsystem indexes were selected based on the following facts and research results. 1) The City Brand Development Index (CBDI) proposed by the Chinese Academy of Social Sciences and reflects the city's status and competitiveness (Warren et al., 2021). 2) City Attention Index

TABLE 1 Evaluation index and data sources. Source: Author.

	Subsystem	Evaluation index	Index representation	Data resource
SEESs Evaluation System	Social	The City Brand Influence Index	City status and competitiveness	China City Marketing Development Report (Chinese Academy of Social Sciences)
		City Attention Index	Attention on a city and its popularity	
		Region population density (person/km^2)	Attractiveness of a city	Dalian Statistical Yearbook
		Sound public policy (number)	Policy management level	Official website of the People's Government of Dalian Municipality
	Economic	Tourism revenue (10,000 yuan)	Appeal to tourism	Dalian Statistical Yearbook
		Regional GDP (10,000 yuan)	Local economic development level	Ganjingzi Yearbook
		Value-added of the tertiary industry (10,000 yuan)	Industrial structure	
		Fixed assets value (10,000 yuan)	Infrastructure, job opportunities, and land value	
	Ecological	Soil contamination level (mg/kg)	Soil pollution control	Project geotechnical engineering investigation report and the pollution control report
		Groundwater contamination level (mg/kg)	Water pollution control	
		Green Area Ratio (%)	Coastal landscape appearance and ecological quality	Historical satellite maps of Google Earth
		Accessibility of coastal shoreline (person/day)	Equality of Ecological resource	

(CAI) reflects a city's popularity gained by publicity (Barclay and Berkes, 2014; Walke et al., 2013; Ban et al., 2017). 3) Region population density was selected to represent the city's attractiveness since the major sporting event could improve the local infrastructure and life quality and attract more full-time residents (Lopez-Jimenez,2022). 4) Related policies must be gradually polished and improved to ensure a successful event. Hence, the management level was represented by the soundness of football-related policies in Dalian City (Refulio-Coronado et al., 2021).

The economic subsystem indexes were selected based on the following facts and research results. 1) Since major sporting events could drive tourism development and attract many tourists, we used tourism revenue to represent travel attractiveness (Calero and Turner, 2020). 2) The local gross domestic product (GPD) could directly represent a region's overall economic development at a specific time. 3) Because the event will promote the progress of modern service industries and optimize the industrial structure, the value-added of the tertiary industry was selected to reflect the industrial structure (Li, 2019). 4) The influences of major sporting events on infrastructure, job opportunities, and land value were represented by the fixed-asset value.

The ecological subsystem indexes were selected based on the following facts and research results. (1 & 2) Since the polluted coastal zone of Dalian Barracuda Bay Stadium has heavy soil and groundwater metal pollution caused by industrial waste as a reclamation material, the heavy metal levels in the soil and groundwater were selected to reflect the ecological pollution situation. 3) The improvement in the coastal shoreline's landscape appearance and ecological quality can be characterized by its Green Area Ratio. 4) The accessibility of the coastal shoreline could represent the conveniences of ecological benefits to a certain extent (Tongfei and Jianjun, 2013), thus representing the fairness of ecological resource distribution. This index could be calculated from the traffic capacity within 3 km. The data sources for the aforementioned indexes are shown in Table 1.

3.3 Determining the objective weights of the evaluation indexes using the entropy weight method

The renewal of polluted coastal zones driven by major events is a complex process. This paper used the entropy-weight method to allow objective weighting of the indexes. The concept of entropy was originally proposed in thermodynamics; later, Hwang and Yoon introduced entropy into social science and established the entropy weight method based on research from L. Boltzmann and C. Shannon (Hwang and Yoon, 1981). Information entropy measures the degree of chaos in a system. It can determine the amount of useful information in the given data (Meng, 1989). Therefore, the entropy weight method is an objective method for determining weights. In the entropy weight method, the lower the index entropy, the more information the index has; thus, it should have a higher weight (Jin et al., 2022). The calculation functions for the weight of indexes are as follows.

3.3.1 Index standardization

Since both positive and negative indexes were exited and each index had different dimensions and units, standardization was performed to non-dimensionalize the data before weighting.

When the index was positive, the standardization function was

$$x'_{ij} = \frac{x_{ij} - x_j^{\,min}}{x_j^{max-j\,min}}.$$

When the index was negative, the standardization function was

$$x'_{ij} = \frac{x_j^{max-ij}}{x_j^{max-j\,min}},$$

where $x_j^{\max}$ represents the maximum value of the index j, x_{ij} represents the data of index j from sample i, and x'_{ij} represents the standardized data of index j from sample i.

After standardization, some indexes appeared to be zero. For convenience in calculation, we shifted the standardized data to eliminate this situation.

$$x''_{ij} = H + x'_{ij},$$

where H is the shift value, generally set to 0.001, and x''_{ij} represents the shifted data of index j from sample i.

3.3.2 Index entropy and difference coefficients

The calculation of the entropy of the index j is as follows:

$$e_j = -\frac{1}{\ln n}\sum_{i=1}^{n} y_{ij} \ln y_{ij}.$$

The calculation of the difference coefficient of the index j is as follows:

$$g_j = 1 - e_j,$$
$$j = 1, 2, \cdots\cdots p.$$

3.3.3 Index weights and weighted scores

The calculation of the weight of the index j is as follows:

$$\omega_j = \frac{g_j}{\sum_{j=1}^{p} g_j},$$
$$j = 1, 2, \cdots\cdots p,$$

where ω_j is the weight. Thus, an index with a larger ω_j contains more information and plays an important role in the evaluation system.

The index evaluation score was obtained by multiplying the standardized index data by the weights. Summing the scores of indexes in a subsystem provided the corresponding score; similarly, summing the scores of all subsystems provided the overall score.

$$Z_i = \sum_{j=1}^{p} \omega_j x'_{ij},$$

4 Results and discussion

4.1 Analysis of the weights of the evaluation indexes

We analyzed the weight of each SEESs indicator. First, a weight analysis was conducted on the three subsystems of the SEESs, and Weihai, Qinhuangdao, Yantai, and Dalian were selected as research objects. As shown in Figure 6A, except for Dalian city, the cities of Weihai, Qinhuangdao, and Yantai, which, together with Dalian city, also belong to the Bohai Economic Rim, were selected to analyze the balance of weight distribution. After calculating the weight of indexes for all four cities, the results indicated that the social and economic subsystems of Weihai, Qinhuangdao, and Yantai, which did not have major sporting events during the study period, showed much higher weights than the ecological subsystem, and that the weight distribution was not balanced. In contrast, the weights of Dalian city's social, ecological, and economic subsystems were effectively balanced under the context of hosting major sporting events. The shape of the weights was similar to a positive triangle, and the differences between the three subsystems were insignificant. These results indicated that the major event could drive the three subsystems to reinforce each other, and that economic and social improvements could become the engines for ecological system renewal.

Furthermore, we conducted weight analysis for the three subsystems of the SEESs in Dalian. As shown in Figure 6B, the weights of Dalian's social, economic, and ecological benefits were 0.2998, 0.3757, and 0.3244, respectively. Economic benefit had the largest weight, which indicated that economic benefit was the main contributor to the renewal outcome, and that the major sporting event significantly impacted the improvement of the regional economy. Ecological benefits accounted for the second largest weight, only slightly lower than that for economic benefits (0.0513 less), indicating that ecological benefits have also changed considerably due to the major event. In particular, the pollution issue in the polluted coastal zone was dramatically improved. The social benefits accounted for the smallest weight. This ranking may be because the Asian Cup was initially scheduled for 2023 and is still an ongoing event. Therefore, it has not yet reached the peak of social benefits.

Finally, we ranked the 12 indicators of the SEESs according to their weight. According to Figure 6C, we ranked 12 indexes by their weight. Among all indexes, the value of the fixed assets has the most prominent weight at 14.09%. This indicated that major sporting events have a significant role in creating jobs, expanding production scales, and promoting land value in the coastal region. Groundwater and soil contamination levels ranked second and fourth. Groundwater and soil pollution control are beneficial for maintaining

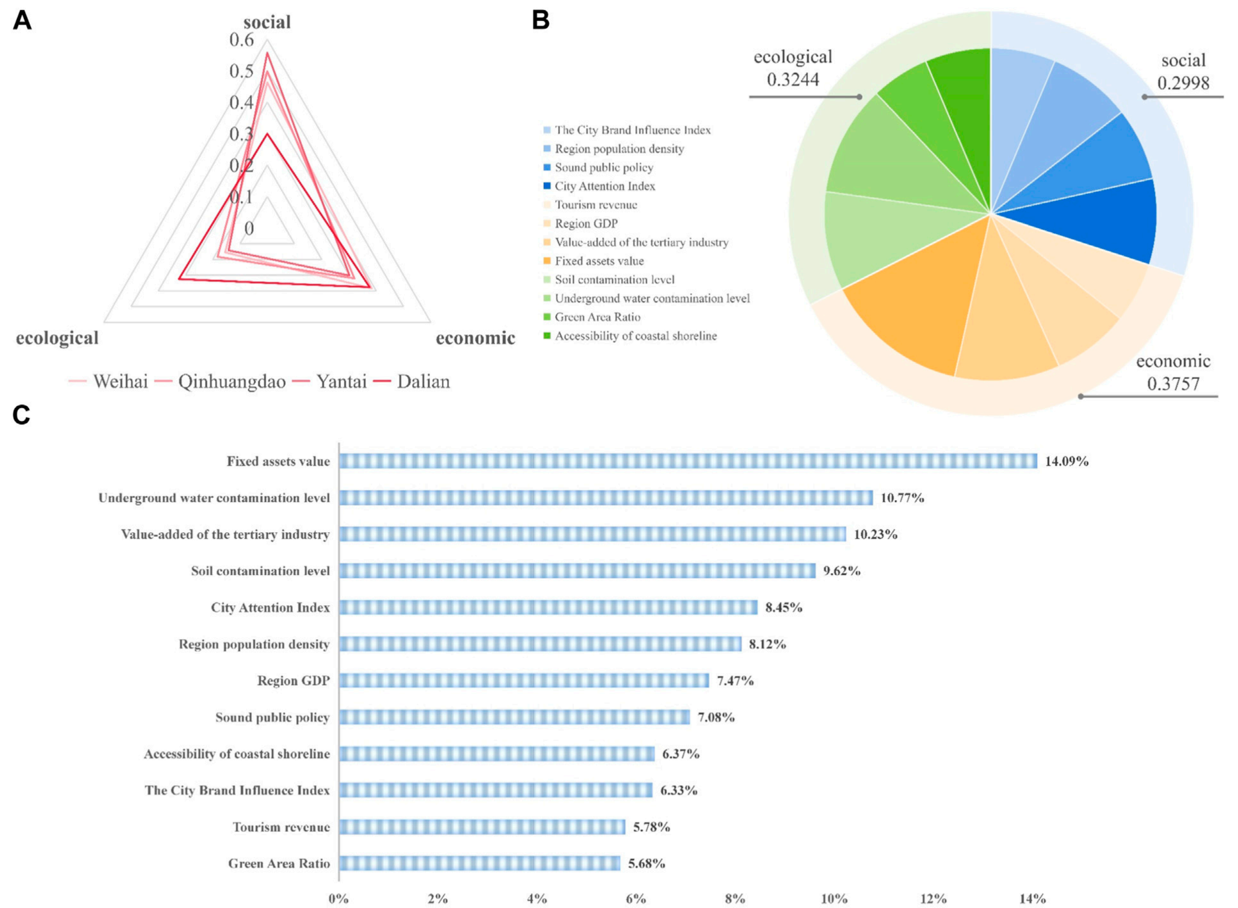

FIGURE 6
Weight analysis of SEES indicators. Source: Author. **(A)** Analysis of weight in each subsystem for different regions. **(B)** Analysis of the weight of the Dalian city SEESs. **(C)** Ranking of indexes by weight.

watershed ecology and a normal hydrological cycle, and pollution remediation is a critical result of polluted coastal zone renewal. The value-added of the tertiary industry (10.23%) ranked third, indicating that the city could utilize the change of hosting a major event to transform the industrial structure and create a modernized service industry. The CAI and regional population density showed average weights, indicating that major events could affect the city's media publication, popularity, and livability. In contrast, the Green Area Ratio (5.68%) and the tourism revenue (5.78%) had the smallest weights among all indexes. The reason behind these insignificant weights could be that the change in landscape view requires time and that tourism was heavily affected by the global pandemic.

4.2 Analysis of annual comprehensive scores

Based on the aforementioned weight analysis, we evaluated the annual comprehensive scores of the three subsystems. First, we summarized the trend of the comprehensive scores and calculated the weight of the three subsystems. Based on the annual scores of the three subsystems of the SEESs, we summarized the annual score trend for each subsystem. According to Table 2 and Figure 7A, the comprehensive score first showed an increasing and then a decreasing trend over the 4 years. The score was at its lowest in 2018; with the stimulation of the Asian Cup between 2019 and 2020, the comprehensive scores rose significantly. The scores peaked in 2020, then decreased slightly in 2021; however, the score overall increased in the 4 years. This finding indicated that the introduction of the major event played a considerable role in improving the comprehensive score; however, after the heat decreased and the pandemic, the comprehensive score decreased slightly. Overall, the score was still greatly improved compared with 2018. Therefore, major events could benefit from resisting negative impacts encountered during renewal.

Based on the annual score of the three subsystems of the SEESs, we summarized the annual score trends for each subsystem. As shown in Figure 7B, the economic benefit score was the main contributor to the comprehensive score in 2018–2019, while the ecological and social benefits became dominant in 2020–2021. The economy showed a considerable boost after 2018 and the economic benefit scores peaked in 2019. The social and ecological benefits scores start to grow significantly after 2019, indicating that major events rapidly contributed to economic benefits and increased ecological and social benefits. The growth of the economy could

TABLE 2 Annual comprehensive scores. Source: Author.

Year	Social benefit score	Economic benefit score	Ecological benefit score	Comprehensive score	Rank
2018	7.77	11.28	0.32	19.37	**4**
2019	9.23	22.8	9.38	41.41	**3**
2020	27.23	15.97	29.75	72.94	**1**
2021	20.25	14.47	32.76	67.48	**2**

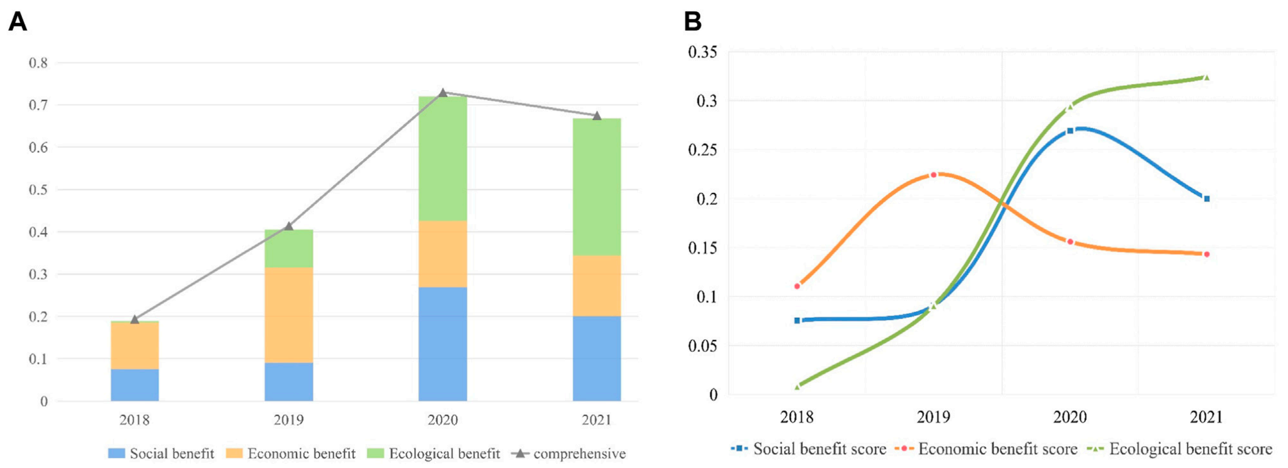

FIGURE 7
SEES scoring analysis. Source: Author. **(A)** Comprehensive SEES evaluation scores by year. **(B)** Social, economic, and ecological score by years.

also motivate increased ecological and social benefits. After 2019, a downward trend in economic benefits was quite apparent; after 2020, the social benefits decreased. However, the ecological benefit always showed a stable growth trend, increasing from 0.32 points in 2018 to 32.76 points in 2021. These results showed that the ecological enhancement from the major event was continuous and highly efficient even under the influence of the pandemic.

4.3 Changes in index scores

4.3.1 Social benefit indexes

To further understand the ecological benefit scores, we analyzed changes in social benefit scores in Weihai, Qinhuangdao, Yantai, and Dalian with or without the involvement of major events. According to Table 3 and Figure 8A, compared with other cities in the Bohai Economic Rim, such as Yantai, Weihai, and Qinhuangdao, the social benefit of Dalian city was not outstanding in 2018. However, with the Asian Cup as the motivator, this social benefit has gradually increased since 2019, showing a surge in 2020 (at 27.230 points), and exceeded other cities. This indicated that a major event strongly motivates improved social benefits during polluted coastal zone renewal. Meanwhile, the relevant policies have been improved; the resident population continues to grow; and the CBDI, the CAI, and the attractiveness and livability of the city have also been improved.

We rated the annual social benefit based on the four indicators of the social subsystem. According to Table 3, the CBDI was 0.423 in 2019, slightly decreased compared to 2018, rose to 0.492 in 2020, and decreased again in 2021. In addition, the region's population density has steadily grown, with a significant increase in 2020 at a rate of 3.8%. Moreover, the change in CAI was most noticeable after 2019, rapidly pulling up after hitting 0.398 in 2019 and peaking at 0.617 in 2020. Regarding football-related policies, the number first increased in 2019 and started to decline in 2021. In 2018–2019, the soundness of football-related policy increased before the CBDI and the CAI in the run-up to the major events. These findings proved that the major event driven-renewal had a policy-driven, top-down nature.

We analyzed the annual social benefit scores and trends of the four indicators of the social subsystem. From Figure 8B, the CBDI and the CAI scores were low in 2019, and the 7 points from the policy soundness became the primary contributor to the improvement of the city's social benefit. In 2020, the CAI and the CBDI peaked, the score for regional population density increased rapidly, and the rise of policy soundness leveled off. In 2021, except for the population density score, the scores for the three indexes decreased. However, they still showed significant improvements compared to 2018. In summary, the motivation from major events on the CBDI and the CAI improved significantly since the announcement that Dalian would be one of the host cities for the Asian Cup in 2019, but it decreased slightly after 2020. In the four-year research period, the overall trend showed intermittent growth.

TABLE 3 Social benefit score. Source: Author.

Year	City brand influence index	Region population density (person/km²)	City attention index	Number of sound policies	Social benefit score
2018	0.457	1964	0.444	24	7.77
2019	0.423	2009	0.398	31	9.24
2020	0.492	2087	0.617	31	27.23
2021	0.464	2161	0.607	20	20.25

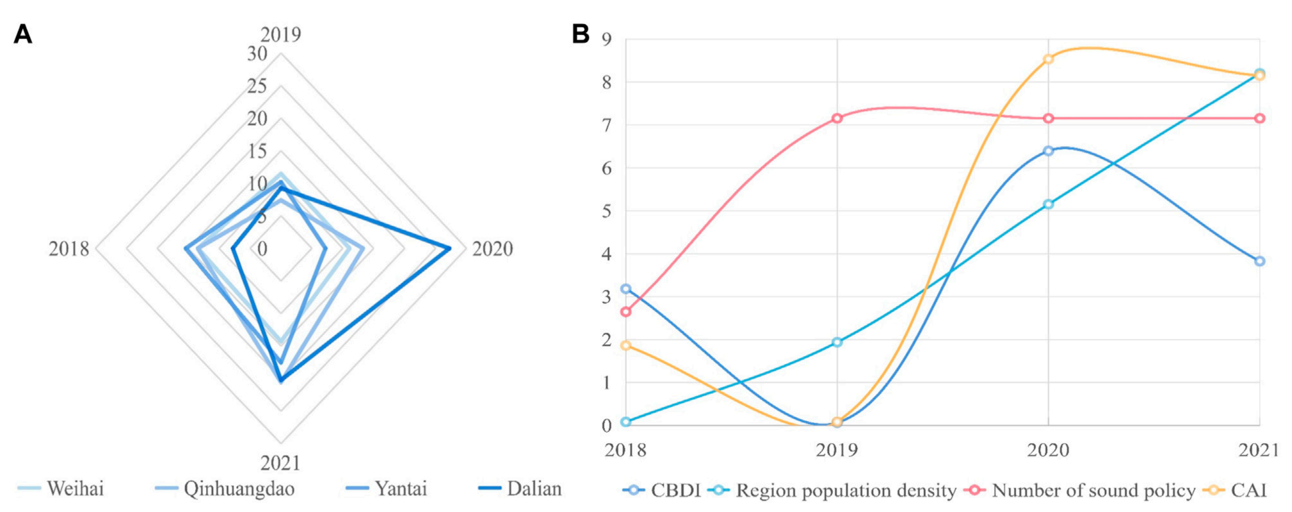

FIGURE 8
Social benefit index scores. Source: Author. **(A)** Changes in social benefit score with or without major events. **(B)** Time changes of social benefit index scores.

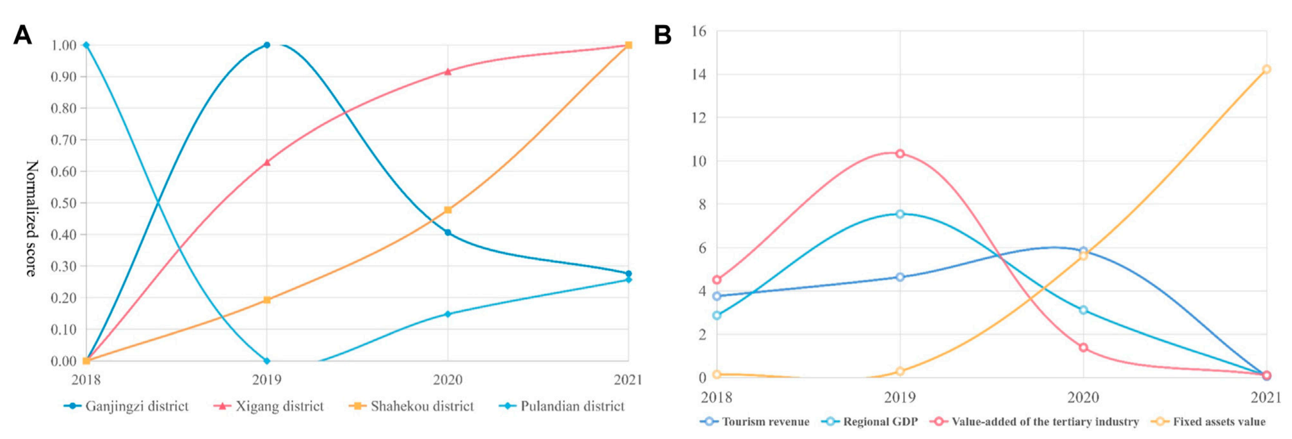

FIGURE 9
Economic benefit index scores. Source: Author. **(A)** Change in economic benefit scores with or without major events. **(B)** Time changes of economic benefit index scores.

4.3.2 Economic benefit indexes

To further understand the ecological benefit scores, we analyzed their changes in Weihai, Qinhuangdao, Yantai, and Dalian with or without the involvement of major events. As shown in Figure 9A, to highlight the spatial and temporal trends of economic benefits during 2018–2021, we normalized the economic benefit scores by mapping the data of Ganjingzi district, where the studied project is located, and other districts in Dalian city (Xigang district, Shahekou

TABLE 4 Economic benefit score. Source: Author.

Year	Tourism revenue (10,000 yuan)	Regional GDP (10,000 yuan)	Value-added of the tertiary industry (10,000 yuan)	Fixed assets value (10,000 yuan)	Economic benefit score
2018	1280	9062487	4428431	2328341	11.28
2019	1440	9812749	4712304	2332189	22.803
2020	1657	9102260	4276274	2473179	15.97
2021	610	8613596	4213293	2700999	14.47

district, and Pulandian district), where no major events have occurred, to the range of 0–1. Comparative analysis showed that the economic growths of Xigang District and Shahekou District were relatively stable. Moreover, the economy in Pulandian District showed a continued decline. In contrast, the economy in Ganjingzi District had a crest in 2019, which proved that as an urban catalyst, major events significantly stimulated the regional economy even in the early stage.

We rated the annual social benefit based on the four indicators of the economic subsystem. According to Table 4, the trend of the value-added of the tertiary industry was similar to that for the regional GDP. Tourism attractiveness improved slightly after 2019 and declined sharply after 2020 due to the global pandemic, with a decline of 63%. However, the value of the fixed assets showed a consistent upward trend under the impact of COVID-19, with a growth rate of up to 6%. The comprehensive score of the economic subsystem first increased and then decreased but was still higher than the score before the major event stimulation in 2018. In summary, major event stimulation could resist the economic downturn caused by the epidemic, and the primary contributor was the value of fixed assets.

We analyzed the annual social benefit scores and trends of the four indicators of the economic subsystem. From Figure 9B, in 2019, the highest economic index was the value-added of the tertiary industry. According to the data source, the ratio of the primary, secondary, and tertiary industries in Dalian city was adjusted from 1:52:47 to 1:50:49. The scores for the fixed assets then climbed significantly in 2020 and 2021 and became the primary contributor to the economic score. The results showed the undeniable advantage of a major event for upgraded industrial structure in the early stages. This impact could be an opportunity to break the dilemma of relying on a single mainstay industry. During the process of a major event, along with the continuous optimization of the industrial structure, the event's roles of expanding productivity, creating job opportunities, and increasing land value becomes more prominent.

4.3.3 Ecological benefit indexes

To further understand the ecological benefit scores, we analyzed changes in ecological benefit scores in Weihai, Qinhuangdao, Yantai, and Dalian with or without the involvement of major events. As shown in Figure 10A, three plots in the Ganzijing District, Dalian City's polluted coastal zone, were selected for comparison. Plot A is the site of Dalian Barracuda Bay Stadium, while Plots B and C are reclamation land next to Plot A. As the project site, Plot A started to manage its ecological environment in 2019. Since then, the ecological environment has significantly improved from 2019 to 2021. Because of the success of Plot A's ecological management, the ecological benefit scores of Plots B and C's also increased, with similar trends as Plot A in 2020 and 2021. This indicated that pollution treatment became effective and rapid when the city had the opportunity to host a major event. In addition, the ecological improvement in one plot will improve the ecological benefits of the surrounding areas, leading to an expansion in the renewal scale.

We rated the annual social benefit based on the four indicators of the ecological subsystem. From Table 5, in the four-year research period, the soil and groundwater contamination conditions gradually reduced from exceeding the standard by 1.4-fold and 21-fold to numbers within the pollution limits. Then, the Green Area Ratio increased yearly as the shoreline landscape improved. Moreover, the two newly constructed subway lines (#4 and #5) and the two new transit bus lines (#811 and #812) enhanced the transportation network around the project and improved the accessibility and fairness of access to the coastal shoreline. With the continued development of the polluted coastal zone of the Dalian Barracuda Bay Stadium, the score would be further improved.

We analyzed the annual social benefit scores and trends of the four indicators of the ecological subsystem. According to Figure 10B, the index with the highest score in 2019 is the Green Area Ratio. However, the increasing rate of the Green Area Ratio slowed at a later stage. Moreover, in 2020, the effect of environmental restoration started to emerge, and soil and groundwater contamination treatment became the main contributor to the ecological benefit score. The results showed that as an implanted production process, a major event could promote the reconfiguration of urban spaces and the restoration of the ecological system at an early stage. However, the outcome of ecological system restoration always lags and takes time to cultivate. The benefit would maintain a steady development over time and become more noticeable.

4.4 Optimization method for the renewal of polluted coastal zones driven by major events

Major sporting events play a significant role in enhancing the comprehensive benefits of the polluted coastal zone and have synergistic boosting effects on the renewal of social, economic, and ecological benefits. Major events can also resist negative impacts, such as pandemics and strikes, during the renewal process. By discussing the weights of the evaluation indexes, the annual comprehensive scores, and trends in index scores, this paper provides a method for the renewal of polluted coastal zones driven by major events and solutions for potential black swan events during the renewal process, including pandemics, wars, or strikes.

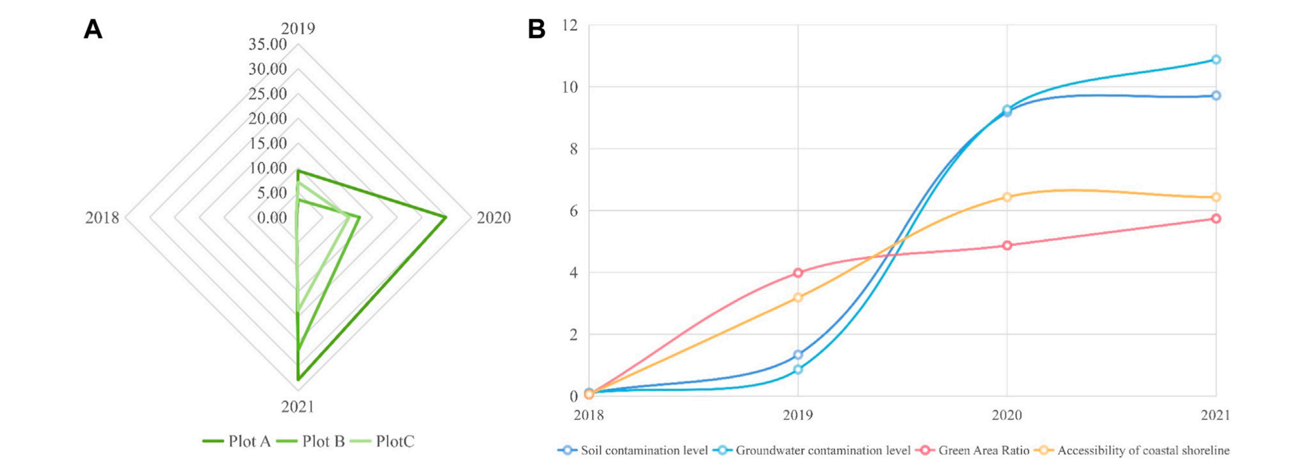

FIGURE 10
Ecological benefit index scores. Source: Author. **(A)** Changes in ecological benefit scores with or without major events. **(B)** Time changes of ecological benefit index scores.

TABLE 5 Ecological benefit score. Source: Author.

Year	Soil contamination level (mg/kg)	Groundwater contamination level (mg/kg)	Green area ratio (%)	Accessibility of the coastal shoreline (person/day)	Ecological benefit score
2018	27.96	1.05	32.23	434920	0.32
2019	26.80	0.98	37.22	481360	9.38
2020	19.50	0.20	38.35	529560	29.75
2021	19.00	0.05	39.45	529560	32.76

4.4.1 Social benefit characteristics and optimization

(1) Directional: Renewal processes driven by major events are conducted top-down and directed by policy. Therefore, the government should focus on the motivation of policy soundness and improving football-related policy during the preparation and early stages of an event. In summary, the optimization should start with building a policy system led by the government, conducted by the association, and supported by the local department, and which incentivizes the involvement of the whole society. Such a system ensures the development and operation of infrastructure and sets a foundation for improving the social benefit in the polluted coastal zone.

(2) Intermittence: The major event could intermittently pull up the CBDI and CAI. Thus, in the middle stage of the event, it is vital to dig into the city's sports culture, build sports fields, advertise fitness activities, and promote football sports to the general public. With the opportunity of a major event, a city should gradually improve its infrastructure and cumulate experience in event hosting. Moreover, the city should actively bid to host other major sporting events or non-professional leagues to create continued attractiveness for sports events and rebrand the city as Football city. The CBDI and CAI could always stay stimulated by adopting the above suggestions.

4.4.2 Economic benefit characteristics and optimization

(1) Sensitivity: As a form of urban catalyst, major events could increase the value of the tertiary industry, optimize the industrial structure, and drive economic growth. To better respond to the Asian Cup, the city should create a sports services area in the polluted coastal zone of Dalian Barracuda Bay Stadium. By developing the sports event, fitness, and traveling industries, the project could stimulate improvements in the modern services industries in nearby areas.

(2) Risk resistance: Driven by a major event, the city could upgrade its industrial structure, expand productivity, increase job opportunities, increase fixed asset value, and resist the economic decline caused by the pandemic. The economic decline caused by the black swan event could be addressed by optimizing fixed asset investment and upgrading infrastructure. Hosting an event is an excellent opportunity to increase the economic value of the surrounding area and create job opportunities, which could supercharge the region's economic resurgence.

4.4.3 Ecological benefit characteristic and optimization method

(1) Lagging: Ecological restoration takes time. Owing to the dynamic and continuous nature of coastal ecosystem restoration, it is necessary to utilize ecological succession and self-recovery capabilities, with human-assisted interventions, to restore disturbed and damaged coastal ecosystems to, or near, their pre-disturbance state. This process requires time; thus, the results and benefits of ecological restoration always show hysteresis (Koo et al., 2011). Therefore, in the process of polluted coastal zone renewal, the city should start to upgrade its transportation system and other infrastructure. This move could improve the coastal landscape and increase the accessibility of the ecological benefits.
(2) Stability: Major events could continue to efficiently improve the ecological benefits, even with the negative influence of the global pandemic. Moreover, a major event could also improve the ecological benefits of the surrounding areas. Therefore, having a major event is a chance for the city to conduct soil and water pollution management, build coastal sports parks, and maximize the stability characteristic of the ecological benefits.

5 Conclusion

5.1 Research conclusion

The ecological restoration and sustainable management of polluted coastal zones have received the attention of many professionals. However, one critical question is how to effectively promote social, economic, and ecological system renewal, further improve the overall benefits, and enhance the resilience of polluted coastal zones.

To explore the renewal driving potential of major events on the polluted coastal zone's social, economic, and ecological aspects, this paper proposed a NbS视角下Social-Economical-Ecological Systems Framework (SEESs) and selected three subsystems and 12 indexes for evaluation. Moreover, using the entropy weight method, we constructed a system for the evaluation of the benefits of polluted coastal zone renewal driven by major events. Then, by analyzing the social, economic, and ecological weight, we summarized the advantage of polluted coastal zone renewal driven by major events.

The results proved that, driven by major sports events, the polluted coastal zone's social, economic, and ecological benefits had balanced progress, with weights of 0.2998, 0.3757, and 0.3244, respectively. Furthermore, all 12 indexes had different spatial and temporal patterns. The social benefits were more directional and intermittent, while the economic benefits were sensitive and had good risk resistance, and the Ecological benefits were stable but lagging. Based on the change characteristics of the three subsystems, we proposed optimization methods for polluted coastal zone renewal driven by major events and provided solutions to cope with the negative impact of black swan events such as epidemics, strikes, and war.

Additionally, we evaluated the changes in the scores for the polluted coastal zone of Dalian Barracuda Bay Stadium area under the impact of the Asian Cup. During the renewal process, the scores of the polluted coastal zone increased in fluctuation, with scores of 19.37, 41.41, 72.94, and 67.48. Major events will first motivate economic growth, then bring social and ecological benefits. However, the growth of economic and social benefits is subject to the impact of adverse events, such as the global pandemic, and starts to level out and decline. On the other hand, the improvement of ecological benefits is more stable.

Finally, we identified the renewal characteristics and optimization methods for the renewal of urban polluted coastal zones driven by major events and provided solutions to cope with the negative impact of epidemics, strikes, and war throughout the process.

5.2 Research contributions

This study aimed to enhance the synergistic improvements of social, economic, and ecological benefits, as well as urban renewal, in the process of ecological restoration in coastal polluted zones. It did so by introducing major events with an obvious driving focus on social policies, supporting circular economy practices, reconstructing urban spaces, and improving environmental quality. This study explored and addressed the practical challenges in the application of NbS, specifically insufficient support and ineffective performance guarantees. The results refine and update the theoretical framework and practice process of NbS, thereby providing valuable insights for future policymaking and planning in coastal area renewal.

Moreover, this paper utilized and applied NbS for its goal of achieving comprehensive benefits and establishing SEESs. Unlike the well-known social-ecological systems (SESs), this paper incorporated the economic subsystem since major events always bring substantial economic benefits. By doing so, we uncovered the mechanisms driving social, ecological, and economic renewal in coastal zones within the context of major sports events, and further provided new perspectives for effective and sustainable urban renewal and ecological restoration in coastal pollution zones.

Furthermore, we developed an evaluation method to assess the renewal of polluted coastal zones driven by major events. This evaluation method confirmed the positive role that major events play in boosting the renewal and coordinated development of the "Social-Economic-Ecological Systems" in coastal zones. It also provides a method for quantitatively studying the sustainable development and overall benefits of the ecological system. By leveraging the strong policy and continuous economic support provided by major events, we could guide the ecological restoration and sustainable implementation of urban renewal, thus serving as a valuable reference for the theoretical framework and practice process of NbS.

5.3 Research limitations

This study has several limitations since the social, economic, and ecological systems are constantly changing and are diverse, fuzzy, and dynamic. Even though this work is based on historical data and limited indexes, we could introduce the newest data in future work and dynamically improve the accuracy of the evaluation system and the score-trend analysis.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

MG wrote the whole paper, collected and analyzed the data, and discussed the experimental results. QG revised the paper, and collected and analyzed the data. KY collected the data and validated the proposed method. BJ revised the paper and provided comments on the proposed method. YY proposed the research idea and provided comments on the discussion. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The effects of the natural visual-aural attributes of urban green spaces on human behavior and emotional response

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Introduction: Nature-based solutions (NBS) have been used to address a wide range of urban environmental challenges, an important aspect of which is to improve human health and well-being. However, most relevant studies focus either on what positive influences nature may have or on identifying what natural factors can have these benefits. Few have investigated the sensory composition of nature and the effects of nature in different sensory aspects on human health. Setting out from the multi-sensory perspective, this study aims to explore human behavior and emotional response from visual and aural contact with urban nature.

Methods: Taking Jiangjia Art Garden in Chengdu as an example, natural attributes such as its visual (landscape) and aural (sound source) characteristics as well as people's activities (behavioral responses) were measured by on-site mapping analysis. This was done while a questionnaire-based survey was conducted to investigate people's emotional responses regarding their overall satisfaction, pleasantness, calm, and agreeableness.

Results: The results indicated that nature-dominated visual landscapes such as grassland, waterscapes, and woodlands, as well as natural sounds such as bird sounds, chirp sounds, and wind sounds were found to be positively correlated to the vitality of activities and people's emotional status. Regarding behavioral responses, it was shown that grasslands and woodlands are more likely to be attractive places for recreation, and the vitality measured became extremely high when these two were paired with lakes. As for the emotional responses, people's perceived overall satisfaction, calm, and agreeableness were equally reflected in their behavioral patterns, suggesting a strong relationship with natural factors.

Discussion: The research findings were visually presented in behavior and emotional maps to provide direct cues of informing the future design of high-quality urban green spaces and promoting the application of aural-visual experience in the design of urban nature areas.

KEYWORDS
nature-based solutions, visual and aural attributes, urban green spaces, behavior and emotional responses, perceptions

1. Introduction

"Nature-based solutions (NBS) are actions inspired by, supported by, or copied from nature" (Cecchi et al., 2015; Cohen-Shacham et al., 2019). The term has been used to address a wide range of urban environmental challenges, an important aspect of which is improving health and well-being. Nature has long been confirmed to have psychological benefits such as restoring depleted attentional resources (Yang D. et al., 2022; Yang Y. et al., 2022), mitigating mental stress (Johnsen, 2013), and arousing a positive affect (Barton and Pretty, 2010).

Sensory perceptions, behavioral patterns, and emotional responses of humans constitute their experiences in urban landscapes (Shao et al., 2022). However, to date, there is little evidence that describes the relationship of the three from the perspective of NBS. This study intends to explore the benefits of nature through the visual-aural aspects of urban green spaces, a typical nature-dominated urban space, on behavior and emotional response, so as to inform the design of urban green spaces in a way that benefits urban residents.

1.1. The benefits of nature on human health and well-being

Awareness regarding the various aspects of NBS has continuously developed throughout history, from healing gardens (see Ulrich and Parsons, 1992; Marcus and Barnes, 1999) to a broader concept of restorative environments (see Kaplan and Talbot, 1983; Ulrich, 1983; Kaplan and Kaplan, 1989), all the way to the more generalized "Healthy Cities Movements" (World Health Organisation, 1948). Nevertheless, it was not formalized until 1984, when the first report about the measurable effects of nature's influence on health was published (Ulrich, 1984). Ulrich then further conceptualized his findings (Ulrich, 1979, 1981, 1983) into a psycho-evolutionary framework he called a stress reduction framework (SRF), stating that psychology undergoes positive changes based on emotional state, including reduced levels of negatively toned feelings such as fear or anger, and increases in positively toned feelings (Zuckerman, 1977; Ulrich, 1979; Ulrich et al., 1991). Another significant study of relevance that contributed greatly to restorative environment theory was the Outdoor Challenge Project, which was conducted (Kaplan and Talbot, 1983) with the purpose of finding convincing evidence that increased exposure to the wilderness offers considerable and lasting benefits for a variety of individuals. This program laid a foundation for Kaplan and Kaplan's (Kaplan and Talbot, 1983; Kaplan and Kaplan, 1989; Kaplan, 1995; Altman and Wohlwill, 2012) attention restoration theory (ART) through proposing several factors relevant to people's restorative experiences that are not unique to the wilderness setting (Kaplan and Talbot, 1983). These were later formalized into four major components in ART: being away, extent, fascination, and compatibility, all having restorative effects on attention (Kaplan and Talbot, 1983; Kaplan and Kaplan, 1989).

Besides exploring what benefits nature may induce, attention has also been paid to investigating what exact natural settings and factors can have or be designed to have the same benefits. For example, views of nature from a window at home or in the workplace (Ulrich et al., 1991; Kaplan, 1993; Tennessen and Cimprich, 1995; Kaplan, 2001) or just a glimpse of a small park on the way to work (Whyte, 1980) might have a positive influence on emotions and thus lead to an increased level of psychological health. Viewing nature from a window at home or in the workplace can support micro-restorative experiences (Ulrich et al., 1991; Kaplan, 1993; Tennessen and Cimprich, 1995; Kaplan, 2001). Ekkekakis et al. (2000) found that traveling through a natural setting for 10–15 min may provide a respite that, although brief, interrupts the process of resource depletion and promote a shift toward increased activation and positive moods (see also van den Berg et al., 2007; Tyrvainen et al., 2014). Grass, bushes, trees, and flower beds are highly predictive of psychological benefits (Nordh et al., 2009, 2013). It was found that ratings for restoration likelihood often increase with the number of street trees and the presence of flower beds (Lindal and Hartig, 2015). This is also the case for urban settings containing these natural factors, such as small-scale pocket parks within neighborhoods (Nordh et al., 2009, 2013), private gardens (Ivarsson and Hagerhall, 2008), and residential and commercial streets (Todorova et al., 2004; Lindal and Hartig, 2015; Yin et al., 2022).

1.2. Exploring the benefits of nature through human perceptions and behavior

Visual and aural senses are the most significant ways people interact with nature (Francomano et al., 2022). This also explains why most studies used photos (Thake et al., 2017), videos and recordings (Snell et al., 2019), simulated settings (Yu et al., 2017; Lafay et al., 2019), and real environments (Yang D. et al., 2022; Yang Y. et al., 2022) as stimuli to explore the benefits of nature on behavioral and emotional response. In soundscape research, many efforts have been made to explore the factors that influence people's psychological health, the most of which are related to natural soundscape. Similar to visual landscape studies, existing research is mostly concerned either with identifying what natural settings or what natural sound sources are aurally beneficial to people. In general, the more urban the setting, the less natural the sounds it contains and the more negative the emotions it causes (Zhu et al., 2021). Protected areas, such as forest parks and heritage sites at the national level, as well as urban green spaces (Liu et al., 2019) including city parks (Sun et al., 2012), leisure green spaces (Zhang et al., 2022), and waterfront (Zhong et al., 2023) at the city level all contain rich and diverse natural sounds that are normally regarded as capable of bringing users positive aural landscape experiences. Though individual differences may exist, natural sounds in urban green spaces such as birdsong, cicadas, flowing water, and the sound of breeze blowing through leaves have positive benefits and contribute significantly to soothing stress (Zhong et al., 2023). In a study focusing on residents' preferred sound sources in urban parks, researchers found that all types of residents had a high preference for natural sounds, especially the elder group (Gong et al., 2022).

Visual and aural landscapes also have impacts on behavior (Meng and Kang, 2016). Visual aspects affect behavior normally in indirect ways through the mediator "preference," which is often defined as "liking" (Peschardt and Stigsdotter, 2013) or finding locations esthetically pleasing (Hartig and Staats, 2006). People prefer to go to places with certain attributes to carry out recreational activities (i.e., walking, jogging, and exercising) (Larson et al., 2014), social activities (i.e., meeting with friends, playing with children, and interacting with others) and leisure and self-reflection activities (Widoretno and Youngmin, 2015). Urban settings dominated by natural features, such as city parks, pocket parks, gardens, and landscape boulevards were often mentioned as favorite places. Engagement with the soundscape in urban areas is also affected by the activity done (Sarwono et al., 2022) and vice versa, though scant evidence has emerged in soundscape research clarifying its relationship with activity type. The sound pressure level is one of the most important factors affecting choice of activity when it exceeds a certain range (Nilsson et al., 2007). There are also studies focusing on the effects of anthropological sounds. The presence of music, especially classical music, in open public spaces can encourage people to linger, to converse, and to hold eating/drinking events (Lepore et al., 2016). Sarwono et al. (2022) also found that talking with friends and playing with children are positively associated with anthropological sounds (i.e., people talking, footsteps, and slow music), while relaxing and reading activities are more likely to occur when the environments are rich in natural sound (i.e., water, wind, birds chirping, and rain).

1.3. The aim of this study

Though contributions were made to investigate the interaction between visual and aural attributes of nature and the emotions and behaviors triggered by them, very few have explored their mutual relationships and influences through a common framework. What's more, these relationships have not yet been utilized in predicting emotional and behavioral responses due to the difficulty of obtaining large-scale perception data. This may also impede the efficient delivery of design instructions for improving natural urban environments.

Setting out from the NBS perspective, this study aims at exploring behavior and emotional responses to visual and aural contact with urban nature. Taking the UGS, Jiangjia Art Garden in Chengdu Outer Ring Ecological Zone as an example, natural attributes of its visual (landscape) aspect were calculated with space syntax and Quantum Geographic Information System (QGIS). This was done while a soundwalk and questionnaire-based survey were conducted to investigate aural characteristics (sound source compositions) of the study site and emotional responses regarding their overall satisfaction, pleasantness, calm, and agreeableness. Onsite observation and mapping were also carried out to indicate activities within the site. The obtained information was used together to formulate a stochastic model, so that the interactive elements of nature in the visual and aural aspects on behavioral and emotional response could be disclosed. These models were then used to predict and illustrate behavior and emotional response within the whole site. Results were then visualized as emotional and activity maps to develop design implications for how Jiangjia Art Garden could be improved by providing people with more beneficial experiences of nature.

2. Materials and methods

2.1. Research site

This study selected Jiangjia Art Garden, a typical urban green space in Chengdu Outer Ring Ecological Zone, as a research site. Chengdu Outer Ring Ecological Zone is a circular urban natural area with over 100 square kilometers planned and constructed under the Park City Agenda promoted across China. As one of the benchmark demonstration projects, Jiangjia Art Garden is expected to become a leisure destination and a well-known landmark for the city of Chengdu. It is located in the south of the Chengdu Outer Ring Ecological Zone and is 1.32 square kilometers in size. Its visual landscape is dominated by lakes, woodland, herbals, and shrubs and is mostly covered by anthropological and natural sounds. Jiangjia Art Garden generally serves as a site for daily leisure activities, sightseeing, parent-child activities and exercising (Figure 1).

Nine measurement spots were selected in the Jiangjia Art Garden based on the following criteria: (1) they should be able to present the visual and acoustic features of the Jiangjia Art Garden; (2) they should cover sufficient distance for an over three-minute walk from the entrance to the first measurement spot to allow enough time for subjects to become mentally immersed in the setting (Aumond et al., 2017; Jo and Jeon, 2020). The three-minute walking distance should be the smallest interval between spots; and (3) there should be enough space for subjects to wander around within each spot. Thus, with the consideration of the size and the accessibility to the public, nine spots were chosen in Jiangjia Art Garden to measure its visual and aural landscape composition, as well as subjects' emotional and behavioral responses to visual and aural environmental landscape stimuli. The scope of each spot was chosen as 50 m x 50 m to provide subjects with enough space to experience the surroundings without losing their sense of space (Figure 1).

2.2. Measurements

This study adopted a multi-method approach to investigate the visual and aural landscape compositions of Jiangjia Art Garden and their effects on behavior and emotional response. This included observation and mapping, calculations based on QGIS and space syntax, questionnaire-based onsite surveying, and focus group evaluation.

2.2.1. Visual landscape compositions calculated with space syntax and QGIS

Given that the study was largely concerned with perception, visual landscape compositions were measured both in terms of the actual landscape distributions and what people can visually perceive within the site using QGIS and space syntax. The buildings and woodlands were set as visual obstacles, the boundaries of which were identified using QGIS Maptiler and Google satellite images to delimit the visible area. Space syntax software Depthmap was used to analyze the spatial visibility of the site over a 50 m × 50 m grid so that the visible area of each unit could be obtained. These were then imported into QGIS to generate the corresponding vector circles. The area of grasslands (G), waterscapes (Wa), hardscapes (H) and woodlands (Wo) within each circle were calculated to indicate what landscape compositions of Jiangjia Art Garden people visually perceived (Figure 2).

2.2.2. Sound sources and emotions measured by soundwalk and questionnaire

Sound sources and emotional responses to the surrounding environment were measured by a sound walk and a questionnaire-based onsite survey conducted at each measurement spot.

A sound source is an attribute that can be characterized by identifying what sounds can be heard in the area and how dominant they are (ISO, 2018). Referring to international soundscape research standards (ISO, 2018), previous relevant studies (Shao et al., 2022) and the pilot study conducted at Jiajiang Art Garden, four types of sound sources (traffic sound, mechanical sound, anthropological sound, and natural sound) were provided as potential cues (Table 1). A sound walk is a standardized method widely used in soundscape research to measure aural perceptions (Liu et al., 2014). It was employed in this

FIGURE 1
Research sites in Chengdu Outer Ring Ecological Zone: Jiangjia Art Garden.

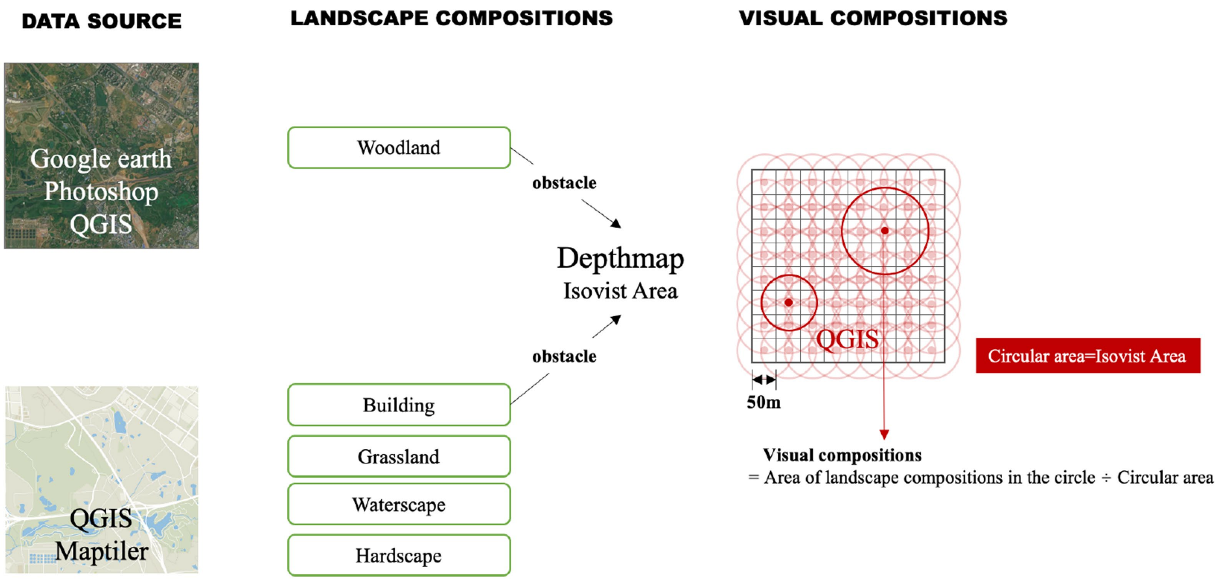

FIGURE 2
Measuring visual landscape calculations with space syntax and QGIS.

study to explore the sound sources perceived in each measurement spot of the site.

One of the most classical theories in environmental psychology to understand human emotions is the Russell's circumplex model (Russell, 1980). Two basic emotional dimensions, pleasantness (positive-negative) and arousal (high arousal-low arousal), were proposed in Russell's model to, respectively, describe the trend and intensity of people's emotional changes (Russell, 1980). The axis also includes a wide range of emotional indicators represent the different stages and levels of human emotional change. Among which, calm, annoying, pleasantness and excitement are regarded as the most typical four (Axelsson et al., 2010). Since excitement usually requires special stimuli (Beza, 2010), calm, annoying and pleasantness are thus adopted in the ISO (2018) and also in the perceived affective quality (PAQs, Axelsson et al., 2010) to measure human emotions in response to their perceived aural-visual qualities.

Consider semantic unity of and the difficulty of understanding the indicators, three emotional aspects (pleasantness, calm, and agreeableness) were selected and validated in a small-scale pilot study as efficient indicators of emotional response from visual and aural contact with the site. This was done while their overall satisfaction of Jiangjia Art Garden was obtained (Table 1).

TABLE 1 Indicators of measuring perceived sound sources.

Indicators		Descriptions		
Sound sources	Traffic sound (S1)	Skateboards	Car horn	Rail
		Bicycle ring	Motor vehicles	Highway
		Heavy vehicles	Airplane	/
	Mechanical sound (S2)	Weeding	Construction	Alarm
		Radio	Loudspeaker	/
	Anthropologic sound (S3)	Exercising	Cleaning	Whistling
		Walking	Parent–child activities	Smiling
		Boating	Bells	Music
		Talking	Pedaling	Singing
	Natural sound (S4)	Insects	Tree murmur	Wind
		Croak	Twittering of birds	Ripple
		Fish dive	Barking dogs	Rain
Emotional responses	Pleasantness (E1)	The level of pleasure you feel in this environment		
	Agreeableness (E2)	How agreeable do you feel about this environment		
	Calm (E3)	The level of calmness you feel in this environment		
	The overall satisfaction (E4)	How satisfied do you feel about this environment		

The questionnaire consisted of two parts. The first part contained questions investigating the dominance of each sound source perceived at each spot (Zhang et al., 2018). The second part had four questions evaluating overall satisfaction, pleasantness, calm, and agreeableness of the site. Both parts used a five-level Likert scale (1–5 representing strongly disagree [1] to strongly agree [5]).

2.2.3. Behavior vitality rated by the expert group through onsite observation

Onsite observation and mapping were also carried out by four trained surveyors to record activities at each measurement spot, represented as behavior vitality (V), used in this study to describe the diversity and intensity of activity. Behavior vitality was adopted from the concept of urban vitality which refers to the people and their activities throughout varied time schedules that can be observed in a specific space and is the product of the number and duration of various activities (Gehl, 1989). During the opening hours of Jiangjia Art Garden, surveyors ranked the behavior vitality of each spot at 2-h intervals from 8:00 to 17:00 (10:00, 12:00, 14:00 and 16:00) and also with a five-level Likert scale. The mean value of four surveyors' ratings was then calculated as the results of behavior vitality for each spot.

2.3. Data collection

The sound walk and on-site questionnaire survey were conducted on sunny days with an Air Quality Index less than 60 and wind speed below 5 m/s during July 2021.

A total of 20 young adults were recruited to evaluate their perceived aural characteristics and their emotional affect at each measurement spot. Subjects were required to be between 20 and 30 years old, since previous studies suggested that age (Lyons, 1983) may influence emotional reactions under certain circumstances. This study is especially concerned with the aural-visual perceptions of young people since they are more sensitive to surrounding environments than other age groups (Kurakata et al., 2008). The recruited subjects all had normal or corrected-to-normal visual acuity, normal color vision, and hearing. The ratio of male to female subjects was controlled at 1:1. The survey was ethically approved, and informed consent was obtained from each subject in advance. Necessary training and introduction were also provided before the survey was formally taken.

The 20 recruited subjects were divided into four groups, and each group was led by one researcher to travel through the nine measurement spots in different orders to avoid having too many people appear at the same spot at the same time. Subjects were asked to take the sound walk and to wander around within each measurement spot by themselves to experience their surrounding environments for 5 min (Bahali and Tamer-Bayazit, 2017) and complete the questionnaire afterward. Each of the 20 subjects filled out the questionnaire nine times in each of the nine measurement spots; a total of 180 responses were collected. Noise data, such as an incomplete questionnaire or questionnaires with the same ratings for every indicator, were manually removed and the number of final valid responses was 139 (approximately 15 per spot). The sample size was in line with previous similar studies, which stated that the total number of valid responses should be over 100 (Kang and Zhang, 2010).

2.4. Data analysis and visualization

The analysis methods for exploring the relationship between human emotions and environmental aural-visual qualities normally conducted in two ways. The first one is to investigate the influencing factors of people's positive or negative emotions through correlation analysis (Kong et al., 2022). However, it is only suitable for revealing the influence of a certain or a few of certain dimensions without presenting their interactions. Another way is to build a linear regression model to predict the overall environmental satisfaction or people's emotional responses based on environmental aural-visual qualities. It can easily describe the complex relations existed between multi-dimensional environmental quality (Shao et al., 2022), but with an obvious disadvantage: the modeling method can be difficult to comprehend in design practices. Thus, this study decided to use the modeling method together with the mapping method, so that the relationship between environmental visual-aural qualities and human emotional and behavior responses can be directly presented.

Data analysis was conducted at two levels: the nine measurement spots and the case study site, while the visualization process was only taken at the site. The information regarding activity, sound source, and emotional response was collected at the spot level. This was then used together with visual characteristics of spots to formulate a stochastic model describing the relation between visual/aural landscape compositions and emotional reaction. Similarly, another mathematical model indicating the influences of visual and aural characteristics on behavioral reactions was also established. These models were then employed to generate the emotional and behavior map for the whole site using QGIS. Design implications to provide people with more appealing experiences can then be developed based on the mapping results describing behaviors and emotions in response to the visual and aural stimuli of Jiangjia Art Garden.

3. Results

3.1. Manipulation checks

Questionnaire data were analyzed using SPSS V26.0 and examined for internal consistency with Cronbach's alpha (Bujang et al., 2018). Calculation of internal consistency (Cronbach's α) was the preferred measure of inter-rater reliability when cases were rated in terms of an interval variable or interval-like variable, such as the Likert scale used in the questionnaire. The α values of the four emotional indicators and four sound-source indicators measured at the nine measurement spots suggested sufficient internal consistency (Cronbach's $\alpha > 0.7$), thereby guaranteeing the reliability of the obtained ratings.

3.2. Descriptive analysis

General descriptions of the measured visual-aural landscape characteristics and the obtained emotional and behavioral responses are shown in Table 2.

3.2.1. Descriptive analysis of visual landscape compositions

The actual landscape distribution of Jiangjia Art Garden indicates that the site is largely dominated by natural attributes such as grassland, woodland, and waterscape. Grasslands (51.9%) are the dominant feature, followed by woodlands (23.7%) and waterscape (6.7%), while hardscape such as pathways, squares, and playgrounds comprise around 17.7% of the total acreage. Grasslands are evenly distributed within the site, while woodlands are mainly centered along the main pathway and greenway. Waterscape is present mostly in the form of artificial lakes. The largest lake, which is composed of four pieces, was designed enclose to the main entrance of the site in a node-like fashion. One medium-sized and two small-scale lakes are located in the northeast and west of the site, respectively, and are set together with dense woodland. Another medium-sized lake is in the middle of a large-scale grassland at the northwest of the site. There are three nodes characterized by hardscape including one at the entrance functioning as a tourist transportation center, one in the middle that constitutes a landscape node surrounded by woodlands and lakes, and another one mainly composed of recreation facilities (Figure 3).

In terms of visual landscape attributes perceived by people, grassland and woodland ranked at the top. People perceived the grasslands as centered at the southeast and the northwest of the site, which is mostly in line with their actual distribution. Also, the presence of waterscape was accurately perceived by the participants. However, differences were found between the actual distributions of woodland and hardscape and their perceived visual distribution. The aggregation of woodland in the western and northwestern area were not accurately perceived, while perceived woodland was mainly located close to the main entrance and the northeastern area. Similarly, hardscape was only perceived around the main entrance of the site, since it was not shown elsewhere within the site (Figure 4).

3.2.2. Descriptive analysis of aural landscape compositions

Sound sources were rated by their dominancy at the nine measurement spots. Natural sounds were especially noticed at spot eight (4.8) and nine (4.9), locations that are relatively far from the main entrance and the surrounding railway. Natural sounds at spot four (3.7) were rated as the least obvious, since their locations are close to the outside of the site. At spots four (4.1), five (4.5), and six (4.6) near the main entrance where the highway passes through, the sound of traffic is considered most dominant. Mechanical sounds (avg. 1.8) were in general weak within the scope of Jiangjia Art Garden, with only spot two (2.8) and four (2.9) rated as higher, while anthropological sounds (avg. 3.0) such as walking, talking, and laughing were rated as evenly distributed across the nine measurement spots (Figure 5).

3.2.3. Descriptive analysis of behavioral vitality

Based on the on-site observation, Jiangjia Art Garden can be divided into four areas with different functions and functional intensities. The area near the south entrance is dominated by social gathering functions. Open spaces and facilities are largely scattered in the middle eastern part of the site, an area that supports plenty of activities, while the middle western area mostly contains sightseeing and lake activities, such as boating and fishing. The northern part of the site, once farmland, has been transformed into an agriculture-themed entertainment space.

The results of behavior vitality measured by the diversity and intensity of activity occurring within each spot suggested that spot two (4.0) has the most diverse and intense activities including resting and talking with friends, photographing, dog walking, and children playing, especially from 8:30–10:00 and 15:00–16:00. Spots five (3.0) and nine (3.0), located at the southern and western side of the site, respectively, also were rated as having a medium level of behavior vitality. The former is dominated by exercising activities that peak between the hours of 8:30–9:30, while the latter is mainly composed of relaxing and resting activities between 8:30–10:00 and 15:00–16:00. Lower levels of vitality appeared at spots four (1.0), six (0.0) and eight (1.0), where mobile activities such as walking and sightseeing are prominent (Figure 6).

3.3. Human behavioral responses predicted by the visual-aural compositions

The measuring and rating results of visual and aural landscape characteristics were then analyzed through their behavior vitality to explore their influential factors and mechanisms.

Results suggested that behavior vitality in research sites is only affected by the visual components of nature with both woodland ($p = 0.000 < 0.05$) and grassland ($p = 0.000 < 0.05$) appearing to be related. The model describing their relation was established and its R^2 was 0.613:

TABLE 2 Descriptive analysis of the obtained data.

		Wo	G	Wa	H	V	S1	S2	S3	S4	E1	E2	E3	E4
Spot 1	Mean	17.0%	58.0%	0.0%	25.0%	2.0	3.5	1.9	2.3	4.9	3.7	1.7	3.3	3.6
	Std. Dev.	–	–	–	–	–	0.7	0.8	0.9	0.3	0.5	0.6	1.0	0.5
Spot 2	Mean	23.0%	53.0%	0.0%	8.0%	4.0	2.5	2.8	4.1	3.9	3.3	1.6	2.3	3.4
	Std. Dev.	–	–	–	–	–	0.8	1.3	0.7	0.7	0.5	0.7	1.1	0.5
Spot 3	Mean	0.0%	33.0%	48.0%	13.0%	2.0	3.1	1.7	4.3	4.0	3.3	1.8	2.3	3.7
	Std. Dev.	–	–	–	–	–	0.9	0.9	0.7	0.8	0.7	0.8	0.9	0.5
Spot 4	Mean	0.0%	80.0%	4.0%	0.0%	1.0	4.1	2.9	3.2	3.7	2.8	2.7	2.3	3.3
	Std. Dev.	–	–	–	–	–	0.7	1.1	1.2	0.8	0.9	1.0	1.0	0.4
Spot 5	Mean	22.0%	57.0%	6.0%	0.0%	3.0	4.5	1.2	1.9	4.5	2.8	2.9	2.2	3.1
	Std. Dev.	–	–	–	–	–	0.6	0.4	0.9	0.5	0.5	0.6	1.4	0.3
Spot 6	Mean	6.0%	78.0%	7.0%	0.0%	0.0	4.6	1.2	2.6	4.3	2.4	2.7	1.9	3.0
	Std. Dev.	–	–	–	–	–	0.6	0.4	0.6	0.6	0.5	0.8	0.7	0.0
Spot 7	Mean	0.0%	75.0%	6.0%	8.0%	1.0	2.4	1.5	3.9	3.8	3.6	1.6	2.5	3.8
	Std. Dev.	–	–	–	–	–	0.9	0.5	1.1	0.6	0.7	0.7	1.1	0.4
Spot 8	Mean	14.0%	54.0%	16.0%	4.0%	1.0	3.8	1.3	2.6	4.8	3.8	2.0	3.0	3.4
	Std. Dev.	–	–	–	–	–	0.4	0.6	0.8	0.6	0.9	0.8	1.3	0.5
Spot 9	Mean	34.0%	52.0%	1.0%	0.0%	3.0	3.8	1.6	2.1	4.9	3.1	1.7	2.7	3.1
	Std. Dev.	–	–	–	–	–	0.4	0.8	0.7	0.3	0.5	0.8	0.8	0.3
Mean		–	–	–	–	1.9	3.6	1.8	3.0	4.3	3.2	2.1	2.5	3.4
The whole site		23.7%	51.7%	6.7%	17.7%	–	–	–	–	–	–	–	–	–

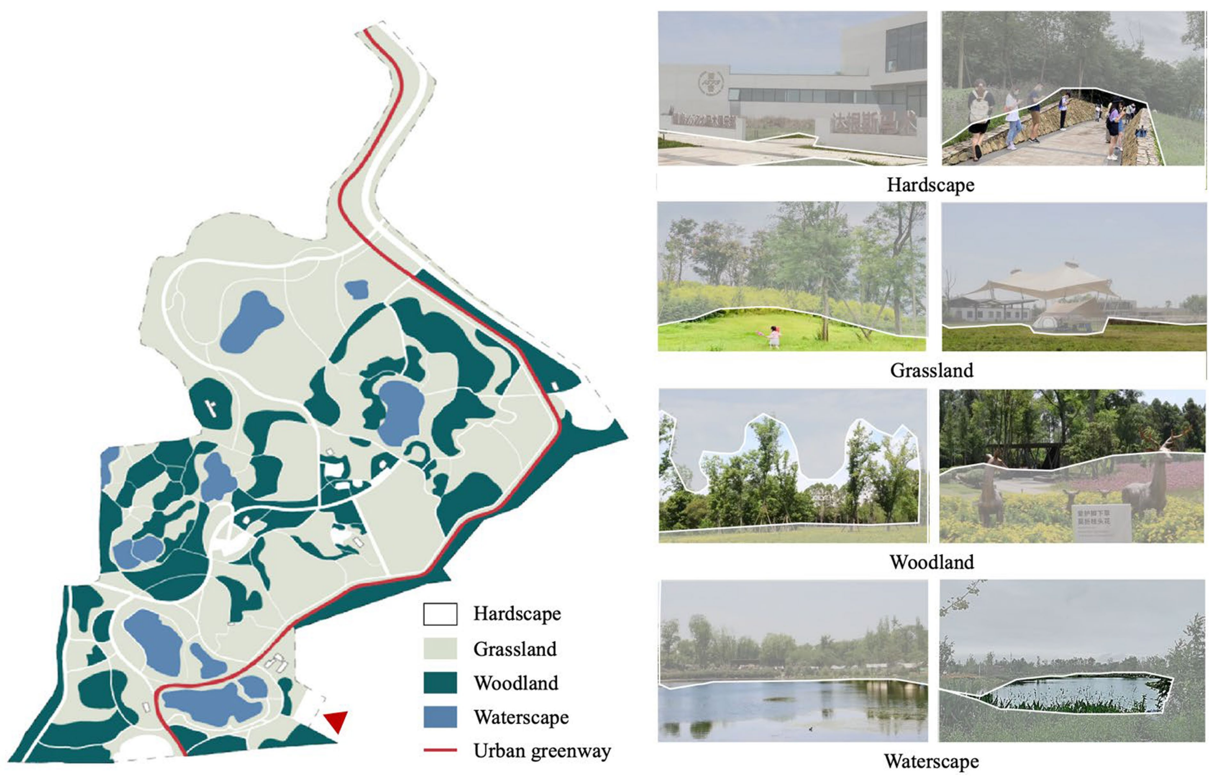

FIGURE 3
Visual landscape characteristics of Jiangjia Art Garden.

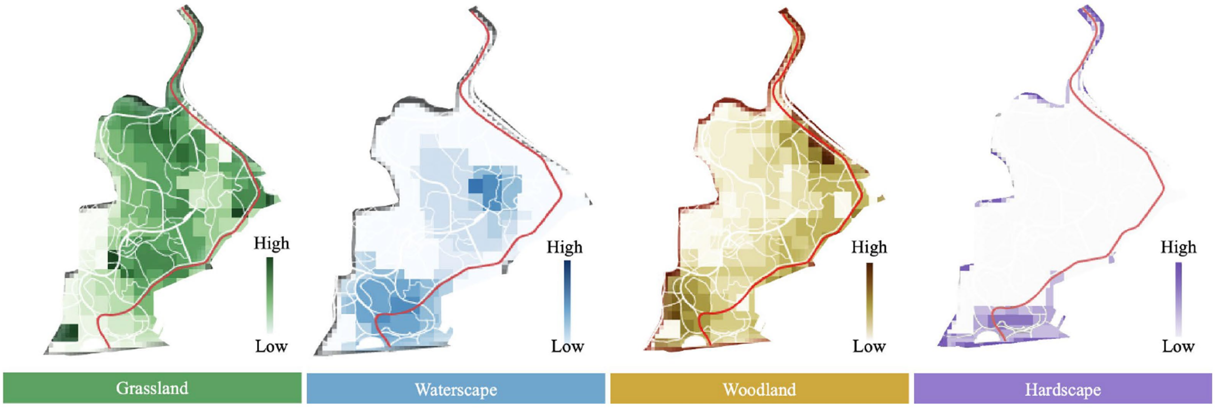

FIGURE 4
Visual landscape compositions of Jiangjia Art Garden.

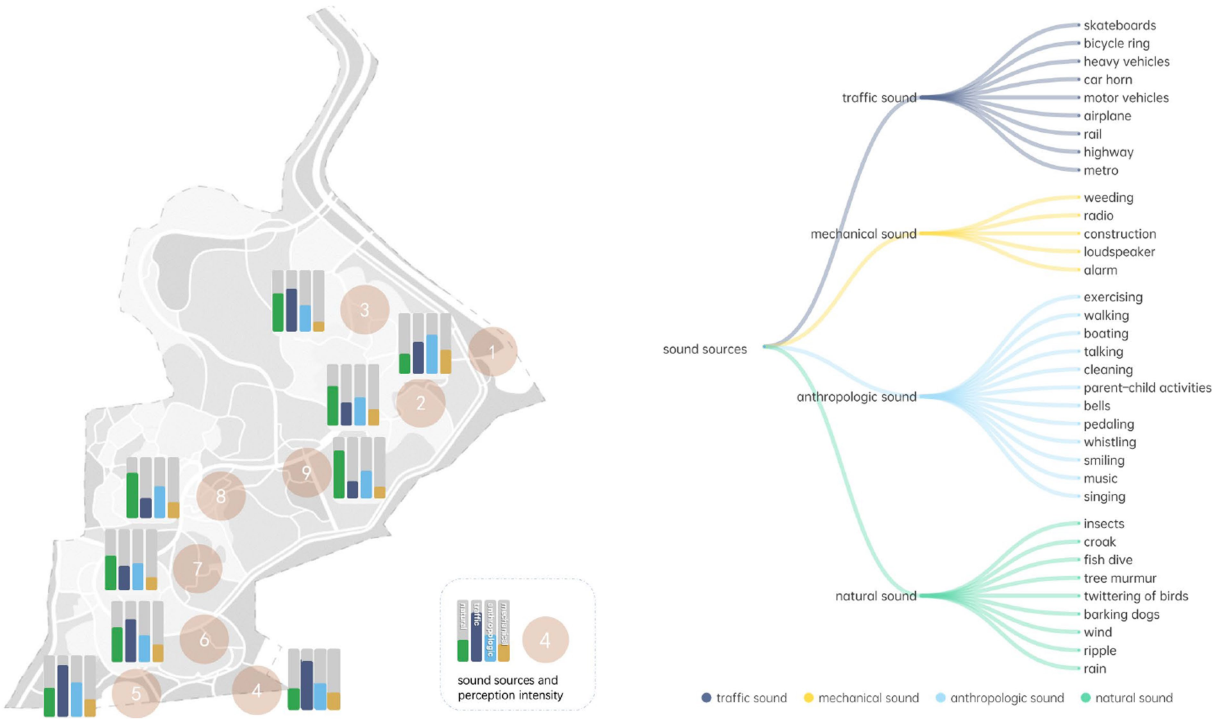

FIGURE 5
Aural landscape compositions of Jiangjia Art Garden.

$$V = 3.002 + 0.058 \times \mathrm{Wo} - 0.029\mathrm{G} \quad (1)$$

The model was then used to predict behavior vitality of the whole site (Figure 7, Right) and compared with the accessible area of Jiajiang Art Garden (Figure 7, Left). The accessibility of the research site is classified into three levels: the open-to-the-public areas refer to those spaces mainly composed of pavements, greenways, and hardscapes; the accessible-but-not-encouraged areas include areas that are informally accessible to park users, such as grasslands, lakes, and woodlands; and the restricted areas are those that are physically inaccessible.

The comparison between two mapping results indicated that in general, activity can only partly be guided by the spatial design. The open-to-the-public areas do not usually attract the most intensive activity, while the highest vitality of activity was most observed in the accessible-but-not-encouraged areas, especially within grasslands and around waterscapes. The restricted areas, however, do not offer activities and thus present the lowest level of vitality.

3.4. Human emotional responses predicted by the visual-aural compositions

The natural components of visual landscapes, woodlands, and grasslands, as well as natural sounds, were confirmed to have

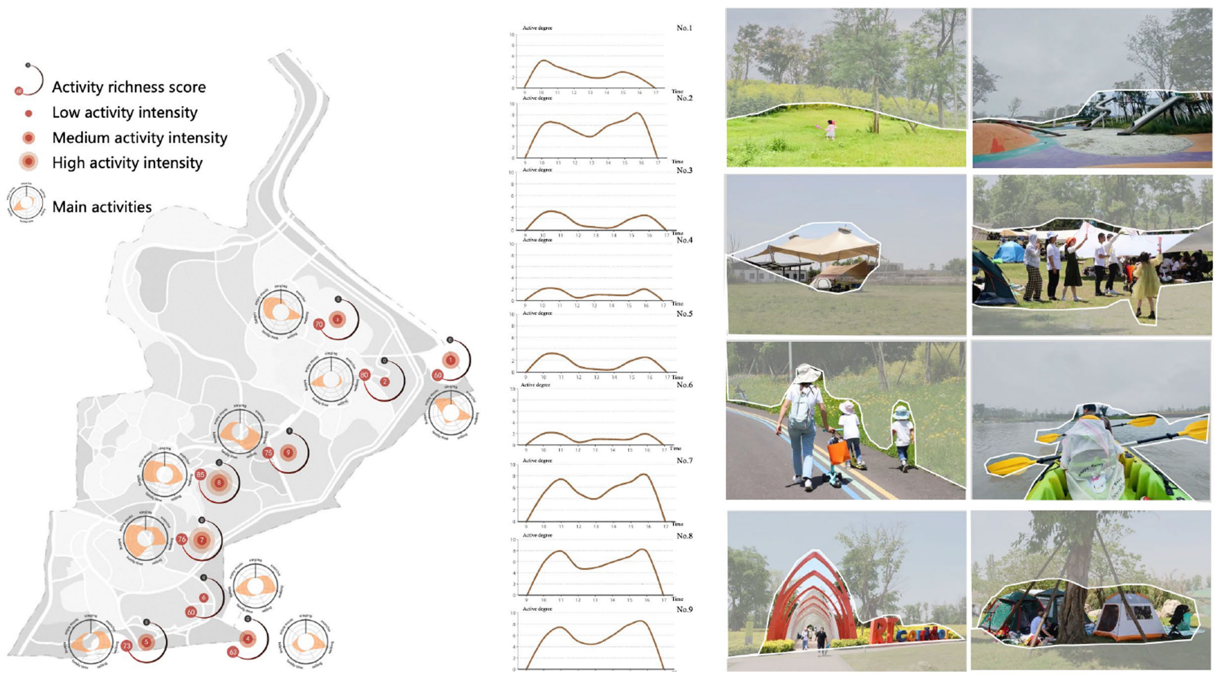

FIGURE 6
Human behavioral responses indicated by behavior vitality.

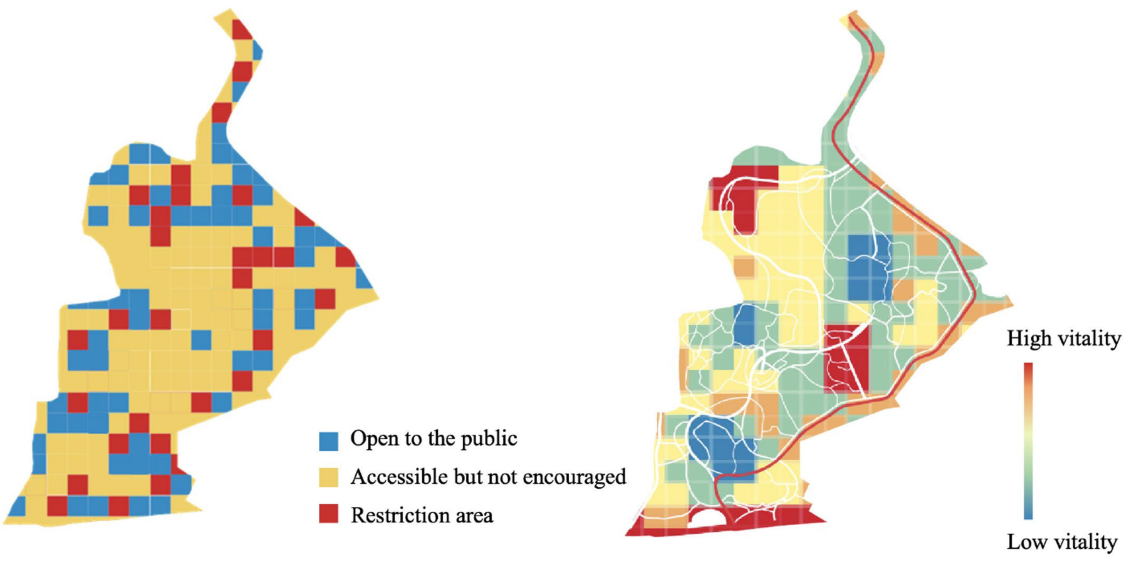

FIGURE 7
Accessible mapping (Left) and behavioral mapping (Right) for Jiangjia Art Garden.

significant influence on emotional response. Hardscape in the aspect of visual landscape and traffic sound in the aspect of aural landscape were also found to be related. The other three landscape compositions including waterscape, anthropologic, and mechanical sound, however, can hardly impacted the reported calm, agreeableness, pleasantness, and overall satisfaction (Table 3).

Results showed that two indicators describing the sound types, traffic sound and natural sound, as well as one visual indicator, hardscape, were strongly correlated with pleasantness. The model generated, with an R^2 of 0.342, was as follows:

$$E1 = 3.225 - 0.384 \times S1 + 0.273 \times S4 + 0.019 \times H \qquad (2)$$

In terms of agreeableness, there was one visual and aural aspect that proved to be relevant, and a model with an R^2 of 0.245 was found as:

 10.3389/fpsyg.2023.1186806

TABLE 3 Correlational analysis between the emotional responses and aural-visual indicators.

		S1	S2	S3	S4	Wo	Gr	Wa	H
E1	Correlation (Pearson's r)	−0.436	0.031	0.238	0.220	0.049	−0.232	0.078	0.397
	Significant (p)	0.000	0.717	0.004	0.009	0.564	0.006	0.362	0.000
E2	Correlation (Pearson's r)	0.481	−0.028	−0.164	0.008	−0.051	0.259	−0.129	−0.354
	Significant (p)	0.000	0.742	0.052	0.927	0.553	0.002	0.129	0.000
E3	Correlation (Pearson's r)	−0.291	0.074	0.051	0.175	0.119	−0.120	−0.047	0.270
	Significant (p)	0.000	0.382	0.546	0.038	0.163	0.161	0.0.538	0.001
E4	Correlation (Pearson's r)	−0.380	0.072	0.322	0.298	−0.183	−0.203	0.231	0.444
	Significant (p)	0.000	0.394	0.000	0.000	0.031	0.016	0.006	0.000

$$E2 = 0.922 + 0.371 \times S1 - 0.023 \times H \quad (3)$$

Only the aural components, traffic and natural sound, appeared to be active in the analysis of the relation between calm and the visual-aural components of the research sites. A model was constructed, and its R^2 was 0.15:

$$E3 = 2.113 - 0.378 \times S1 + 0.378 \times S4 \quad (4)$$

The overall satisfaction was found to be influenced by the visual component of the woodlands and the aural components of traffic and natural sound. A linear model with an R^2 of 0.434 appeared as:

$$E4 = 3.513 - 0.01 \times Wo - 0.266 \times S1 + 0.22 \times S4 \quad (5)$$

The estimated coefficient values for all indicators and model-fitting information are listed in Table 4.

This set of models was employed to visually represent the participant's emotions (Figure 8). The tendencies of the four measured emotional aspects were consistent. In general, the northern area of the site was found to trigger better emotional responses than the southern area. The ratings of calm, agreeableness, and overall satisfaction decreased from north to south within the site, while the middle area, characterized by the waterscape, showed the highest level of pleasantness.

4. Discussion

4.1. Human behavioral responses and their component visual-aural landscape influences

This study used behavior vitality to describe the intensity and diversity of human activity in Jiangjia Art Garden. Also, it explored the relationship between activities and the visual-aural landscape attributes based on data collected at spot level, employing this relationship to construct a model to predict behavioral responses for the whole site.

In general, behavioral responses were only influenced by two visual natural components, woodlands and grasslands. Woodlands were found to encourage activity and grasslands can lessen the behavior vitality of the area, that are quite opposite with the findings in previous studies. Grasslands are generally regarded as preferred in UGSs for public activities because they provide open and wide spaces with soft "pavement" (Fu et al., 2019), while woodlands are normally less welcome because they provide limited spaces for gathering and staying activities. The survey was conducted in July, when the temperature is high, and the sunlight is strong. Compared to grasslands, woodlands can provide more shade and therefore are more attractive to visitors. Additionally, most grasslands in the site are posted with signs warning people not to step on the grasslands, which also may impede staying activities.

Considering both the distribution of visual landscape components and the accessibility and vitality mapping results, it can be concluded that activities do not usually comply with the designed functional requirements of spaces. People are most active where grasslands, water features, and woodlands coexist and where the accessible-but-not-encouraged spaces dominate. Results not only confirmed the accuracy of the generated model but also were in line with existing evidence suggesting that activities, especially informal ones, can largely be influenced by individual preference (Cheung, 2013; Cai et al., 2021; Xu et al., 2022). People continuously make minor modifications to the original arrangement of spaces, personalize their temporarily used spaces based on their needs and the rules of design, and thereby make these spaces their own (Thwaites et al., 2013). They prefer to choose their own activity areas, defining what is accessible for themselves, as shown in this study and in previous research (Kruize et al., 2019).

Another thing worth explaining is the vitality curves of spots 3 and 5, spots 4 and 6 appear to be similar with each other. This is possibly due to that the vitality average of each spot were processed through several calculations. During the opening hours of Jiangjia Art Garden, four surveyors observed and ranked the functional diversity and intensity of each spot at 2-h intervals from 8:00 to 17:00. The average of their ratings was used to present the diversity and intensity of each spot at each measurement time. The average of functional diversity and intensity was then calculated for each measurement spots to present their behavior vitality. Besides, the observation and evaluation were taken in three consecutive days in July 2021, and thus, the average of behavior vitality of three recorded days was calculated and used to generate the map. Though each spot may be rated as different in terms of diversity and intensity in each measurement day, they finally got the same average numbers at the 10:00, 12:00, 14:00, and 16:00 calculated within 3 days.

4.2. Human emotions and visual-aural landscape attributes

Emotional responses were also measured and investigated for the influence of various visual-aural landscape attributes. Models were

TABLE 4 Model fit and estimation of B coefficients of models.

	Model fit (R^2)	Attribute	Estimate B	Standard error	*t*-value	*p*-value
E1	0.342	Constant	3.225	0.408	7.909	0.000
		S1	−0.385	0.066	−5.824	0.000
		S4	0.273	0.083	3.277	0.001
		H	0.019	0.009	2.110	0.037
E2	0.245	Constant	0.922	0.374	2.656	0.009
		S1	0.371	0.080	4.641	0.000
		H	−0.023	0.011	−2.027	0.045
E3	0.150	Constant	2.113	0.531	3.982	0.000
		S1	−0.378	0.086	−4.412	0.000
		S4	0.378	0.116	3.269	0.001
E4	0.434	Constant	3.513	0.199	17.609	0.000
		S1	−0.266	0.029	−9.129	0.000
		S4	0.220	0.044	4.948	0.000
		Wo	−0.10	0.003	−3.66	0.000

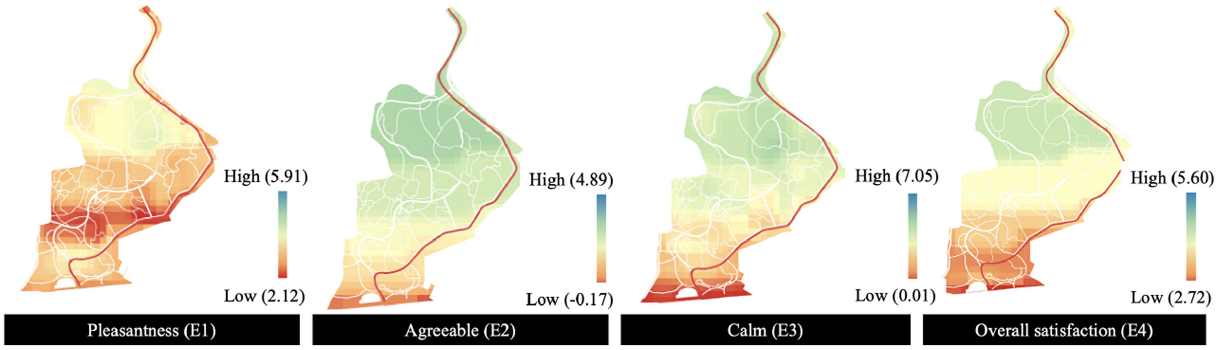

FIGURE 8
Emotional mapping for Jiangjia Art Garden.

then established, so as the relationship between pleasantness, calm, agreeableness, and the overall satisfaction subjects experienced in Jiangjia Art Garden and their relevant environmental components can be illustrated.

A total of four components, traffic and natural sounds in the aural aspect, as well as woodlands and hardscapes in the visual aspect, were identified as strongly related. Natural sounds showed consistent positive effects across the four emotional dimensions. The positive influences of natural sounds such as tree murmurs, twittering of birds, winds, and rain have been widely confirmed in previous research (Aletta et al., 2016; Ren et al., 2018; Buxton et al., 2021; Yang D. et al., 2022; Yang Y. et al., 2022). People's perceptions are determined, or at least influenced, by their cognitions of former experiences in similar settings (Zajonc, 1980), combining their embedded feelings, images, and thoughts. Though urban parks are regarded as typical natural settings where users expect to experience nature, this kind of expectation can be relatively low for a park located in the central city of Chengdu which suffers from surrounding traffic and construction noises. However, this lower level of expectation may strengthen people's positive responses since they take natural sounds perceived within the site as an extra surprise.

Another natural component of visual landscapes, woodlands, had a negative impact but only on overall satisfaction. While woodlands can provide shade in summer, they can also obstruct long-range view. Now that openness is one of the factors that affect environmental preference the most (Nasar and Jones, 1997) and the positive relation between preference and human emotions have been widely confirmed (Zhuang et al., 2021), these may provide supports for the inhibition influences of woodlands have on human emotions. Besides, the obstructed view in woodlands may also implies hidden danger and make people feel unsafe (Fu et al., 2019).

In terms of non-natural components, traffic sound and hardscapes both showed opposite impacts on emotion across the four models. Traffic sound had a negative influence on pleasantness, calm, and overall satisfaction, but enhanced agreeableness. This again supports the above assumptions about expectations regarding place identity (Yin et al., 2022). Hardscapes in visual landscape can promote pleasantness but can negatively influence agreeableness. Hardscapes normally occur in gathering spaces along with sculptures, fountains, and resting facilities. These can either provide people with objects of interest or opportunities to rest that both can contribute to a sense of pleasantness.

4.3. Limitations

Though the models and the mapping results in general meet with research purposes and no obvious contrast was found between outcomes of this study and previous research, there were limitations regarding the experimental design and data analysis processes. First, the survey was conducted in summer. The high outdoor temperature and the strong sunlight (Zhang et al., 2023) may have influenced behavior and emotions, especially decisions on where and when to conduct resting activities. These factors sometimes had an effect only on certain emotions, since four dimensions of emotional response were investigated. Under the same experimental conditions, participants' standard responses may be slightly impacted but their comparison results should be equally as convincing. Although behavior, emotional response, and sound sources were all measured on a 5-point Likert scale, the four typical visual components of Jiangjia Art Garden were presented by a percentage. The differences on the components' order of magnitudes may influence the correlation and modeling results. Other potential limitations may include the number of survey participants and the specific group (young adults) of participants. The final amount of analyzed data regarding behavior and emotional response was only slightly higher than the minimum required sample size due to the data-cleaning process. For studies using stochastic models, the larger the sample size, the higher the probability of obtaining a more accurate model. This may also lead to an unstable range of R^2 in this study. Soundscape research normally rates an R^2 above 0.3 (Yang, 2019; Lionello et al., 2020) as convincing for the linear model, but for many emotion studies, evidence suggests that models with an R^2 over 0.1 can also provide sufficient reliability (Lionello et al., 2020). The overall results are therefore regarded as reliable, but models based on this study could further be improved by increasing the sample number in future attempts.

5. Conclusion

This study confirms that both seeing and hearing nature can have positive influences on behavioral and emotional response, thereby promoting the health and well-being of urban dwellers. Nature-dominated visual landscapes such as grasslands, lakes, and woods, as well as natural sounds such as bird sounds, chirp sounds, and wind sounds were found to be positively correlated with activity vitality and emotional status. Regarding behavioral responses, the evidence shows that grasslands and woodlands are more likely to attract activity and that vitality becomes extremely high when they are coupled with lakes. Though hard pavements provide spaces for people to gather and rest, they hardly promote activity vitality. In addition, places with more natural sounds have a higher volume of activity. Emotional response, overall satisfaction, calm, and agreeableness all show similar influences on behavioral patterns, suggesting a strong response to natural factors. The research findings could inform the future design of high-quality urban green spaces and promote the application of aural-visual experience in the design of urban nature areas.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed in accordance with the Declaration of Helsinki and approved by the Ethics Committee of Tongji University (protocol code 2020tjdx075 and date of approval 09/11/2020). The patients/participants provided their written informed consent to participate in this study.

Author contributions

YY, YH, and YS: conceptualization. YY and YS: methodology and funding acquisition. YM: software, investigation, and visualization. YY and YH: validation, resources, data curation, writing—review and editing. YY, YM, and YS: formal analysis. YY and YM: writing—original draft preparation. YS: supervision and project administration. All authors contributed to the article and approved the submitted version.

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Conflict of interest

YH was employed by the company Acoustics and Vibration Group, Bureau Veritas.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Nonlinear effects of blue-green space variables on urban cold islands in Zhengzhou analyzed with random forest regression

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Urban cold island effects have become increasingly relevant with accelerating climate change. However, the relationship between such effects and their causal variables remains unclear. In the present study, we analyzed the relationship between blue-green space variables and land surface temperature (LST) and park cooling intensity (PCI) in central Zhengzhou City using a random forest regression model. Cool urban areas corresponded to the location of blue-green spaces. The average temperatures of these spaces were 2 °C and 1 °C lower than those of the built-up areas and the full study region, respectively. Blue-green spaces also had a maximum temperature that was 8 °C lower than those of the built-up areas and the study region. The three primary variables determining LST were blue space proportion and area and vegetation cover, whereas the three variables determining PCI were blue-green space width, vegetation cover, and patch density. At a width of 140 m, blue-green spaces caused a PCI peak, which further improved at 310 m. The proportion of blue space had a stepwise effect on PCI. A vegetation coverage of 56% represented the lower threshold of LST and the higher threshold of PCI. These results reflect a nonlinear relationship between blue-green variables and urban cold islands. In conclusion, the study provides data that could inform the efficient use of blue-green spaces in urban construction and renewal.

KEYWORDS

climate change, land surface temperature, nonlinear relationships, random forest regression, urban cold island effect, Zhengzhou City

1 Introduction

The urban heat island effect has become one of the most pressing ecological and environmental challenges globally, due to the rapid acceleration of global urbanization (Yu et al., 2019b; Liang et al., 2020; Ren et al., 2021). Urban parks formed by landscapes including bodies of water and green vegetation are effective ways to alleviate the urban heat island effect and improve local thermal environments (Santamouris et al., 2011; Sun et al., 2012; Gunawardena et al., 2017). These parks are known as "urban cold islands (UCIs)" and have attracted widespread attention for their potential in enhancing the UCI effect and mitigate increasingly strong urban heat island effects.

Promoting the UCI effect is key in developing sustainable, resilient, and adaptive urban ecosystems (Kong et al., 2014a; Yu et al., 2021; Çevik Değerli and Çetin, 2022). Blue-green spaces in cities serve as efficient heat regulation mechanisms, improving the urban thermal environment and thereby mitigating the urban heat island effect. Specifically, urban green spaces provide cooler outdoor environments via direct shading during the day and evapotranspiration at night (Fan et al., 2019; Yu et al., 2023), while urban blue spaces decrease air temperatures through their high evaporation rates and specific thermal capacitance (Huanchun et al., 2020; Xi et al., 2023). By enhancing vegetation coverage and integrating water bodies, these spaces can lower the surface temperatures of buildings and roads, reduce heat radiation, and generate cooler climatic conditions, which can contribute to more enjoyable outdoor environments for urban residents (Cetin, 2020; Adiguzel et al., 2022). Additionally, blue-green spaces fulfill vital ecological functions such as improving urban air quality, absorbing carbon dioxide, purifying water bodies, enhancing biodiversity, and providing habitat and ecosystem services (Bozdogan Sert et al., 2021; Zeren Cetin et al., 2023a; Zeren Cetin et al., 2023b). They also help address water resource issues, mitigate flood risks, and enhance urban resilience (Yumino et al., 2015; Zhao et al., 2021; Adigüzel and Çetin, 2022). Considering these benefits, a more in-depth understanding of the variables that influence the cooling effects of blue-green spaces and their function could offer crucial insights into further mitigating the urban heat island phenomenon.

A strong correlation exists between blue-green spatial patterns and land surface temperature (LST) (Sun and Chen, 2017; Xue et al., 2019; Lan et al., 2022), with the degree of cooling being dependent on the size, shape, connectivity, and complexity of blue-green spaces (Gunawardena et al., 2017). For example, the size and distribution of urban green spaces considerably influence their ability to alleviate the heat island effect (Huanchun et al., 2020). Moreover, many landscape indicators, such as landscape shape index and patch density, have been widely used to reveal the relationship between the geometric properties of blue-green space and the UCI effect. The patch density and average patch size of vegetation play a key role in its cooling capacity (Lu et al., 2012; Kong et al., 2014b). Additionally, surface UCI intensity is negatively correlated with patch density and the average patch shape of the green space (Gao et al., 2022). Although these studies explain the relationship between variables and surface temperature, there is less discussion of the case of urban parks with both water and green space. To date, there is no academic consensus on how to improve the urban thermal environment through UCIs.

Cities are complex nonlinear open systems with high levels of uncertainty (Gallopín, 2020; Padovan et al., 2022). To simplify the research process, most studies on the UCI effect currently rely on linear models for analysis (Li et al., 2019; Xue et al., 2019; Liu et al., 2021). However, these models are inappropriate when variables are cross-correlated, and their use can lead to misleading results (Belgiu and Drăguţ, 2016; He et al., 2022). For example, Guha and Govil (2021) and Ullah et al. (2023) found that LST decreases with an increasing normalized difference vegetation index in green areas. Jaganmohan et al. (2016) discovered that small, intricately shaped green spaces have a negative impact on cooling, whereas green space areas larger than 5.6 hectares have a positive effect. However, larger blue-green spaces do not necessarily lead to better UCI effects. According to Cheng et al. (2015), large parks are not more advantageous than small parks in terms of lowering surrounding temperatures. Other studies support this finding, indicating that park size has a threshold in terms of cooling efficiency (Yu et al., 2020; Kraemer and Kabisch, 2022; Li et al., 2022). Once the threshold is exceeded, the cooling efficiency of urban parks will significantly decrease, which has implications for urban park planning and management. In addition, these models are highly sensitive to outliers and may not accurately represent the complex relationships between various factors (Sharma et al., 2011; Mohammad and Pradhan, 2021; Xiao et al., 2022a). Due to these limitations, traditional linear models often struggle to accurately describe UCI phenomena. Therefore, identifying an efficient and accurate nonlinear model is crucial for studying the UCI effect.

The random forest regression (RFR) model, an ensemble learning method based on decision trees, has been widely recognized as a powerful tool for studying the UCI effect (Wang et al., 2022a; Xiang et al., 2023). This model is specifically designed to analyze complex interactions among nonlinear and multi-dimensional independent variables. For instance, exploring the elements that influence the UCI effect during day/night using RFR models tend to lead to more in-depth results (Oukawa et al., 2022), and RFR exhibits good performance at different cooling distance scales (Wang et al., 2022b). Compared to traditional linear regression models, the RFR model offers several advantages. First, it does not require feature scaling or transformation, and can handle independent variables with different scales and units, allowing for more convenient and efficient processing of multi-dimensional data (Mishra et al., 2020). Additionally, the RFR model can capture nonlinear relationships between independent variables and the target variable (Fan et al., 2023), including nonlinear relationships and higher-order interactions, making it suitable for modeling complex relationships (Hatami Bahman Beiglou et al., 2021). Specifically, the RFR model has significant advantages in quantifying the threshold sizes of different landscape types (while accounting for the effects of landscape composition and configuration) to optimize the cooling efficiency of blue-green spaces. This is crucial for decision-makers and actionable urban park planning.

Improving knowledge on how to optimize the spatial configuration of cities to enhance UCI effect remains a prerequisite for creating sustainable cities. The present study aimed to investigate the impact of urban blue-green spaces on the UCI effect in Zhengzhou using remote sensing satellite images. After deriving surface temperature with atmospheric correction, we employed an RFR model to analyze the mechanisms influencing the UCI effect. Our study had the following aims: (1) to examine the spatial distribution of urban blue-green spaces and its influence on the UCI effect, and (2) to investigate the nonlinear relationship between LST and the variables related to urban blue-green spaces. The results of our study can expand our scientific understanding of the nonlinear influences of blue-green space characteristics on LST and PCI and provide a scientific basis for formulating sustainable and resilient urban parks and rational planning of the spatial layout of urban spaces.

2 Materials and methods

2.1 Study area

This study was conducted in Zhengzhou City (112°42'E–114°14'E, 34°16'–34°58'N), in Henan Province, central China. The region has a temperate and semi-humid continental climate with an average summer temperature of 19–30 °C. Zhengzhou is an important emerging city in Asia with a diversity of blue-green spaces. However, rapid urbanization and climate change have generated thermal environment problems in Zhengzhou. In June 2022, the city reached a historic maximum temperature of 42.3°C, highlighting the urgent need for research on how to improve living conditions and mitigate the impacts of increasingly frequent extreme urban heat events.

2.2 Data sources

Remote sensing data were obtained from Landsat-8 OLI/TIRS satellite images on July 16, 2020, with good imaging quality, clear ground features, and no clouds and/or band stripe. The spatial resolution was 30 m. To mitigate the impact of atmospheric conditions on the quality of remote sensing images, the multi-spectral bands underwent radiometric calibration and atmospheric correction.

Urban surface types were categorized into blue, green, and built-up areas using a supervised classification approach. The analysis was ultimately performed on 114 well-developed urban blue and green spaces in the central part of the city, with reference to the high-definition images of HSPA-2 (Figure 1). Data processing was performed using ENVI 5.3 and ArcGIS 10.8.

2.3 Data processing and analysis

2.3.1 Retrieval of LST data

This study adopted an atmospheric correction method to retrieve the LST of built-up areas in Zhengzhou. First, the atmospheric influence on surface thermal radiation was estimated. This atmospheric influence was then subtracted from

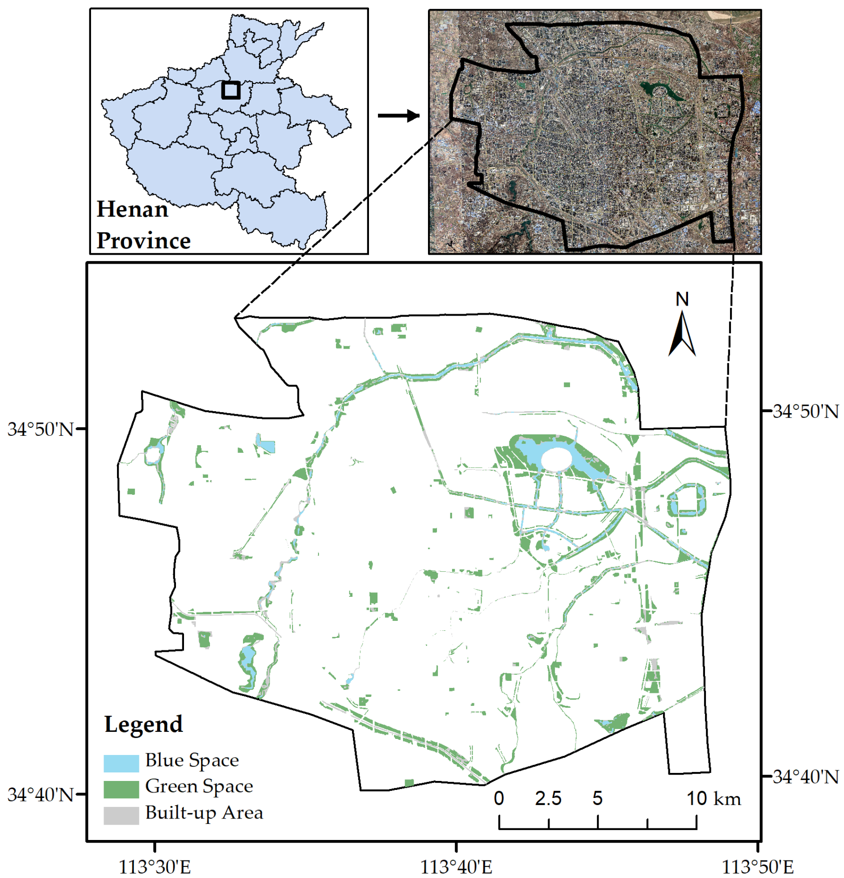

FIGURE 1
Distribution of blue and green spaces in central Zhengzhou during 2020.

the total thermal radiation observed by satellite sensors, yielding surface thermal radiation intensity, which was subsequently converted into a corresponding surface temperature using the following equations (Chibuike et al., 2018):

$$T_s = K_2/\ln(\frac{K_1}{B(T_s)} + 1) \quad (1)$$

$$B(T_s) = [L_\lambda - L^\uparrow - \tau(1 - \epsilon)L^\downarrow] \quad (2)$$

$$L_\lambda = [\epsilon B(T_s) + (1 - \epsilon)L^\downarrow]\tau + L^\uparrow \quad (3)$$

where ϵ is surface specific emissivity, T_S is surface true temperature, $B(T_s)$ is blackbody thermal radiation brightness, is atmospheric transmittance, $L^\uparrow$ is atmospheric upward radiation brightness, $L^\downarrow$ is atmospheric downward radiation energy, L_λ is thermal infrared radiation brightness. K_1 and K_2 are coefficients, with $K_1 = 774.885\ \mathrm{W} \cdot \mathrm{m}^{-2} \cdot \mathrm{sr}^{-1} \cdot \mu\mathrm{m}^{-1}$ and $K_2 = 1321.079\ W \cdot m^{-2} \cdot sr^{-1} \cdot \mu m^{-1}$.

2.3.2 Variable selection and measurement

To comprehensively evaluate the influence of urban blue-green spaces on UCI, variable selection was conducted based on three aspects.

First, variables were selected based on existing research on the relationship between urban green-blue spaces and UHI. Previous studies have shown that the cooling effect of UCI is related to the vegetation coverage of the urban blue-green space (Alavipanah et al., 2015) as well as its geometric attributes, such as width (Peng et al., 2021), water body area (Xue et al., 2019; Liu et al., 2022), and proportion (Sun and Chen, 2017). This ensures that the chosen variables are correlated and can accurately analyze this relationship.

Second, the variables were divided into three categories to provide a more detailed understanding of the different aspects of urban green-blue spaces and avoid oversimplification, in order to reflect the complexity of urban green-blue spaces.

Third, the selected variables cover different aspects of urban green-blue space, such as area, width, density, and coverage, all of which affect UCI. This selection of variables is supported by existing research and rational reasoning, providing a comprehensive and detailed approach to studying the relationship between urban green-blue space and UCI.

As a result, this study selected blue-green space area and width, patch and edge density, percentage of blue and green space, blue and green space area, and fractional vegetation cover as variables with strong influence on UCI (see Table 1 for abbreviations and categories). Variable values were calculated using the satellite images and the following equations (Figure 2).

Patch density (PD) is the degree of landscape fragmentation and reflects an area's spatial complexity. It is calculated using the following formula:

$$PD = \frac{N_i}{A_i} \quad (4)$$

where N_i is the number of patches in blue-green space i and A_i is the total area of blue-green space i.

Edge density (ED) reflects the degree of blue-green spatial fragmentation, meaning that the larger the value, the higher the fragmentation. It is calculated using the following formula:

$$ED = \frac{E_i}{A_i} \quad (5)$$

where $\boldsymbol{Ei}$ is the total boundary of blue-green space i and A_i is the total area of blue-green space i.

Park cooling intensity (PCI) was also used to evaluate the cooling effect of urban blue-green spaces. This variable is determined based on the difference between a given temperature range inside and outside the blue-green space. It is calculated using the following equation (Cao et al., 2010; Chibuike et al., 2018):

$$PCI = \Delta T = T_u - T_P \quad (6)$$

where T_u denotes average surface temperature within a certain range outside the boundary of the blue-green space and T_P denotes LST within the blue-green space. The 500 m surrounding the blue-green spaces of central Zhengzhou were selected as the cooling areas for PCI, as per previous studies (Cao et al., 2010; Chibuike et al., 2018; Huanchun et al., 2020).

TABLE 1 Selection of variables with a strong relationship to UCI.

Variable Type	Variable Name	Abbreviations	Unit
Blue-green space	Blue-green space area	BGSA	ha
	Blue-green space width	BGSW	m
	Patch density	PD	—
	Edge density	ED	km/ha
Blue space	Percentage of blue space	BSP	%
	Blue space area	BSA	ha
Green space	Percentage of green space	GSP	%
	Green space area	GSA	ha
	Fractional vegetation cover	FVC	—

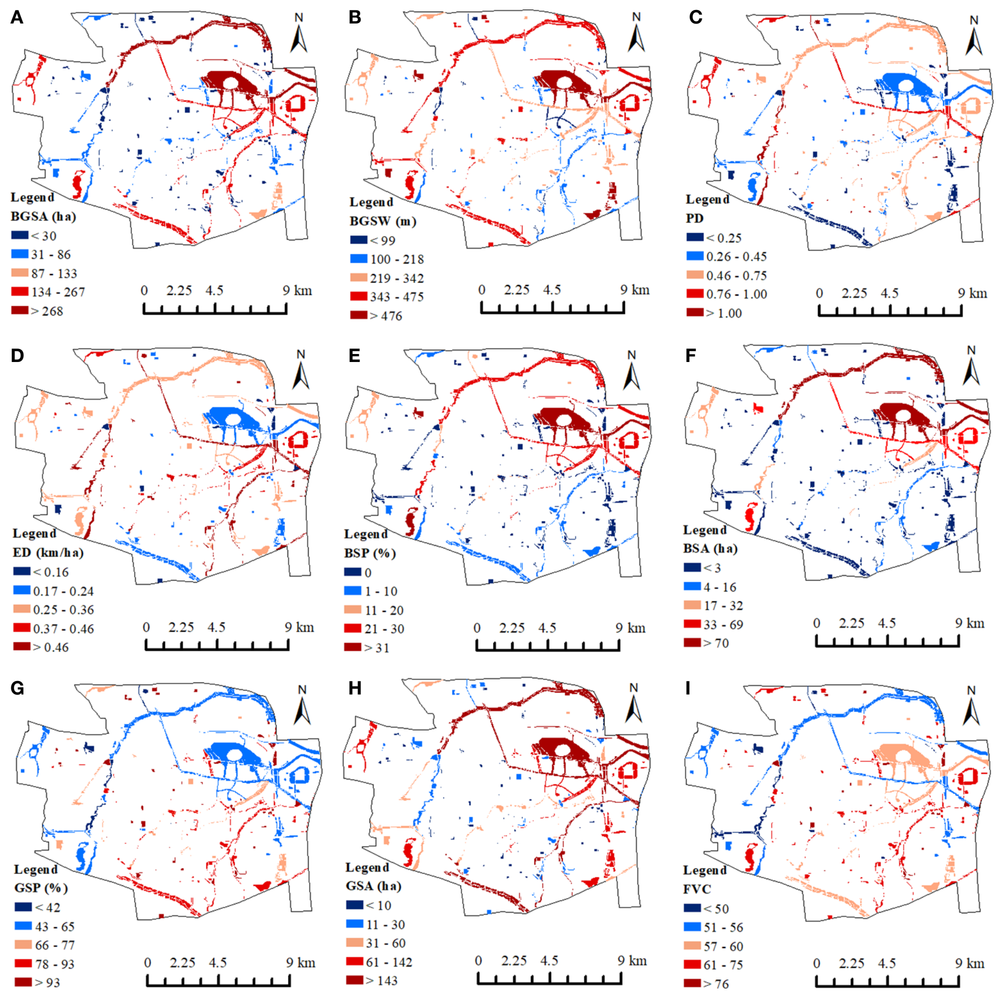

FIGURE 2
Variable measurements in central Zhengzhou. **(A)** BGSA (ha); **(B)** BGSW (m); **(C)** PD; **(D)** ED (km/ha); **(E)** BSP (%); **(F)** BSA (ha); **(G)** GSP (%); **(H)** GSA (ha); and **(I)** FVC (%). See Table 1 for definitions of variable abbreviations.

2.3.3 RFR

The RF model is a machine-learning algorithm that can process large amounts of data quickly and accurately (Sharma et al., 2011). The RFR algorithm is formed by integrating multiple decision tree models $\{h(X, \theta_k), k = 1, 2, \dots\}$ (Breiman, 2001), as follows:

$$P(x) = \left(\frac{1}{K}\right)\sum_i^K h(X; \theta_k) \tag{7}$$

where $P(x)$ is the result of the RF combination model and p_i is the single-tree regression model.

Using the "Random Forest" package in R, the relationship between UCI variables and surface temperature was evaluated. Variable importance was assessed with two measures: percentage increase in mean squared error (%IncMSE) and increased node purity (IncNodePurity) (Gao et al., 2022; Oukawa et al., 2022; Wang et al., 2022b). The %IncMSE reflects a given variable's contribution to the prediction accuracy of the target variable, whereas IncNodePurity measures the difference in the root sum of squared errors before and after the variable's split, as determined by the Gini index. Partial dependence plots were used to reveal complex dependence patterns among independent variables.

3 Results

3.1 Spatial patterns of urban thermal environment

Urban parks with blue-green space area (BGSA) > 100 ha were predominantly situated on the outskirts of Zhengzhou City, such as Longhu Park in the northeast and Riverside Park on the periphery (Figure 2A). Urban parks with BGSA< 30 ha were mainly located in the older Zhengzhou City center. Urban parks with BGSA > 134 ha had an average of 21% of blue space (BSP), indicating that larger BGSA also tended to contain more blue space (Figure 2E). The distributions of PD and ED were similar; both were higher in long or sprawling riverfront parks along the urban periphery (Figures 2C, D).

Our analysis demonstrated that the urban thermal environment and the spatial patterns of urban blue-green spaces were highly correlated (Figure 3). Built-up areas had higher temperatures than the urban blue-green spaces (Table 2). Furthermore, average temperatures were higher in the southeastern and western parts of Zhengzhou, with dense residential areas, but lower in the northeastern part, which contains large parks. The highest temperature (51°C) was recorded in a built-up area, whereas the lowest temperature (27°C) was recorded in a blue-green space. Overall, average temperatures in the blue-green spaces were 2°C lower than the average in built-up areas and 1°C lower than the average in the entire study area. The maximum temperature in blue-green spaces was 8°C lower than in the built-up areas and the entire study area.

3.2 Importance of Variables Influencing UCI

Our regression models were constructed using LST and PCI as dependent variables and blue-green spatial metrics as independent variables. We used root mean square error (RMSE), mean absolute error (MAE), and R-squared (R^2) to quantify the accuracy of each regression model. The RMSE, MAE, and R^2 were 0.767, 0.643, and 0.752, respectively, for LST. The RMSE, MAE, and R^2 were 0.742, 0.641, and 0.673, respectively, for PCI. R^2 is the squared correlation between observed and predicted values. The MAE is the mean absolute difference between observed and predicted values, whereas RMSE is the deviation between observed and predicted values; the former metric is less sensitive to outliers than the latter. A higher R^2, in combination with lower RMSE and MAE, indicates greater model accuracy.

In terms of %IncMSE, the top five variables affecting LST were BSP, fractional vegetation cover (FVC), blue space area (BSA), BGSA, and PD (Figure 4). In terms of IncNodePurity, the top five variables affecting LST were BSP, FVC, BSA, BGSA, and ED. Thus, BSP, FVC, and BSA were the three key factors influencing LST.

In terms of %IncMSE, the top five variables affecting PCI were blue-green space width (BGSW), FVC, PD, BGSA, and green space area (GSA). In terms of IncNodePurity, the top five variables were BGSW, FVC, PD, ED, and BGSA. Therefore, the three most important variables for determining PCI were BGSW, PD, and FVC.

3.3 Biased dependence of UCI variables

Partial dependence plots indicate that LST was negatively correlated with BGSA, BGSW, PD, BSP, BSA, GSA, percentage of green space (GSP), and FVC, but positively correlated with ED (Figure 5).

Among these variables, LST peaked at 36.37 °C when BGSA was close to 0 ha, decreased when BGSA reached 24 ha, but did not considerably change beyond that size. Therefore, increasing BGSA has diminishing returns for urban LST past a certain threshold value. Similarly, the thresholds for BSA and GSA were 19 ha and 24 ha, respectively, beyond which they had no significant effect on LST. This result suggests that urban blue-green spaces can be effective even when maintained at a scale that balances the needs of other urban sites. Next, BSP exhibited a step-like pattern, first causing a considerable cooling effect at 0–3%, then cooling further at 20–27% before stabilizing. Thus, the presence of blue space lowered the surface temperature. Green space also lowered temperatures, but exhibited a different trend; at 70%, GSP exhibited a small cooling effect, whereas, at 95%, LST decreased rapidly. This may be attributed to an interaction between green space density and microclimate regulation.

Our results also suggest that fragmenting and simplifying blue-green spaces can improve LST. We observed that LST decreased as PD increased, but only after PD was less than 0.6. This result indicates that some degree of landscape fragmentation is conducive to lowering LST; however, after a given threshold, fragmentation will not substantially alter LST. In contrast, when ED was between

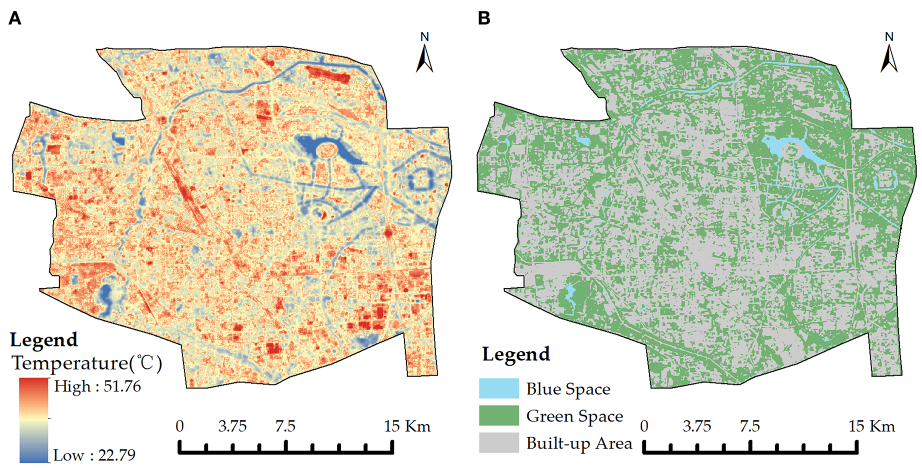

FIGURE 3
Inversion results of surface temperature in central Zhengzhou during 2020 **(A)** and spatial distribution of blue and green spaces **(B)**.

TABLE 2 Urban thermal environment during 2020 in Zhengzhou.

Study area	Average temperature (°C)	Minimum temperature (°C)	Maximum temperature (°C)
Blue-green space	37	27	48
Built-up area	39	28	56
Full site	38	27	56

0.2–0.3, LST rose rapidly, indicating that simplifying the shape of blue-green spaces is conducive to maintaining a lower LST. Subsequently, LST showed a slight decrease when ED was 0.40 and 0.67. Finally, FVC exhibited a stepwise effect, causing a decrease in LST at 56%, 66%, and 78%, although the final change in LST was less apparent.

Partial dependence plots revealed that PCI was positively dependent on BGSA, BGSW, PD, BSP, BSA, GSA, and FVC, but negatively dependent on ED (Figure 6). The threshold values for BGSA, BSA, and GSA were 24 ha, 19 ha, and 25 ha, respectively; BGSW caused a small peak in PCI at 140 m and a higher peak at 310 m. Additionally, PCI remained high, with small fluctuations, at BSP = 4%. When the GSP was below 61%, PCI was consistently low, whereas, at other percentages, PCI oscillated considerably, resulting in higher PCI when GSP was between 61% and 88%.

Similar to the LST results, the threshold for PD was 0.6, with PCI being the lowest at this value. For ED, PCI was highest at 0.10 and the second-highest at 0.45. As ED increased, PCI exhibited low to moderate levels of fluctuation. Lastly, FVC again caused a stepwise effect; PCI rose slightly at 56% and then rapidly at 73%, then stabilized when FVC reached a high value of 79%.

4 Discussion

4.1 Effects of urban blue-green space distribution patterns

Our findings suggest that the distribution of urban blue-green spaces and UCI is highly correlated with urban development paths

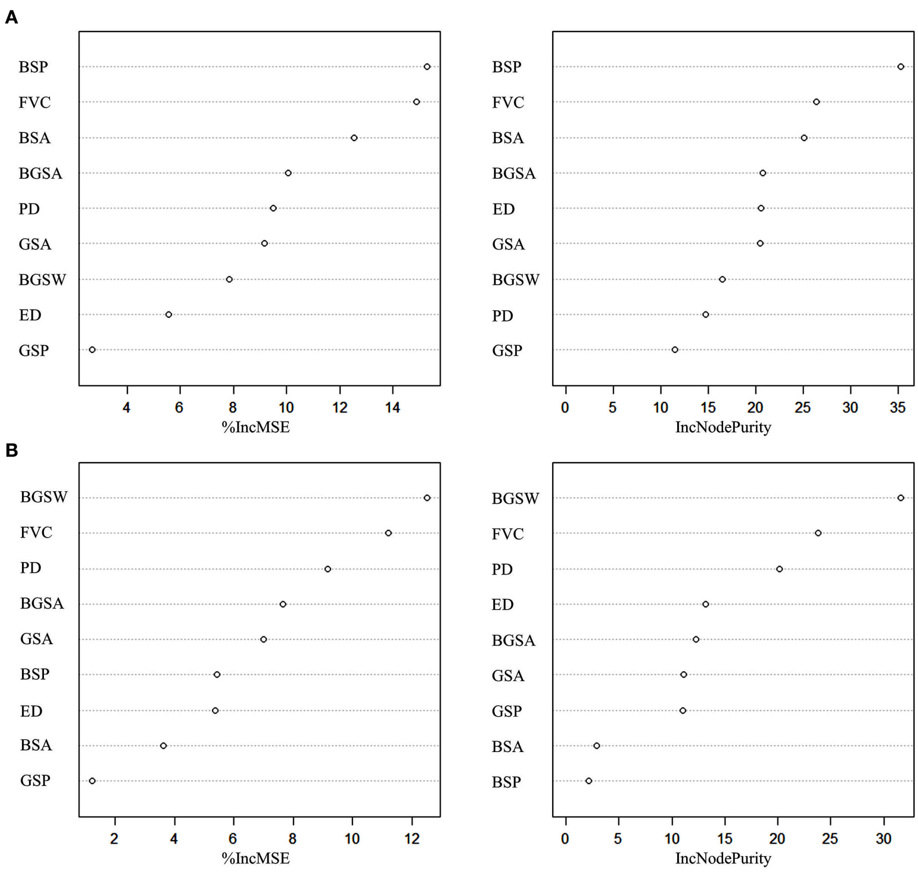

FIGURE 4
Importance ranking of blue-green space variables in influencing LST **(A)** and PCI **(B)** based on percentage increase in mean squared error (%IncMSE) and increased node purity (IncNodePurity).

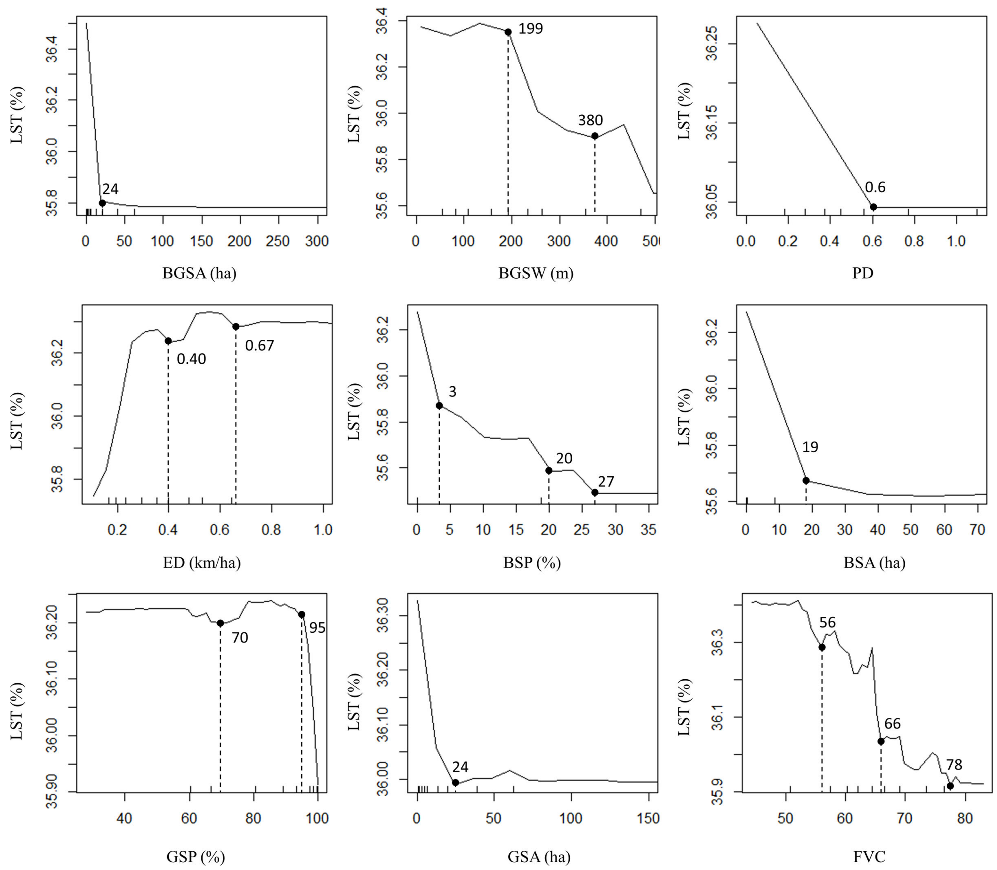

FIGURE 5
Bias dependence analysis for LST.

in Zhengzhou City. This study conducted a comprehensive examination of hotspot and coldspot distributions of urban LST using the ArcGIS spatial hotspot analysis tool. The results were categorized into three distinct categories: spatial aggregation greater than zero (hotspot), spatial aggregation equal to zero (random), and spatial aggregation less than zero (cold spot).

The central downtown area of Zhengzhou City exhibited a considerably higher temperature than the rest of the city (Figure 7). This concentration of heat is linked with the high concentration of urban development aimed at addressing housing shortages in the older downtown region. The prioritization of buildings over public blue-green spaces has resulted in a pronounced heat island effect (Yu et al., 2019a; Saha et al., 2021; Xue et al., 2022). Conversely, the low-temperature center was in the northeast, corresponding to Zhengdong New Area, which has comprehensive environmental construction and features numerous large urban parks that regulate the local climate (Kwak et al., 2020).

Urban planning is the main driving force behind the blue and green spatial patterns of cities. Effective urban planning that produces a reasonable blue-green spatial layout can considerably influence the thermal environment of cities (Lemoine-Rodríguez et al., 2022; Wu et al., 2022; Chang et al., 2023). To create a balanced urban thermal environment, it is necessary reconsider current urban planning strategies and prioritize a more comprehensive approach to blue and green infrastructure development. These improvements should include increasing the proportion of blue-green spaces to alleviate high temperatures in the old city center (Liu et al., 2023; Qi et al., 2023; Zhu and Yuan, 2023). In general, plans for urban renewal should take blue-green spaces in the downtown area into consideration, prioritizing a decentralized arrangement that increases the proportion of such spaces in high-temperature regions.

4.2 Comparison of regression models for predicting the UCI effect

Table 3 displays the error and fitting performance of the RFR model vs. other models in studying the UCI effect. Representative regression models were selected, including nonlinear (i.e., RFR, Back Propagation Neural Network Regression (BP Neural Network Regression), XGBoost Regression, and Decision Tree Regression) and linear (i.e., Multiple Linear Regression (MLR), Ridge Regression, Lasso Regression, and Partial Least Squares Regression (PLS Regression)) models (Lach et al., 2021; Lin et al., 2022; Xiao et al., 2022b; Wang et al., 2023).

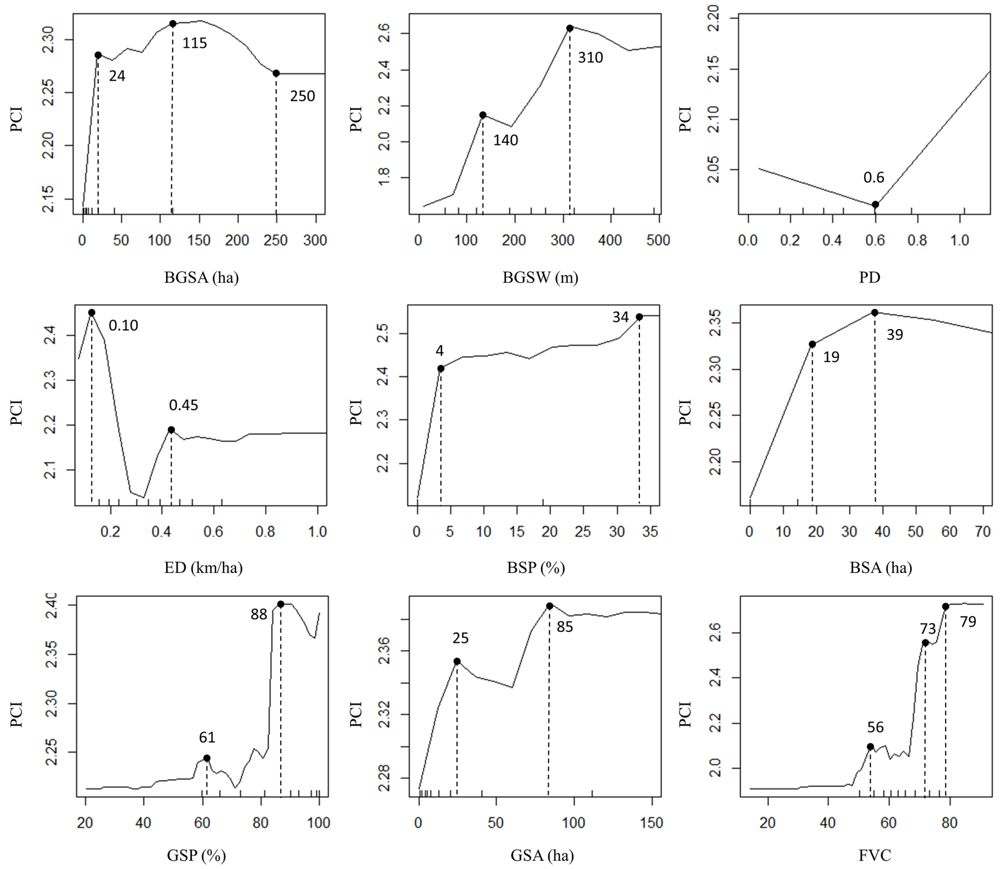

FIGURE 6
Bias dependence analysis for PCI.

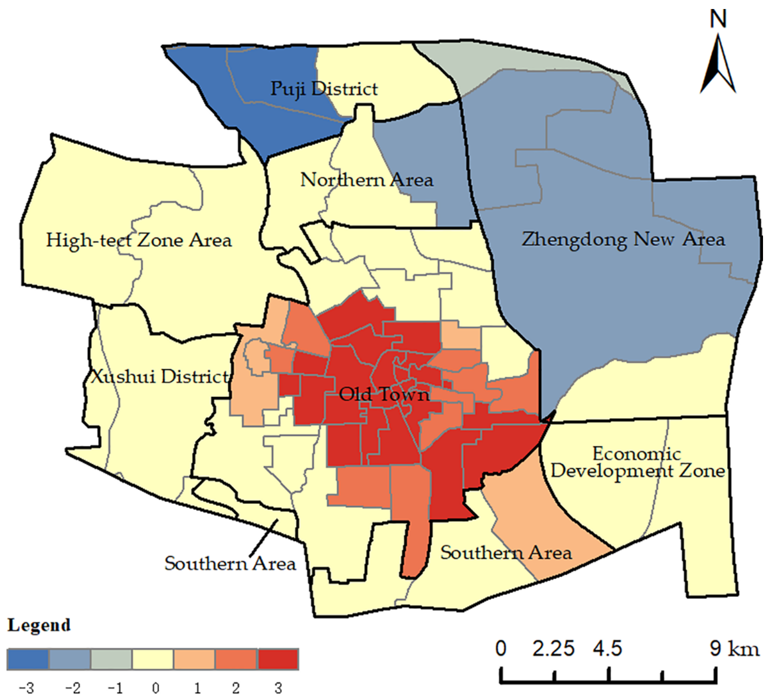

FIGURE 7
Coldspot/hotspot analysis of LST in Zhengzhou.

TABLE 3 Comparison of various regression models.

Model type	Dependent variable	LST			PCI		
	Regression Model	RMSE	MAE	R^2	RMSE	MAE	R^2
Nonlinear	Random Forest Regression (RFR)	0.767	0.643	0.752	0.742	0.641	0.673
	Back Propagation Neural Network Regression (BP Neural Network Regression)	0.993	0.767	0.609	0.821	0.689	0.444
	XGBoost Regression	1.142	0.913	0.616	1.251	1.041	0.37
	Decision Tree Regression (DTR)	1.247	1.042	0.468	1.501	1.157	0.305
Linear	Multiple Linear Regression (MLR)	1.021	0.845	0.545	1.212	0.937	0.28
	Ridge Regression	1.032	0.851	0.535	1.216	0.942	0.275
	Lasso Regression	1.038	0.86	0.529	1.216	0.945	0.274
	Partial Least Squares Regression (PLS Regression)	1.143	0.964	0.429	1.292	0.98	0.181

The nonlinear regression models performed better overall. Among the nonlinear regression models, RFR had the best performance with the lowest RMSE and MAE values, and the highest R^2 value, indicating more accurate prediction and the strongest correlation with the dependent variable. RFR has advantages such as its capacity to handle high-dimensional data and identify the most important features, model complex nonlinear relationships, and its strong resistance to overfitting (Al-Aghbary et al., 2022; Qi et al., 2022). BP Neural Network Regression and XGBoost Regression also performed well, possibly because these models can automatically learn high-order relationships between features, making them for suitable for complex nonlinear problems. In contrast, linear regression models such as MLR, Ridge Regression, Lasso Regression, and PLS Regression performed relatively poorly, possibly because they did not consider the interactions between features or effectively screen or reduce these features.

4.3 Impact of variables on urban LST and PCI

4.3.1 Key factors affecting LST

The three most important variables that influenced urban LST were BSP, FVC, and BSA. Blue space had a greater impact on LST than green space. Our findings are in line with previous research using correlations (Xue et al., 2019), RF models (Wang et al., 2022b), and logit fitting models (Feng and Shi, 2012), all confirming that the proportion and area of water bodies affect park LST markedly more than green spaces. Water has a greater heat capacity than impermeable surfaces, lowering temperatures in summer and elevating the intensity of UCIs (Wang et al., 2019b; Yang et al., 2020; Zhou et al., 2022).

In urban parks, green spaces are often larger in area than blue spaces. Thus, FVC in green spaces also plays an important role in influencing the UCI effect (Wiens et al., 1993; Algretawee, 2022). Transpiration is the main mechanism underlying the surface cooling effect of urban vegetation (Wang et al., 2019a; Al-Saadi et al., 2020). Several prior studies have demonstrated the impact of vegetation cover specifically. Wang et al. (2020) used ordinary least squares linear regression and determined that the percentage of trees accounted for 40.3% of the mean LST variation. Additionally, vegetation cooling efficiency was found to be highly correlated with FVC (Yang et al., 2022b).

Notably, the spatial resolution of remote sensing images may affect green area estimation. Green area pixels may contain a small number of other land types, resulting in a mixed signal when analyzing remote sensing images. As a result, when considering green areas, the influence of FVC on the UCI effect is greater than the influence of other variables, such as GSA.

4.3.2 Key factors affecting PCI

The three most important variables that determine PCI were BGSW, FVC, and PD. Parks with narrower BGSW tended to have a longer border with the adjacent urban environment, allowing for more exchange of cold air. This effect then decreases the temperature difference between cold islands and the surrounding region, reflecting a lower PCI.

Similarly, the role of PD in determining PCI can be attributed to landscape fragmentation. As PD increases, landscape fragmentation increases, resulting in a more complex patch shape that limits local ecological circulation and airflow exchange (Luck and Wu, 2002). However, energy flow is accelerated between the park and its surrounding thermal environment, thus decreasing the temperature difference and PCI.

The effect of FVC on PCI is based on a different mechanism. Green space generates a local microclimate of heat-energy exchange with air through photosynthesis and transpiration (Lu et al., 2012). Moreover, the tree canopy emits long-wave cold radiation to the surrounding environment, lowering the temperature of adjacent areas, which increases the temperature difference and PCI (Berry et al., 2013). A dense tree canopy would also impair airflow exchange between the park microclimate and the surrounding environment, further intensifying PCI.

4.4 Nonlinear mechanisms of variables influencing UCIs

Existing linear regression models are limited in their capacity to accurately depict the complexity of the UCI effect and account for correlations between influencing variables. Multiple studies using linear regression models have identified multicollinearity when investigating UCI. For example, a previous study reported correlation coefficients ranging from 0.105 to 0.214 (Cai et al., 2018). Partial correlation analyses (Peng et al., 2021) and Pearson's coefficients (Peng et al., 2016) yielded a maximum correlation of 0.6. In the present study, our RF algorithm obtained an R^2 value of 0.85, indicating that multiple variables jointly regulate the cooling effect of blue-green spaces. Multicollinearity constraints thus hamper the accuracy of linear models (Logan et al., 2020; Lu et al., 2021).

Fortunately, the RFR model eliminates variable autocorrelation. Our RF-based analysis revealed that the effects of individual variables on LST and PCI were not linearly correlated. Instead, the effects changed or ceased to be important after a critical threshold. Before this threshold, variables had a direct relationship with the UCI effect. Similarly, previous research on park parcels and the UCI effect showed that beyond a given size threshold, land plots can form a relatively independent internal space, creating a microclimate and maintaining a stable regional ecology and airflow exchange (Geng et al., 2022; Yang et al., 2022a). As a result, their effect becomes nonlinear.

The findings of the present study indicate that urban green-blue spaces effectively regulate surface air temperatures. With an increase in the surface area of these spaces, the marginal cooling effect becomes more pronounced. Therefore, an increasing global population will further exacerbate the strain on urban land resources that are needed to provide housing and ecosystem services. In future blue-green space management in cities, the threshold values we identified could be used to determine the shape and size of green-blue spaces that would optimize their UCI effect; specific factors to consider are maintaining a certain scale and ratio of blue space, increasing FVC, and forming regularly shaped plots.

5 Conclusions

In the context of escalating urbanization and climate change, our study of the spatial characteristics of urban thermal environments offers crucial insights. By investigating the nonlinear relationships between the UCI effect and its causal variables, we identified key factors that influence the cooling effects of blue-green spaces in urban areas.

Our study suggests that the distribution of UCIs follows urban developmental paths influenced by urban planning, and is closely related to the distribution of urban blue-green spaces. Central downtown areas have a pronounced heat island effect due to the prioritization of buildings over public blue-green spaces. To create a balanced urban thermal environment, cities must prioritize a more comprehensive approach to blue and green infrastructure development.

Our study identified several key factors that determine the cooling effects of blue-green spaces in urban areas, including BGSA, BSA, GSA, BSP, and GSP, which determine how effectively these spaces can mitigate the urban heat island effect. The nonlinear relationships between these variables highlight the importance of maintaining an optimal spatial area and appropriate proportions of blue-green spaces to maximize their cooling effects and improve the urban thermal environment. We should also avoid excessive fragmentation and simplification of blue-green spaces to maintain their integrity and connectivity. Urban planning should consider these nonlinear relationships when designing urban blue-green spaces on limited urban land. We can apply these strategies when constructing and renewing urban blue-green spaces to create cooler urban areas and mitigate the impacts of climate change. Our study provides data that may inform more optimized use of blue-green spaces in urban development.

In conclusion, our study provides valuable insights into the efficient use of blue-green spaces in urban construction and renewal to mitigate the urban heat island effect and improve urban thermal environments. By optimizing blue-green space variables such as area, proportion, and vegetation cover, urban planners can effectively create cool urban areas and reduce the negative impacts of climate change. By incorporating our insights into urban planning and promoting the development of sustainable green infrastructure, cities worldwide can mitigate the urban heat island effect to improve quality of life for their urban inhabitants.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

Conceptualization, SQ; Data curation, SQ; Formal analysis, SQ; Funding acquisition, MJL and TL; Investigation, MHL and HL; Methodology, SQ; Project administration, TL; Resources, YC; Supervision, MJL, TL and YC; Validation, SQ; Visualization, SQ; Writing – original draft, SQ; Writing – review & editing, TL. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Boundary green infrastructure: a green infrastructure connecting natural and artificial spaces

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As a naturally-based solution (NBS), green infrastructural network constructing can improve urban ecological resilience and support sustainable urban development. However, as the Frontier of urban expansion, the boundary of built-up areas has little research on the boundary green infrastructure (BGI) connecting natural and artificial spaces. In order to make up for the shortcomings of relevant research, we propose a method for identifying BGI and analyze its landscape pattern characteristics. We selected 15 European cities as cases to extract the boundaries of built-up areas. Moreover, we used morphological pattern analysis (MSPA) to identify the ecological source and select the best distance threshold for the landscape connectivity model to identify the BGI range. Through the gradient area method and MSPA, the BGI landscape pattern characteristics of the case cities were analyzed quantitatively. The BGI scale was affected by the area of the built-up area and the threshold of GI landscape connectivity distance. Additionally, the BGI space contained a small number of large ecological sources and many scattered and small fragmented patches. The best landscape model of BGI was the surrounding pattern, followed by the aggregation pattern, which had good landscape connectivity; however, the fragmentation of the scattered pattern was high. Lastly, the ecological core area in BGI was the main landscape type; it has a high landscape connection function for the GI network inside and outside the built-up area and promotes biological exchange inside and outside the built-up area. This study proves that BGI has an important ecological significance, can guarantee the scientific nature of the NBS method, and ensures the ecological security pattern of cities.

KEYWORDS

green infrastructure, BGI, boundary green infrastructure, urban development, ecological resilience, biodiversity

1 Introduction

The rapid development of urbanization has caused many ecological problems, severely degrading the city's and surrounding areas' environment (Peng et al., 2018a). The ecosystem has been unable to bear the ecological pressure brought by urban development, leading to the decline of the ecological resilience of the city (Jie Yi et al., 2022). Balancing ecological protection and urban construction and realizing sustainable urban development has become a pressing

Abbreviations: NBS, Naturally-Based Solution; BGI, Boundary Green Infrastructure; MSPA Morphological Spatial Pattern Analysis; UGI, Urban Green Infrastructure; RGI, Rregional Green Infrastructure; NL, Number of Links between patches; LC, Landscape omponent score.

problem worldwide (Kabisch et al., 2017; Su and Haonan, 2022). Naturally-based solutions (NBS) emerged as a new approach to social challenges in this context (Mackinnon, 2008; Eggermont et al., 2015). The green infrastructure (GI) network, as an NBS method (Nadja et al., 2016; Mabon, 2019), is an important strategy to enhance ecological resilience and achieve sustainable development (Panagopoulos et al., 2016; Song et al., 2018). As the Frontier of urban expansion, the contradiction between human activities and environmental protection is prominent (Manachini et al., 2013). Therefore, it is essential to study the GI located at the boundary of an urban built-up area for the research and practice of NBS.

GI is an ecological network formed by the interconnection of multi-functional natural areas and open green spaces (Tzoulas et al., 2007; Bartesaghi Koc et al., 2017). Landscape connectivity is the basis of species communication among ecological patches, and maintaining such connectivity is vital to ensure sustainable development (J. Peng et al., 2018b; Wimberly et al., 2018). Therefore, GI located at the boundary of urban built-up areas (BGI) must ensure the GI network structure's connectivity and functional transition inside and outside built-up areas. Chen et al. built GI networks in urban fringe areas to improve landscape patterns and enhance landscape connectivity (Cui et al., 2020; Zhong et al., 2020; Liang et al., 2022); however, few studies considered the multi-level landscape connectivity characteristics of GI in urban fringe areas. There are two main reasons for the fragmentation of GI networks inside and outside urban built-up areas. First, urban built-up areas are used as resistance surfaces for biological migration (Dong et al., 2020; Xindi Zhang, 2022). Second, the GI area in urban built-up areas is small; hence, they are not usually selected as ecological sources (Liuyang et al., 2018). Therefore, ignoring GI at the boundary of built-up urban areas negatively affects ecological processes, causing the separation of GI networks inside and outside built-up areas, and it is difficult to maintain the security and stability of the ecosystem. Therefore, a BGI range identification method can be established from the perspective of landscape connectivity characteristics to determine the GI space near the built-up area boundary that can generate effective landscape connections for internal and external GI networks.

BGI—an important connecting space of the GI network inside and outside built-up areas—comprises patches and corridors (Forman, 1995). Studies on GI patterns mostly focus on urban central areas and regional scales (Xiao Ran et al., 2015; Gu et al., 2017; Jiaxing et al., 2019; Jeong et al., 2020; Kan et al., 2021; Jiang et al., 2022). Additionally, analysis models, such as landscape pattern (Wang et al., 2019), landscape connectivity index, and landscape pattern index of GI (Huang et al., 2021; Modica et al., 2021), are usually applied to analyze and evaluate GI patterns based on specific scope and elements. However, studies on the spatial structure and landscape pattern characteristics of BGI are relatively weak. Studying the structural composition and landscape pattern characteristics of BGI helps reveal the GI network's structural characteristics and ecological processes, strengthen the connection degree of natural and artificial GI space, and improve the structural integrity.

As a part of the GI network, BGI is the NBS method for improving urban ecological resilience. Based on the landscape connectivity characteristics of BGI, we established the spatial identification method of BGI and analyzed its landscape pattern characteristics. Distance threshold is the maximum diffusion distance of biological flow used to determine the presence or strength of landscape connectivity between patches in the study area (Meng et al., 2016; Qinghe et al., 2017). As an important method to measure landscape patterns and function, the landscape connectivity model based on graph theory can obtain the optimal distance threshold (Almenar et al., 2019). In this study, we used PC, IIC, and other connectivity indexes to analyze and determine the optimal diffusion distance threshold. Based on this, the spatial range of BGI with landscape connectivity function for GI networks inside and outside the built-up area was defined. Moreover, we selected the gradient area and morphological spatial pattern analysis (MSPA) methods to evaluate the overall landscape pattern and structure of BGI. In this study, 15 United Kingdom, France, and German cities were selected as research objects. Based on ArcGIS, GuidosToolbox, and other software, MSPA and landscape connectivity model based on graph theory were adopted to identify the spatial scope of case BGI and analyze the landscape pattern. The results can provide a reference and basis for urban BGI spatial identification and pattern optimization.

2 Material and methods

The city is a complex system (Bonnes et al., 1990). Due to the high degree of human intervention inside the built-up area, urban green infrastructure (UGI) is mainly artificial green space integrating various ecosystem service functions (Chengcheng et al., 2021). The primary function of regional green infrastructure (RGI) outside built-up areas is to maintain ecosystem stability and protect biodiversity, including natural ecological spaces, such as woodland and grassland (Tang Xiaolan, 2011).

In this study, BGI is the GI located at the boundary of the urban built-up area, including a certain range of UGI and RGI on both sides of the boundary, which plays a role of landscape connection for the GI network between the built-up area and the region (Figure 1). In the BGI space, BGI connects the GI network inside and outside the built-up area, ensures multi-level landscape connectivity, and maintains the stability and biodiversity of the urban ecosystem. The primary functions of GI inside and outside the built-up area transition are to ensure that the biological flow in the regional GI network can move to the built-up area and extend the composite functionality of GI in the built-up area outward.

The study of BGI space in the cases is divided into two parts (Figure 2). First, delineating the BGI space scope, which involves two steps. a) Identifying the built-up area boundary of the case city. b) Determining the most suitable landscape connection distance threshold between the built-up area and the regional GI network of the case according to BGI's landscape connection characteristics. Second, analyzing the case cities' BGI spatial landscape pattern and structure.

The data in this study is mainly the land cover data of case cities in Germany, the United Kingdom, and France in 2020 (spatial resolution 30 m, data source: http://www.globallandcover.com/).

2.1 BGI spatial identification

2.1.1 Built-up area boundary extraction

The entropy analysis of land use types is an information model that expresses the richness and orderliness of land use types through the number of land use types and the proportion of the unit area

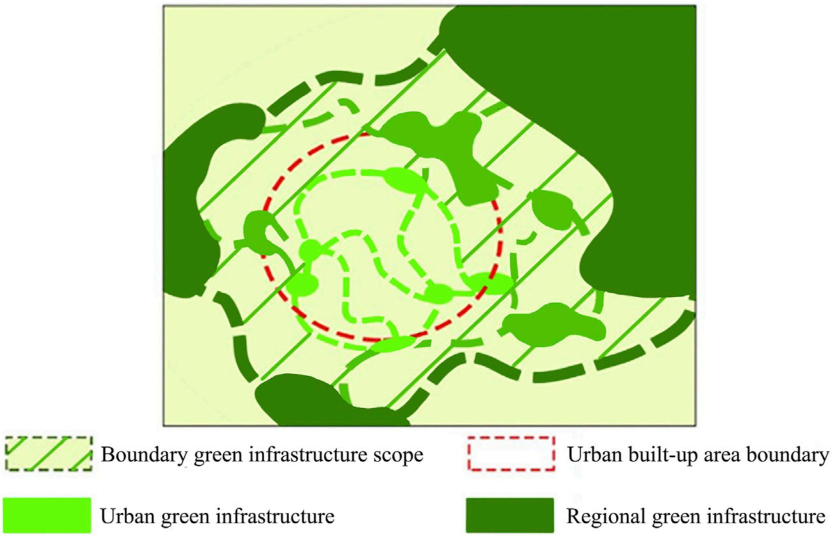

FIGURE 1
BGI location diagram.

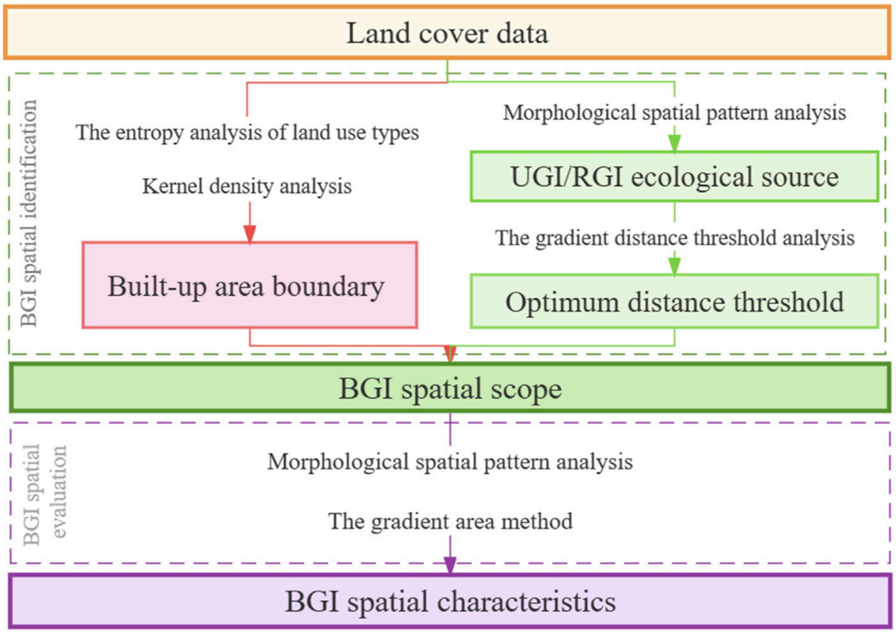

FIGURE 2
The methodological framework used in this study.

occupied by the types (Figure 3). Its principle is similar to that of thermodynamics, in which entropy represents the degree of molecular disorder in a thermodynamic system (Prunkl, 2018). We selected the standard deviation (S) of a simple statistical variable to represent the richness of land use type information. The formula is as follows:

$$S = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - u)^2} \tag{3–1}$$

Where S is the standard deviation; N is the number of land use types; x_i is the area percentage of a certain land type; u is the average area of land use type in the unit. The land cover raster data is reclassified into Built-up and Non-built-up lands. Notably, on both sides of the built-up area boundary, the land use type is single, and the information entropy is very low. However, the boundary of the built-up area, land use type changes, and information entropy increase. In this study, the standard deviation threshold of land use was set between 0.3 and 0.4, and the boundary of land use type

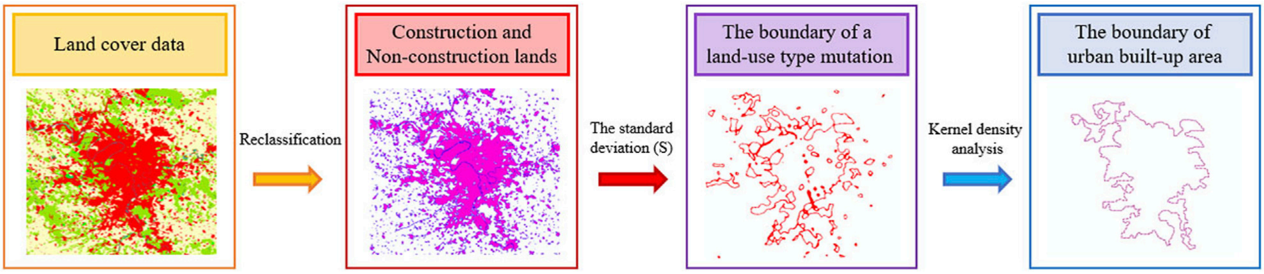

FIGURE 3
Urban built-up boundary extraction process.

with sudden change was selected and identified as the boundary of urban built-up area (Liuyang et al., 2018). However, this method gives the "salt and pepper particles" phenomenon and cannot extract a stable and clear built-up area boundary line; therefore, it requires correction.

Through kernel density analysis of the binary raster data of land type, the raster data is converted into vector point elements, and the result of boundary extraction of the built-up area is optimized. When the land type changes, the point density of a single attribute decreases rapidly, and the kernel density value drops sharply. Therefore, kernel density analysis can reflect the spatial boundary of a sudden change in land use type, and it is calculated as follows (Zhang and Lu, 2009):

$$f(x) = \sum_{i=1}^{n} \frac{1}{\pi r^2} \varphi\left(\frac{d_{ix}}{r}\right) \quad (3\text{–}2)$$

Where $f(x)$ is the comprehensive index value of core density per unit area; r is the search radius in km; n is the number of samples; d_{ix} is the distance between elements i and x in km; φ is the distance weight.

2.1.2 Ecological source selection

MSPA can identify ecological patches that significantly impact the ecological connectivity of the study area (Soille and Vogt, 2009). Notably, the MSPA method can only identify patches and corridors with ecological protection significance using land use raster data (Julien Carlier, 2019). According to morphology, spatial pattern, impact on the overall landscape connectivity, and other factors, the ecological land raster data is divided into seven non-overlapping landscape types (Nan-nan et al., 2021). The ecological core and bridging areas have high ecological connectivity and can protect regional biological diversity. This method has important significance in improving the scientific nature of ecological source selection.

Within the boundaries of built-up areas, the GI primarily enhances the function of recreation service, biodiversity protection is relatively weak, and the ecological land area is small. In this study, ecological patches with an area of ≥0.5 km^2 were selected as the ecological source area at the built-up area scale (He et al., 2019). At the regional scale, the ecological land within 50 km outside the built-up area boundary was selected for MSPA analysis based on the reachable range of species diffusion (Meng et al., 2016). As an important ecology for regional biodiversity conservation, the biological habitat must have sufficient scale. Therefore, the core area of ≥5 km^2 was selected as the ecological source area at the regional scale (MT et al., 2017).

2.1.3 Distance threshold selection

The gradient distance threshold analysis can identify the study area's most suitable landscape connection distance threshold (Baranyi et al., 2011; DU et al., 2019). We selected the threshold range of landscape diffusion distance in the built-up area and regional scale based on the study area and biological migration characteristics.

There are few tracks of large wildlife activities in urban built-up areas, and the study scale is relatively small (Wei al. 2009). Therefore, 15 distance threshholds at 200 m interval from 200 to 3,000, plus 4,000, 5,000 and 10000 selected to analyze of the built-up area scale. Outside the built-up area, combined with the characteristics of biological migration (Meng et al., 2016), we selected 1,000, 2,000, 2,500, 3,000, 3,500, 4,000, 4,500, 5,000, 5,500, 6,000, 6,500, 7,000, 7500, 8000, 8500, 9,000, 9500, 10000, 15000, 20000 m; therefore, 20 distance thresholds were used for regional scale analysis.

The stable range of landscape connectivity can be preliminarily determined using the number of links between patches (NL) and landscape component score (NC) as the indicators of landscape connectivity (Montis et al., 2019). Furthermore, the importance index of each BGI patch is calculated within the stable distance threshold range of landscape connection (Table 1). Moreover, by comparing the importance index of each patch, the most suitable threshold of landscape connection distance is determined. The higher the consistency of the index change trend of each patch, the more effective the selection of distance threshold (DU Zhibo al. 2019).

2.1.4 BGI spatial scoping

Using the boundary of the urban built-up area as the baseline, the best distance threshold for buffering UGI inward and outward of the boundary was determined. Additionally, the combination of the inner and outer buffer zones constitutes the BGI spatial range of the case city. This scope can ensure that BGI space has an effective landscape connection between the area and the GI of the built-up area and can identify the GI connection and transition space between the built-up area and the area.

TABLE 1 The interpretation of landscape connectivity indices.

Type	Index	Interpretation
Overall indices	Number of Links (NL)	Refers to the number of connections between habitat nodes in the landscape, i.e., between any two patches. If the distance is less than the set distance threshold, the number of links between the two patches is considered to exist
	Number of Components (NC)	It refers to a whole composed of patches connected functionally or structurally. An isolated node or plaque will form a component, and there is no functional relationship between different components
Patches importance indices	Patch comprehensive connectivity index (dIIC)	Calculate the index change value after removing a single patch to determine the importance of the integrated connectivity of the patch. The higher the integrated connectivity value, the higher the importance of the patch in the landscape
	Patch connectivity probability index (dPC)	It describes the probability of species moving between any two patches. The higher the index value, the higher the connectivity of patches in the landscape
	Patch coincidence pobability Index (dLCP)	The probability of patches being randomly connected as habitats represents the coherent role of patches in the landscape

TABLE 2 Definition of landscape type based on MSPA.

Landscape type	Ecological significance
Core	Larger habitat patches in foreground pixels, providing relatively larger habitats space for species; represents ecological sources of importance for protecting biodiversity
Bridge	Narrow area connected the cores, representing a corridor that connects patches in an ecological network; essential for biological migration and landscape connectivity
Edge	Similar to the Bridge, but only represents the corridors that communicate within the same core for the migration of internal species
Loop	Transitional zone between the core zone and the external non-green space, its width varies according to the migration characteristics of different species
Perforation	Transitional zone between the core zone and the internal non-green space, its width varies according to the migration characteristics of different species
Branch	Extending area of green space; only one end is connected to the green space
Islet	Isolated, broken small patches that are not connected to each other, with low connectivity

2.2 BGI spatial feature quantification

2.2.1 BGI landscape composition analysis

To ensure the stable development of ecological functions, ecological patches should have a specific scale (Urban, 2001; Baguette et al., 2013). The purpose of the gradient area method is to retain the habitat patches of great significance for biodiversity conservation and remove a large number of fragmented, isolated patches. Setting the area threshold by comprehensively considering the number of patches, patch area, and the proportion of screened patches to the total area of the ecological space can ensure that the basic ecological functions and processes are unaffected (Xiaolin et al., 2021). We extracted the continuously distributed forest land, grassland, and other vegetation cover land included in the BGI space as the BGI patch and calculated the patch area. Additionally, we selected 16 area thresholds between 0 and 3 km^2 in steps of 0.2 km^2 (Mao Quan et al., 2019). Next, we analyzed the changing trend of patch number, area, and proportion of total ecological land area with the area threshold to determine the patch size and composition in the landscape.

2.2.2 BGI landscape pattern quantification

The MSPA method can divide the grid data of patches into core, island, perforation, edge, loop, bridge, and branch (Table 2). The core area and bridge are the landscape types with the connectivity of the landscape structure (Yong Zheng et al., 2022).

3 Results

3.1 BGI space identification

3.1.1 Extraction results of the built-up area boundary

The extraction results are presented in Figure 4 and Table 3. The built-up areas of the case cities were >100 km ^{2}. London and Paris had the highest built-up area, 1174.16 km^2 and 1521.5629 km ^{2}, respectively. However, Nuremberg and Toulouse had the smallest built-up area, 100.1155 km ^{2} and 100.0332 km^2, respectively The size of the built-up area reflects the construction scale of the city. Moreover, the differences in the built-up areas of the case cities were large. It can analyze cities with different built-up areas scales and better study the BGI characteristics of cities with different sizes.

3.1.2 Ecological source identification

Figure 4 shows the case cities' UGI and RGI ecological sources, and each city's ecological source area and quantity are listed in Table 3. London had the highest number of UGI ecological sources,

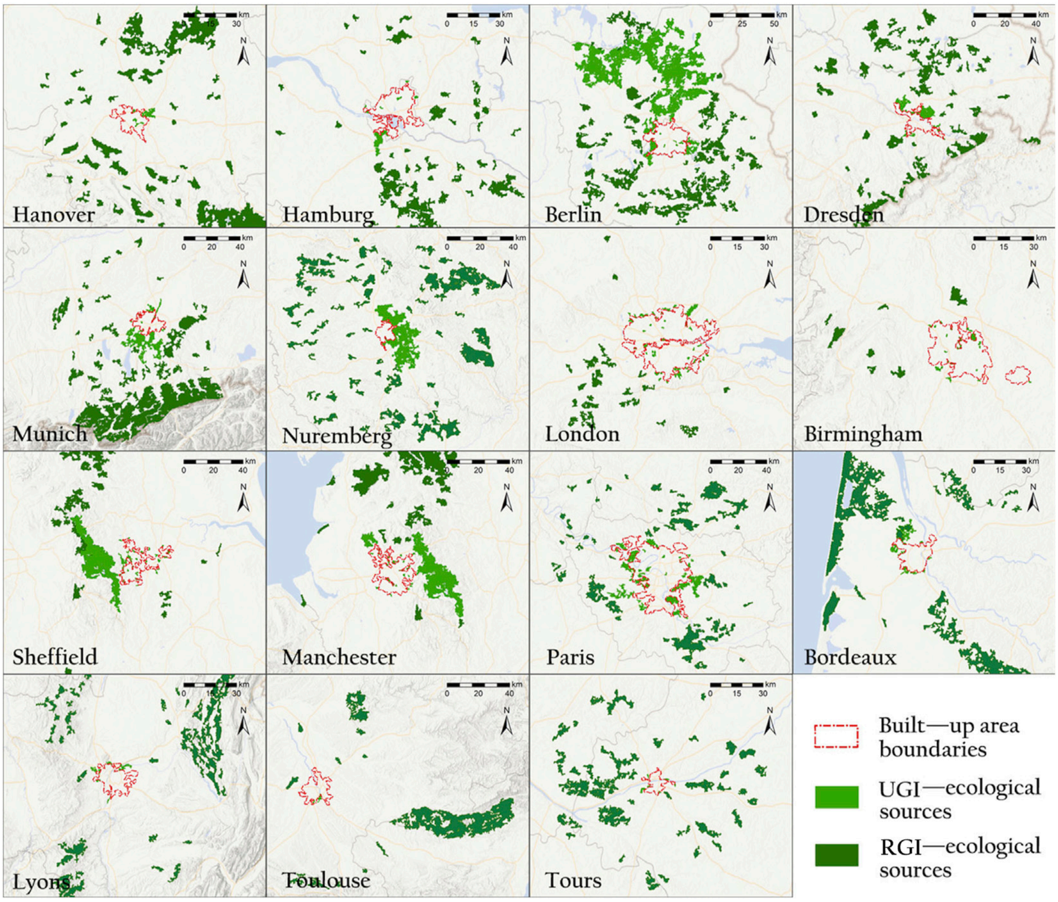

FIGURE 4
Distribution of UGI and RGI ecological sources.

with 45 patches, mainly small parks and greenbelts. However, the UGI ecological source area in the built-up area of Berlin was the largest, with strong ecological functions. Notably, there were only 4 UGI ecological sources in the built-up area of Toulouse, with a total area of only 3.328 km^2; therefore, biodiversity protection was relatively weak. Berlin had the highest number of regional ecological sources outside the built-up area, with 66 patches. However, the total area of regional ecological sources in Sheffield, Manchester, and Berlin was >3,000 km^2, which can maintain regional ecological security (Ma et al., 2004) and biodiversity. The GI inside and outside the built-up area of the case cities had certain ecological and landscape connectivity functions, which can provide a good basis for identifying and analyzing BGI.

3.1.3 Determination of optimum distance threshold

Berlin—the city with the best UGI landscape connectivity in German case cities—had many ecological patches, and a relatively close distance between patches is superior to the other five case cities (Figure 5). Additionally, the landscape connectivity of four United Kingdom cities was good in the built-up area. At the 10,000 m distance threshold, all the landscape elements were connected into a landscape component, and the NC value reached 1. According to the NL value, the UGI landscape connectivity in London's built-up area was the strongest, and that in Birmingham was relatively weak. Among the French cities, Paris had many UGI patches, high NL value, and a small and stable increase trend. However, the number of UGI patches in other cities was <10, and the patch distribution was relatively discrete. The overall NC and NL values changed step wisely with the distance threshold in a stepwise manner.

In the RGI analysis result shown in Figure 6, London, Manchester, and Sheffield in the United Kingdom had good connectivity. With the change of distance threshold, there were stages of a small change rate of NC and NL and stable value. Furthermore, the number of RGI patches in Birmingham was relatively small, and the distribution was relatively discrete; therefore, the NC and NL values changed stepwise with the increased distance threshold. Moreover, the number of RGI patches in German case cities was large and closely distributed. With the change in distance threshold, the change in NC and NL values was relatively stable. Excluding Dresden, other cases could be connected into a landscape component when the distance reached 20000 m, indicating that the regional ecological source can meet the needs of biological migration and diffusion. Furthermore, the number of RGI patches in Toulouse, France, was relatively small, and the distribution was relatively sparse, resulting in the NC and NL change curves showing a constant interval with the increase of the distance threshold.

TABLE 3 Ecological source extraction results of UGI, RGI.

Case Country	Case city	Built-up area (km^2)	UGI		RGI	
			Quantity	Area (km^2)	Quantity	Area (km^2)
United Kingdom	London	1174.1600	45	64.9450	23	271.7972
	Birmingham	651.6437	20	28.2266	8	113.2634
	Sheffield	302.2855	29	543.8582	18	3,359.5077
	Manchester	459.4656	25	581.6185	19	3,535.1707
Germany	Hanover	187.3413	5	25.5083	46	2420.0632
	Hamburg	418.4669	10	48.2607	43	1256.6128
	Berlin	593.4302	22	2196.1155	66	3,394.8261
	Dresden	200.2891	11	101.1098	51	1227.2470
	Munich	225.4226	9	208.4119	47	2338.0627
	Nuremberg	100.1155	3	367.8156	63	1672.9128
France	Paris	1521.5629	34	329.2047	57	1308.1500
	Bordeaux	262.8390	9	76.6908	21	1807.7616
	Lyons	252.6015	7	15.1362	38	1055.3337
	Toulouse	241.4913	4	3.3282	16	1001.3949
	Tours	100.0332	6	8.1909	40	869.9130

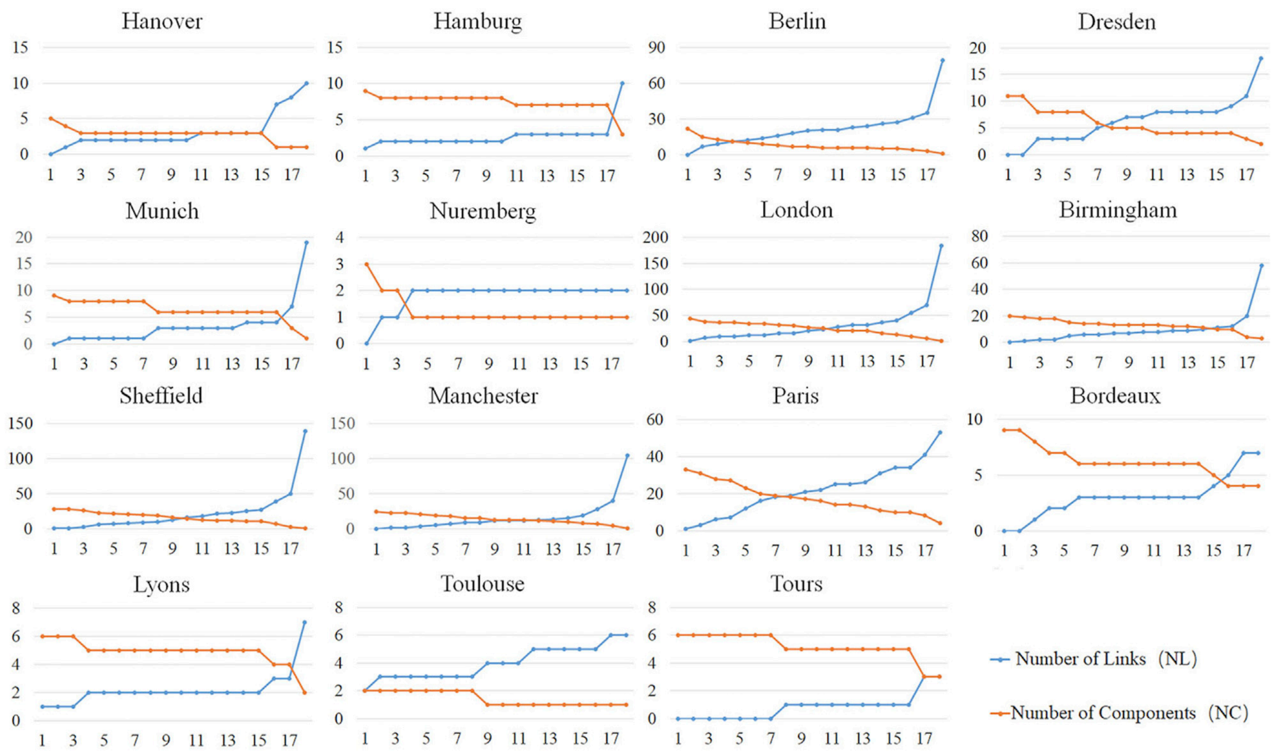

FIGURE 5
Changes in the distance threshold of UGI NL and NC.

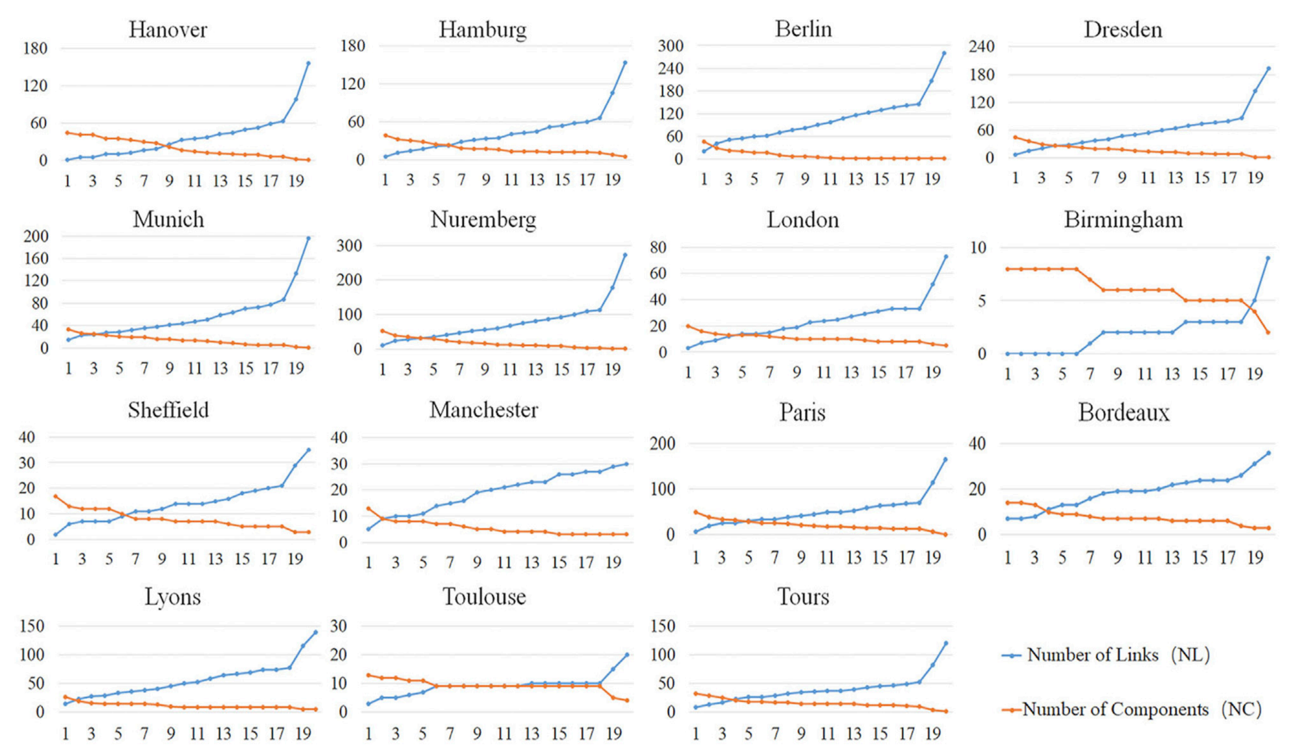

FIGURE 6
Changes in the distance threshold of RGI NL and NC.

The trend of curve change in Figure 5, Figure 6 can be divided into several stages.

(a) The NC value decreased rapidly, and the NL value increased rapidly. The increase in landscape connectivity indicates that it promotes ecosystem stability. When the change of distance threshold causes a drastic change in landscape connectivity, it indicates that the landscape connectivity is unstable, and this interval distance threshold is unsuitable for the correlation analysis of landscape connectivity in the study area.
(b) The NC value gradually decreased or remained unchanged, and the NL value slowly increased or remained stable. In this interval, the landscape component fraction changes slightly, and the number of connections increases steadily, indicating that the landscape connection stability is less affected by the change in distance threshold. Therefore, the landscape connection in this section is in a relatively stable state, which is suitable for studying landscape connectivity.
(c) The NC curve changes slightly; however, the NL curve significantly increases. The landscape connection between patches becomes increasingly strong with the increased diffusion distance. However, the NL value changes significantly, which cannot reflect the study area's landscape pattern and ecological process, and it is unsuitable to be selected as the stable distance threshold range.
(d) The NC value is = 1. This means that all ecological sources are connected and can be considered biological habitats. However, this situation does not conform to the actual landscape pattern in the study area and cannot be used as the stable distance threshold range for the landscape connectivity study.

The selected stable distance threshold ranges are listed in Table 4. The NL curve of RGI in Bordeaux showed a staged growth, and the NC curve showed a fluctuating stable state; therefore, two stable distance threshold intervals were selected. Since the number of UGI patches in Nuremberg, Toulouse, and Toure was very small, when the diffusion distance reached a fixed value, the NC and NL values did not change; therefore, there was no threshold range to maintain the stable connection of the landscape.

For example, in Berlin, 20 RGI patches were screened, and the distance thresholds of 7,000, 7,500, and 8000 m were set. Additionally, the changes in plaque importance index dLCP, dIIC, and dPC were analyzed, and the results are shown in Figure 7. Moreover, when the distance threshold is set to 8,000 m, the difference in plaque importance index is the smallest, and the index trend of each patch is the most consistent, so it is selected as the optimal distance threshold. Notably, when the distance threshold was 8,000 m, the difference in plaque importance index was the smallest, making it the best distance threshold. The appropriate distance threshold between each case city's RGI and UGI ecological source was determined similarly, and the results are presented in Table 4.

The appropriate distance threshold between patches is affected by the distance between patches. The closer the patch distribution, the more stable the landscape pattern, and the lower the appropriate distance threshold. Sheffield's UGI pattern was good, with many patches, a large total area, and a relatively close distribution. Moreover, Munich's RGI pattern was good, and the area and quantity of ecological sources were large and close, which is conducive to biological diffusion.

TABLE 4 The result of the optimal distance threshold selection.

Case Country	Case city	UGI		RGI	
		Range (m)	Distance threshold (m)	Range (m)	Distance threshold (m)
United Kingdom	London	2200–2600	2600	6000–7000	7000
	Birmingham	1800–2200	2200	6500–7500	8000
	Sheffield	800–1600	1200	6000–7000	7000
	Manchester	1600–2200	2200	8000–10000	6500
Germany	Hanover	2200–5,000	2800	4,500–6000	6000
	Hamburg	2000–2200	2800	7000–8000	6000
	Berlin	2200–3,000	2200	6000–7000	8000
	Dresden	1800–3,000	3,000	5,000–5,500	9500
	Munich	2200–3,000	2000	8500–9500	5,500
	Nuremberg	800	800	7500–8500	8500
France	Paris	2200–2400	2200	6500–7000	6500
	Bordeaux	1200–2800	3,200	5,500–6500, 8500–9500	8500
	Lyons	800–3,000	2800	7500–8500	8500
	Toulouse	1800	1800	4,000–10000	10000
	Tours	1600	1600	5,500–7000	6500

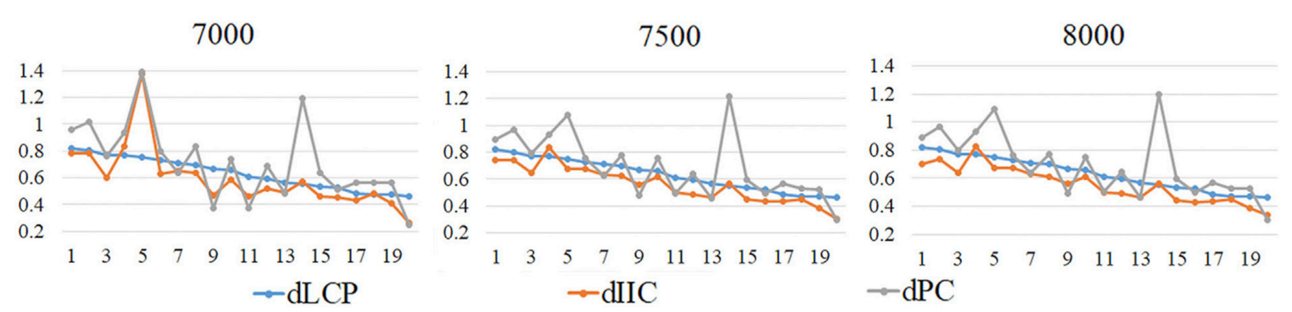

FIGURE 7
Changes in the distance threshold of Berlin patch importance indices.

3.1.4 BGI width determination

The width and area of BGI in each case city are shown in Figure 8, and the spatial distribution of BGI is shown in Figure 10. BGI scope is affected by the appropriate distance threshold of GI and the scale of the built-up area. The closer the distribution of ecological patches inside and outside the built-up area, the stronger the landscape connection and the smaller the coverage width of BGI.

3.2 BGI spatial evaluation

3.2.1 Differences in the characteristics of BGI pattern

The total ecological land area of case BGI was >100 km^{2,} and the number of BGI patches was >100 (Table 5). In the BGI space, the ecological land has a certain scale. The larger the ecological source area, the better the ecological function. At the urban boundary, the intensity of human activities was gradually weakened. Additionally, the total ecological area and the number of patches increased, higher than those in the urban built-up areas. Within the scope of BGI, the increase in the number of patches indicates that the number of nodes in the GI network has increased, and the landscape connection has improved.

Among the numerous patches, a large area of ecological core could provide habitats for organisms, and small and scattered serve patches as stepping stone patches. Using the gradient area threshold analysis of the BGI patches in the case cities, the composition of the BGI patches in each case was analyzed according to the inflection point of the curve in Figure 9. The results are presented in Table 5.

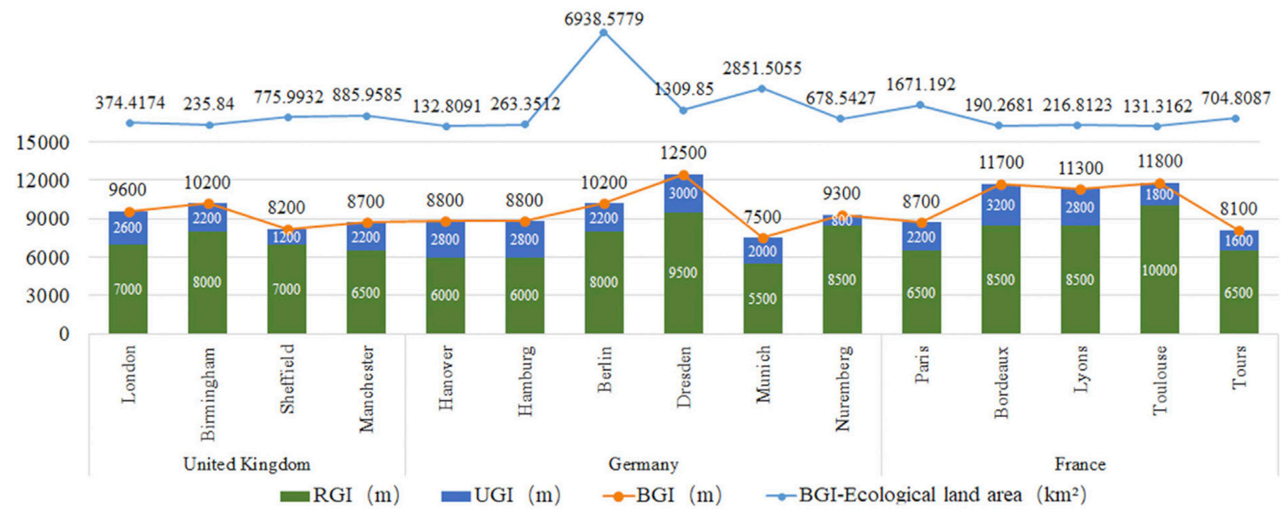

FIGURE 8
Case city BGI width and area.

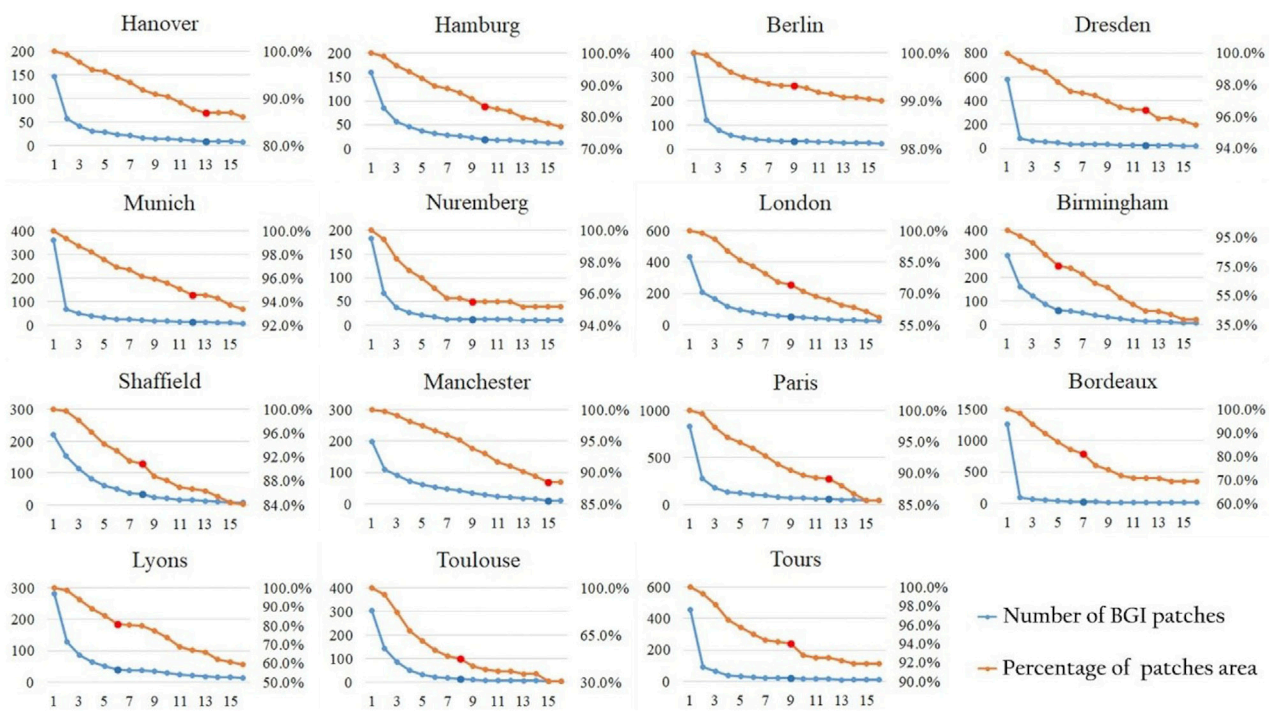

FIGURE 9
Changes in the minimum area threshold of the patch.

The number of scattered small patches in Birmingham's BGI was large, accounting for about 25% of the total area. Moreover, the BGI was relatively broken, and the proportion of large patches was relatively low. Furthermore, the BGI in Toulouse contains many small ecological patches, and the landscape pattern was severely fragmented. Hanover's BGI had a high proportion of medium and large patch areas, a complete overall ecological pattern, and stable function. In all cases, the BGI space contained a large area of ecological sources to ensure biodiversity and ecological security, and many small patches were stepping stones in the biological migration and diffusion path.

According to the distribution location and spatial pattern of BGI in Figure 10, the BGI model of the case cities can be divided into three types.

1) Surrounding pattern: The patches can be closely surrounded by the urban built-up area, forming a circular or semi-circular structure conducive to biological flow between GI networks

TABLE 5 Analysis results of gradient area threshold.

Case Country	Case city	BGI-ecological land area (km^2)	Number of all patches	Number of selected patches	Area of remaining patches (km^2)	Proportion of area (%)	Proportion of quantity (%)
United Kingdom	London	374.4174	432	54	1.6	74.395	12.500
	Birmingham	235.84	295	61	0.8	75.527	20.678
	Sheffield	775.9932	220	35	1.4	90.887	15.909
	Manchester	885.9585	198	12	2.8	88.478	6.061
Germany	Hanover	132.8091	147	10	1.4	99.313	6.803
	Hamburg	263.3512	159	19	1.8	83.226	11.950
	Berlin	6938.5779	397	35	2.2	87.719	8.816
	Dresden	1309.85	580	23	2.4	95.916	3.966
	Munich	2851.5055	363	13	2.2	94.613	3.581
	Nuremberg	678.5427	183	13	1.2	95.705	7.104
France	Paris	1671.192	829	64	2.2	89.144	7.720
	Bordeaux	190.2681	1259	30	1.2	81.263	2.383
	Lyons	216.8123	282	40	1	81.011	14.184
	Toulouse	131.3162	303	15	1.4	47.805	4.950
	Tours	704.8087	456	20	1.6	93.993	4.386

and the biological migration and diffusion in BGI space. There are two types of surrounding patterns. First, a large ecological source outside the built-up area with a very high landscape structure and functional connection seen in Berlin and Paris. Second, many small artificial green spaces clustered to form a green ring structure surrounding the built-up area seen in London. This type of BGI has a high overall structural connectivity; however, the functional connectivity of the patch is weaker than that of the large regional ecological source.

2) Aggregation pattern. Local patches are clustered and distributed around the built-up area, and multiple clustered and distributed GI network nodes connect the GI landscape. For example, in Hamburg, Bordeaux, and Sheffield, the ecological patches were clustered and distributed and had a certain scale without forming a semi-ring or ring structure. The more the number and area of patches, the stronger the landscape connection function between the two ecological networks and the better the landscape stability.
3) Scattered pattern. The patches are scattered in the BGI space, and the patch area is generally small. The landscape connection function of BGI was relatively weak in Birmingham and Toulouse. Small-area ecological patches are suitable stepping stones in the biological migration path and play a relatively weak role in biodiversity protection. The scattered distribution pattern can easily cause landscape fragmentation.

3.2.2 BGI landscape pattern analysis

Figure 11 and Table 6 present the analysis results of MSPA. The proportion of core in BGI was the highest (>30%) in all case cities. Munich had the highest proportion of BGI core area, and Berlin had the largest BGI core area. As a landscape type with high structure connectivity function and less disturbance, the core mainly serves as the habitat of organisms and protects diversity. Therefore, the case cities' BGI can protect biodiversity, of which Berlin and Munich had the strongest biodiversity protection function, and Toulouse had a relatively weak ecological function.

The edge area comes after the core area. In all cases, the proportion of marginal areas in BGI was >10%. Moreover, the area of BGI edge in Berlin and Munich was large; however, the proportion was small, 13.22% and 12.73%, respectively. This situation is because the edge area usually surrounds the ecological core area, and the patch's size, quantity, and geometric shape can significantly affect the area and proportion of the edge area.

The third area is the branch, which can promote the material and energy exchange between the core area and the outside world. The area of branch lines in Berlin BGI was the largest; however, the proportion was the lowest due to the huge total area of Berlin BGI. Additionally, the branch has certain landscape connectivity, which enhances landscape connectivity and biodiversity protection by establishing ecological corridors.

As a narrow and long area connecting the ecological core areas, the bridge can serve as a corridor for biological migration and diffusion, which is essential for biodiversity protection. In the MSPA analysis of the case cities, Toulouse and Lyon BGI had the highest proportion of bridging areas. Notably, insufficient bridging area leads to a lack of connectivity between BGI patches and limited species migration and gene exchange, which is unconducive for maintaining biodiversity.

Furthermore, the loop is a shortcut for species migration within the patch, which is conducive to species migration within the same patch. In these cases, the area of the BGI loop in Lyon accounted for 1.739%; however, that of other cities was <1%, indicating that there are few patches in the BGI core area.

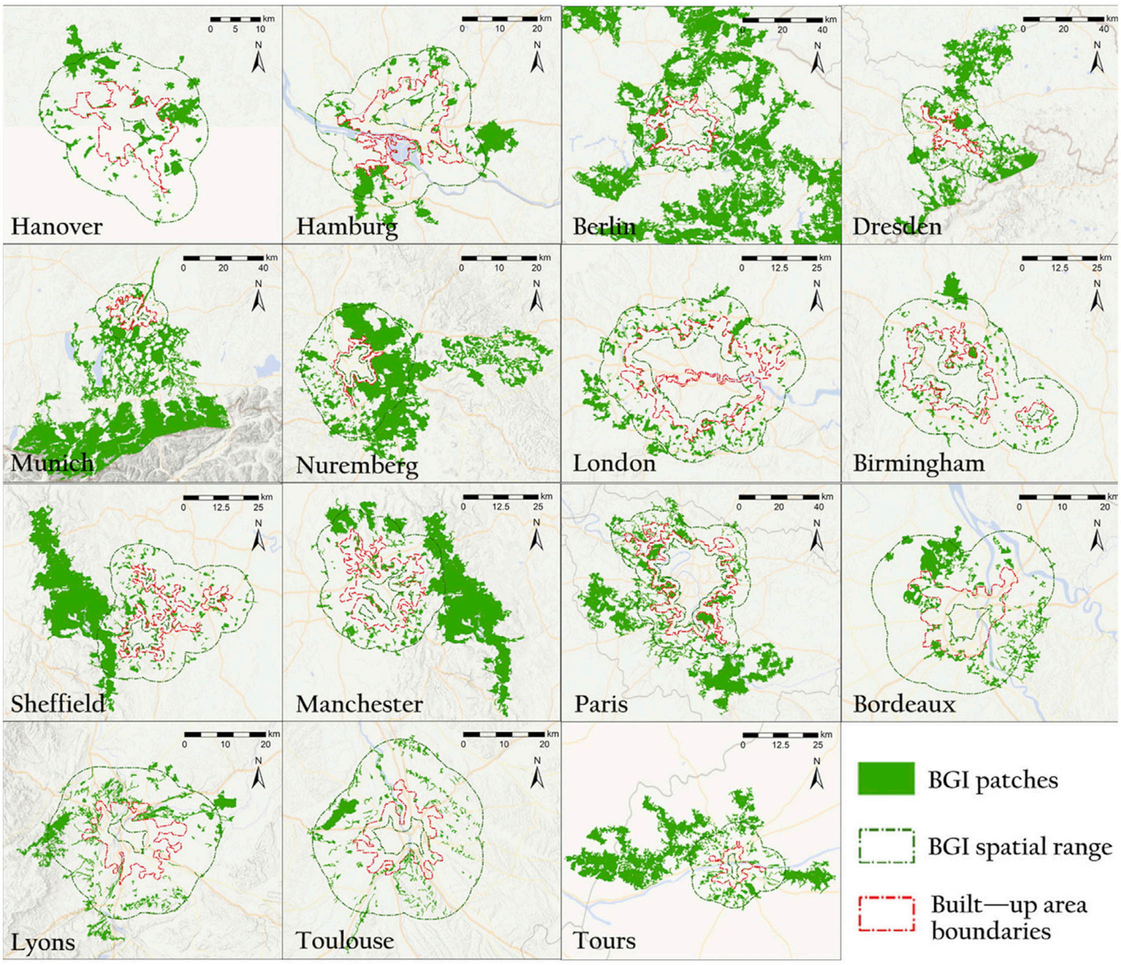

FIGURE 10
Spatial distribution of BGI in case cities.

The perforation and the edge are the transition areas between the core and other land types; however, the perforation is located in the core of the patch, which easily affects the ecological process in the core. The low proportion of perforation area in BGI indicates that the impact on the interior of the BGI patch is small, and the ecological process in the core area can be well protected.

The landscape connectivity of islands is relatively low, and the possibility of internal material and energy exchange and transmission is relatively small. The BGI of the case cities contained a small number of islands, and the proportion of isolated patches in the BGI was small. This indicates that BGI had a relatively low landscape fragmentation degree, good landscape connectivity, and small stepping-stone ecological patches to ensure the activity and diffusion of organisms.

According to the MSPA analysis results, the core in BGI space was the most important landscape type, with the highest proportion and the largest area. This suggests that BGI' primarily protects the normal migration and organism diffusion, maintains of ecosystem's stability, and ensures the GI network's landscape connectivity. Furthermore, the high proportion of edge was due to the weakening of the development intensity at the boundary of urban built-up areas compared with that in the built-up areas; however, there were still human activities around the edge of BGI patches. Moreover, the extremely low proportion of perforation indicates that human development and construction of GI patches are usually not in the core areas to prevent interference with ecological processes in the core areas. Additionally, the branch, bridge, and loop area all had certain proportions, indicating that BGI can provide corridors for the migration and diffusion of species, which is conducive to GI network connectivity and biodiversity protection.

4 Discussion

In the BGI space of the case, cities such as Berlin, Paris, and Bordeaux have large ecological sources, while cities such as Birmingham, Toulouse, and London only have small-area ecological patches (Figure 10). Among them, the BGI space in Berlin contains many large ecological sources with the highest total ecological area, and ecological patches are interconnected to form a surrounding pattern. The BGI space in Bordeaux also contains large ecological sources, but the patches are only locally clustered and cannot form a circular structure. The BGI of Birmingham is composed of many small patches, and the patches are scattered, with poor landscape connectivity and serious fragmentation. Similarly, there is no large

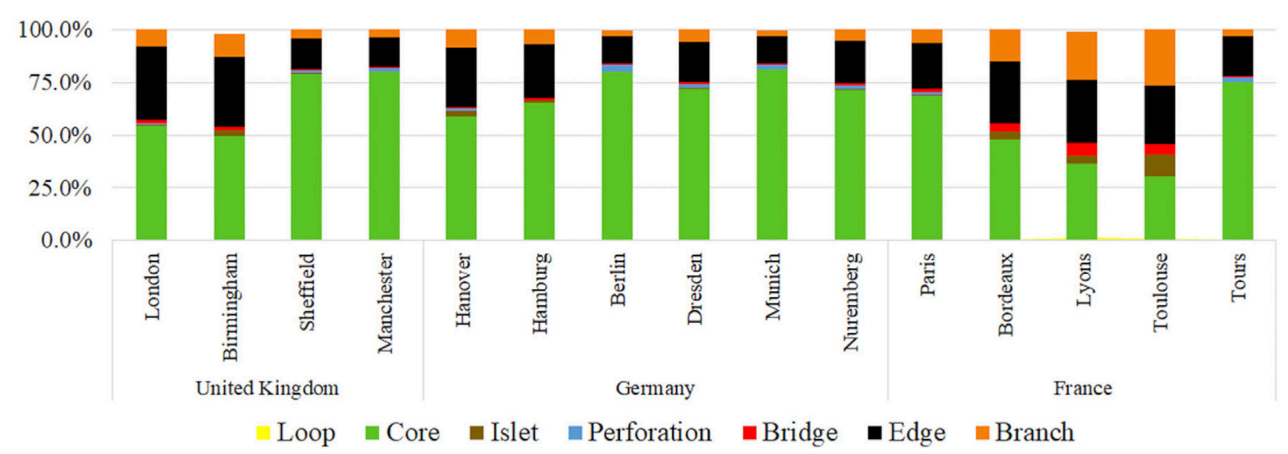

FIGURE 11
Case City MSPA landscape type scale.

TABLE 6 The area of MSPA landscape type in the case city.

Case Country	Case city	Area (km²)	Core (km²)	Islet (km²)	Perforation (km²)	Loop (km²)	Bridge (km²)	Edge (km²)	Branch (km²)
United Kingdom	London	374.42	204.10	2.53	1.42	1.69	5.89	130.60	33.69
	Birmingham	235.84	116.90	6.10	0.46	1.05	3.70	79.35	24.78
	Sheffield	775.99	614.30	2.19	10.14	1.39	4.69	115.10	32.01
	Manchester	885.96	709.90	2.37	11.84	2.34	5.039	126.80	32.15
Germany	Hanover	132.80	78.26	3.69	1.21	0.74	1.06	37.83	12.38
	Hamburg	263.35	172.40	3.39	0.14	0.47	2.60	67.44	20.33
	Berlin	6938.58	5,554.00	6.87	231.1	22.1	43.03	917.60	189.5
	Dresden	1309.85	944.20	8.94	20.54	5.16	16.11	249.90	72.97
	Munich	2851.50	2319.00	3.10	56.57	8.42	22.26	363.00	87.66
	Nuremberg	678.54	485.40	4.18	9.27	2.10	8.39	136.00	36.51
France	Paris	1671.19	1153.0	5.93	14.11	7.45	27.24	367.2	107.00
	Bordeaux	190.27	91.46	6.93	0.50	0.67	7.10	56.20	31.20
	Lyons	216.81	79.28	7.73	0	3.77	13.38	65.08	50.45
	Toulouse	131.32	40.14	13.3	0.08	1.28	6.85	36.68	34.82
	Tours	704.80	529.20	2.31	14.88	1.47	5.32	134.18	25.14

ecological source in BGI space in London, but the patches are closely distributed and the landscape connectivity is high, forming a circular structure composed of many small-area patches. Therefore, in the BGI space, the larger the area of the ecological source and the stronger the connection function, the better the ecological function can be played. Moreover, the landscape pattern of BGI also plays a crucial role, the closer the distribution between the patches, the stronger the landscape connectivity, and the more conducive to the connection between the urban and the regional GI network.

In this study, BGI can play an important role in ensuring the integrity and connectivity of urban and regional GI network structures, which is consistent with other studies on the strengthening of urban-rural ecological connections between urban and rural GI at urban and rural margins (Zhong et al., 2020). The connectivity of urban and rural ecological networks is limited by the lack of ecological areas and the lack of stepping stone patches in some urban marginal areas (Cui et al., 2020; Zhong et al., 2020; Liang et al., 2022). In contrast, the border green infrastructure of European case cities can better maintain the biological flow between GI networks. By summarizing the pattern of case BGI and identifying different spatial pattern characteristics, the BGI of European case cities can support the

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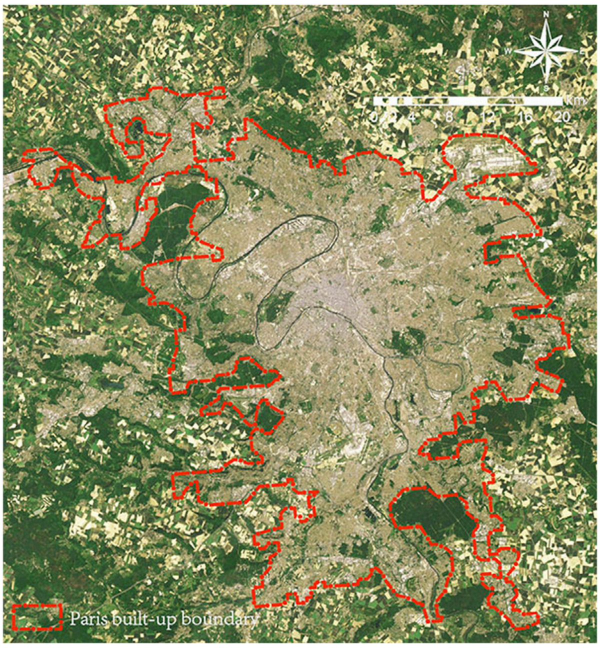

FIGURE 12
Results of boundary extraction of Paris urban built-up area.

connection between cities and regional GI networks. In addition, the results of the MSPA analysis showed that the BGI plaque of the case could provide services for human activities and also had a high biodiversity conservation function. In summary, BGI contains the composite functions of urban green infrastructure and regional green infrastructure and is an important part of the GI network.

When extracting ecological sources, MSPA considers the area factor and the structural characteristics and connectivity functions of landscape elements, preventing the subjectivity of source extraction and improving accuracy. However, MSPA analysis has a strong scale and edge effects, and the analysis results at different research scales are quite different (Ya-Ping et al., 2016). Therefore, it is important to select the appropriate analysis scale when using MSPA to analyze the characteristics of landscape patterns. To retain the small but important landscape elements in the built-up area and ensure the accuracy of the results, the grid size of the built-up area scale was set to 30 m, and the grid size outside the built-up area was set to 90 m (Tanner and Fuhlendorf, 2018). However, the reasonable selection of grid data granularity and edge width for different research areas still needs further research.

When extracting the boundaries of urban built-up areas, the edges of built-up areas extracted using the land-use entropy method were severely fragmented and showed an obvious sawtooth shape. Moreover, many holes were observed in the built-up area extracted by the POI kernel density analysis method, and the POI category was inconsistent with the land type (Jinhua et al., 2021). Notably, the boundary of the built-up area extracted in this study was accurate and can overcome the information-missing phenomenon of the extracted results. The comparison between the extraction results of the built-up area in Paris obtained by this method and the remote sensing satellite images is shown in Figure 12. The built-up area was close to the actual boundary, improving the "salt and pepper particles" phenomenon of the boundary of the built-up area determined using the land-use entropy method to extract the built-up area. Therefore, this method reflects the boundary details of urban built-up areas and has good applicability. Moreover, the extraction effect of built-up area boundaries in cities of different sizes had good accuracy.

The distance threshold needs to be determined when analyzing the landscape connectivity between the built-up area and the regional GI using Conefor software. However, the selection of distance threshold requires careful consideration of many factors, among which the diffusion range of species is the key factor, which varies widely for different species. Furthermore, when the landscape connectivity index is used to screen the landscape distance threshold, the appropriate distance threshold is closely related to the current distribution of BGI landscape patches. In this study, IIC, PC, and other landscape connectivity indexes were used to screen the appropriate distance threshold of the study area, and the selection index was small. Lastly, when selecting the distance threshold, the rationality of landscape connectivity and the ecological process of different scales should be considered to determine the most suitable distance threshold for the case city.

5 Conclusion

In conclusion, high-intensity urban development has led to the isolation of built-up areas and natural ecological space. GI network planning–has been ignored at the boundary of built-up areas, and its scientific and rational nature has been questioned. The innovation of this study lies in identifying the scope of BGI and analyzing its landscape pattern characteristics using the GI network's continuity, transition, and systematic characteristics at the boundary of urban built-up areas. Based on the landscape connectivity model, MSPA, and other methods, this method can effectively analyze the best landscape distance threshold of UGI and RGI and delimit the scope of BGI. Additionally, we analyzed and summarized the landscape pattern and structural characteristics of BGI space, providing reference and guidance for planners and decision-makers. By studying the European case cities, we proved that BGI is a vital in the GI network under the context of rapid urbanization.

Overall, a BGI with a landscape connection between UGI and RGI at the boundary of the urban built-up area was observed, and its scope was affected by the scale of the built-up area and the optimum distance threshold of UGI and RGI. Moreover, the BGI contained many small ecological patches and a small number of large ecological patches. Moreover, the proportion of large patches in the BGI area was high, and the total area of broken small patches was small. Additionally, large-scale ecological patches in BGI spaces performed major ecological functions. Patch distribution in BGI space can be divided into the surrounding, aggregation, and scattered patterns. The BGI of the surrounding pattern can improve the landscape connection between UGI and RGI and enable the migration and diffusion of organisms inside and outside the built-up area. The best landscape model of BGI was the surrounding pattern, followed by the aggregation pattern; however, the fragmentation of the scattered pattern was high. Lastly, The ecological core area in BGI is the main landscape type, followed by the marginal area. Therefore, BGI can promote the habitat and migration of organisms, maintain biodiversity and ensure ecological security, and is an important part of the NBS method in the context of rapid urbanization.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

JY Conceptualization, Methodology, Resources, Writing–original draft, Writing–review and editing. BW Methodology, Vali-dation, Investigation. XL Validation, Visualization, Resources. ML Writing–review and editing, Visualization. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Four recommendations to tackle the complex reality of transdisciplinary, natural experiment research

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Natural experiments are often used to study interventions in which randomization to control versus intervention conditions are impossible. Nature-based interventions (i.e., programs designed to increase human interaction with nature and improve human health) are commonly studied as natural experiments. We used a natural experiment design to explore the benefits of ecological rehabilitation of parks on biodiversity and resident health in low-income, minoritized neighborhoods in Detroit, MI. Given the complexities and interconnectedness of lived experiences, community needs, and ecological health, this research design has presented challenges. Based on our experiences, we pose four key recommendations for researchers and practitioners conducting natural experiments, nature-based interventions, and those working in low-income, minoritized neighborhoods. We use the explicit examples of challenges faced as rationale for these recommendations. The key recommendations are (1) Engage with community leaders; (2) Build a transdisciplinary team and work closely; (3) Examine privilege; and (4) Create a unified vision.

KEYWORDS

nature-base solutions, greenspace, biodiversity, equitable, public health

1. Introduction

Natural experiments are a robust alternative to Clinical Trials, particularly when randomizing to experience the intervention is not feasible or ethical (1). Many community-based interventions fall into this category. Community-based interventions that aim to empower communities and improve health equity are particularly complex. Rarely can intervention and controls be replicated, randomized, or stratified with ease and even when they can, the complexities of lived experiences can derail even the most well-planned experimental design. So, natural experiments offer a useful and cost-effective (2) alternative to understand the effect(s) of community-based interventions on residents. Moreover, exploring the outcomes of interventions along-side practitioners and grass-roots organizations can lead to increased uptake of findings into adaptive, evidence-based approaches (3).

Such knowledge sharing from real-world, community-based interventions studied using natural experiments is critical for improving the health of people and places with the highest need. Community-based interventions are on the rise, particularly nature-based ones. Nature-based interventions are programs that aim to increase human interaction with nature and/or restore an ecosystem to improve human health (4, 5). Epidemiological data show that people who live near natural areas, parks, and greenspaces have better health outcomes (6). But, natural experiments of nature-based interventions can be complex, given the need for research across disciplines to measure outcomes for biodiversity and human health.

Based on four years of natural experiment research, we outline four key recommendations for researchers and practitioners who plan to employ a natural experiment design to measure the health benefits of nature-based interventions, particularly in high need areas such as low-income, minoritized neighborhoods. We use experience from a study of an ecological park improvement intervention (7) in Detroit, MI, United States.

Detroit, similar to other post-industrial cities, has experienced formidable decline in its population. The city currently has a majority Black/African American population, comprising 78% of the city's residents [using U.S. census terminology for race/ethnicity (8)] and high levels of poverty [32% (8)]. The population decline has led to countless abandoned buildings (9), vacant lots, and lower tax revenue mandating reductions in city services. Research has shown that, in the worst cases, vacancy can facilitate drug dealing and crime (10). Vacancy and lower tax revenue for city services, including the parks department, are challenges to Detroit but also serve as opportunities for potential low-cost land use alternatives such as ecological rehabilitation. However, the co-benefits of ecological rehabilitation (11) in urban areas for human and ecosystem health has gone largely unstudied (12), especially in the context of equity.

The intervention we studied involved ecological rehabilitation (i.e, removal of turf grass, litter, and broken cement, planting native species, installing trails, benches, and signage, and conducting engagement activities) of four parks (not being maintained as conventional parks) and surrounding vacant lots through a partnership between Detroit Parks and Recreation Department (DPRD) and Detroit Audubon (a bird conservation organization). The objective of the rehabilitation project was to transform unmaintained parks to habitat beneficial for birds. Our research team's objective was to explore whether park rehabilitation, and resulting changes in biodiversity, influenced the health of neighboring residents. The original timeline involved rehabilitation in 2019–2020. However, the pandemic shifted the intervention to 2019 and 2021. The study is called the Study of Active Neighborhoods in Detroit, or StAND (7).

Our transdisciplinary team of researchers aimed to measure changes in physical activity, stress, cardiometabolic health, and bird diversity over time, in both intervention and control neighborhoods [for more details, see Pearson et al. (7)] using a flexible longitudinal/repeated panel design. The team has expertise in kinesiology (Pfeiffer), biostatistics (Gardiner), ecotheology and community activism (Asana), geospatial techniques (Pearson), ecological acoustics and avian ecology (Buxton), and environmental physiology/endocrinology (Horton). Having completed four annual waves of data collection, here, we identify four key recommendations and provide rationale for these recommendations based on lessons learned over the course of conducting this research (Figure 1). These recommendations are for researchers conducting natural experiments or nature-based intervention research, and those working in places and populations with high need.

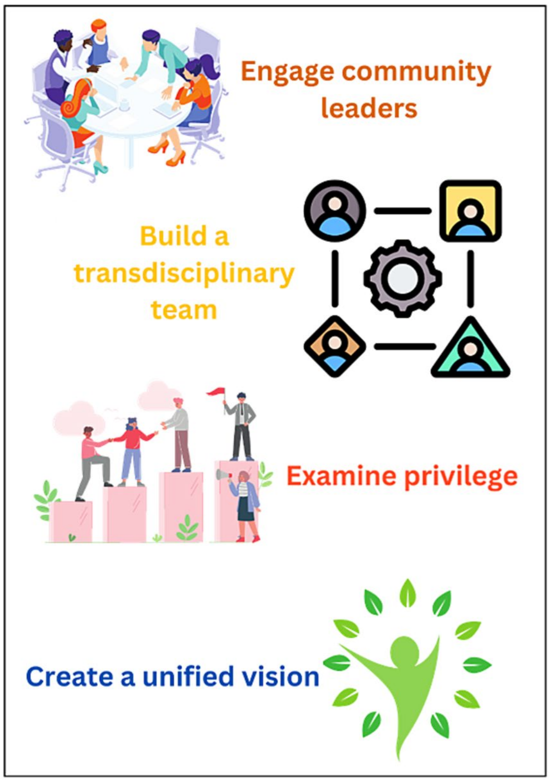

FIGURE 1
Four key recommendations for researchers and practitioners involved in nature-based solutions research.

1.1. Engage community leadership

Community liaisons are frequently cited as highly important conduits in community-based interventions. Involving a liaison who is willing to engage in difficult conversations (with the residents, the practitioners, and the research team) can help the researchers have a pulse on the community, interpret research findings, and give the community a voice. The evidence is growing that community-engaged projects lead to better outcomes (13). However, consensus on what constitutes best practices for engagement has not been established (14). We recommend that prospective researchers invest time and effort in building meaningful and authentic relationships with the communities in which they plan to work, including attending community events, and staying informed of the activities of all partners (15, 16).

Organizations that seek strong nature-based interventions in heavily disinvested Black/African American communities must work with individuals from within the locus of that cultural community to identify culturally relevant interventions. Some data suggest that social equity issues make it challenging for resident involvement in greenspace improvements in marginalized communities (17). Working in low-income, predominantly minoritized areas often means that trust of White researchers is low [for good reasons, based on past harms (18)]. Our data collection required direct engagement with residents as a layer of engagement (1, 7). In preparation for this study (two years before funding was awarded), AP led a community workshop to make connections and listen to perspectives of residents on parks and greenspaces (19). From this experience, AP met VA, who has now worked as the Community Liaison for StAND since 2019. VA is a long-term resident of Detroit, with decades of experience in community organizing, and familiar with the communities to lead the engagement of the research team with between Detroit Audubon, DPRD, and residents.

We learned the value of following community leadership again and again. For example, the blinding of field staff and participants was an important part of the design in terms of neighborhood intervention versus control status for three reasons: (1) to minimize bias in the data, (2) to homogenize interactions with participants (whether conscious or unconscious), and (3) because ultimately carrying out the intervention was beyond the study team's control so promising the intervention to any participant was deemed unethical. In our case, blinding was simply defined as non-disclosure of why each neighborhood was selected to be part of the study. During training each year, the investigators explained the concept of blinding to field staff. Training during the first year of the study provided a valuable learning experience. A few weeks into training, the investigators learned that the field staff did not fully understand blinding, which eroded their trust. Field staff questioned the motives of the investigators, as they perceived the investigators were holding back important information from participants. Under the leadership of the community liaison, the investigators worked to re-build rapport, establish credibility, and further explain blinding in research. Based on this experience, we modified future training sessions to better explain blinding up front and to anticipate and answer questions.

Another example involved ensuring that community leadership was central to the decisions of the practitioner, Detroit Audubon. The impact of the urban greening interventions often depends on acceptance or support by the residents (16, 20–22). Research on urban greening projects suggests that such interventions may be disruptive rather than beneficial when communities are not engaged in the design (16, 21). When working with conservation groups, the goals of rehabilitation may not align with community goals, and capacity for in-depth engagement is often low. Moreover, engagement in natural areas and birding in particular, are still predominantly White activities, where privilege and racism work to exclude non-White people (23). John James Audubon, the namesake of The Audubon Society and Detroit Audubon, was a prominent 19th century naturalist who used slaves to support his birding activities. Thus, care must be taken when restoring habitat for birds and bird watching in predominantly Black/African American neighborhoods. Although this layer of community engagement was the responsibility of Detroit Audubon, as a conservation organization they were not deeply experienced in community engagement. Thus, our Community Liaison advised Detroit Audubon in their engagement activities, including necessary incorporation of culture-specific considerations pertaining to Black/African American perceptions of greenspace improvements. Particularly, these perceptions about abandoned park spaces relate to whether park improvements would even take place, and whether there is even a need for nature rehabilitation for birds. Rooted in an historical distrust of promised improvements based upon memories of deliberate urban disinvestment in Black/African American neighborhoods in Detroit, Michigan, it proved challenging to identify and recruit community stakeholders for buy-in to support ecological rehabilitation in one heavily disinvested community. Despite numerous in-person and virtual presentations with detailed information about proposed improvements, interest flagged over many months. Further, the COVID-19 pandemic exacerbated the problem of strong community buy-in, resulting in almost no interest in the proposed upcoming park improvements.

1.2. Build a transdisciplinary team of experts and work closely

A transdisciplinary approach that integrates eco-theology, community activism, and community-based participatory research with ecology and public health may be important in particular communities and can provide avenues to better facilitate stakeholders' participation. Early in the design process, engage with experts across disciplines to ensure that the methodology to measure both ecological and health changes is robust. Often community engagement specialists, ecologists and public health or social scientists do not "speak the same language" and time and effort is required to make sure all disciplines can work toward complementary goals.

Evaluating the co-benefits of urban ecological rehabilitation projects that aim to benefit both humans and biodiversity of plants, birds, and insects requires working across disciplines and institutions. Any trade-offs between conservation and community goals should ultimately be resolved through community guidance. We have found that despite mounting interest in interdisciplinary work to tackle "wicked problems" of the 21st century, few projects exist to act as a model for our own research. For example, in an assessment of the effectiveness of nature-based solutions in urban areas, one review found only two studies that explored co-benefits, or both environmental and social or health-related outcomes (24, 25). Thus, before embarking on our research program, we were unable to draw from previous experiences to explore successes and challenges of interdisciplinary research on the outcomes of natural experiments or coupled human and natural systems.

Our intention was to measure health outcomes pre- and post-intervention, however, if the benefits of restoration are delivered through increased species diversity and slowly developing vegetation cover, it is difficult to determine which time periods represent these analytical cut-points. Most urban environments are "novel ecosystems" – fundamentally different from natural ecosystems (26). Thus, understanding goals and benchmarks for restoration is challenging and restoration outcomes are difficult to predict (27, 28). In our case, soil quality and seed banks varied widely among the restoration sites, where weeds grew much better at sites with high quality soil, making establishment of native species challenging. These sites will require more consistent mowing and tilling, and limited resources are available for intensive upkeep. Moreover, these complexities prohibit clear delineation of an "intervention year." While urban ecosystems may not be identical to more pristine ones, there are measureable changes and benefits of their rehabilitation. Clearly measuring the benefits of rehabilitation for biodiversity and humans will help illuminate the pathways through which nature-based interventions best improve health, and for whom.

Beyond diversity among the investigative team, we recommend engagement with the conservation experts and practitioners leading the nature-based intervention. By their very definition, natural experiments are not within the control of the researcher. This can pose threats to study design and timing as priorities or funding may change for the interventionists, which can lead to fewer sites receiving the intervention, a revised form of the intervention, or delays. These changes may even occur after baseline data are collected, incurring costs to the research study and misbalancing the intervention versus control recruitment targets. For example, our protocol reported the intention to collect data for five intervention and five control sites, while we currently have four intervention sites and seven control sites for reasons beyond the research team's control (7). Audubon Detroit and DRPD shifted their priorities away from restoring small, neighborhood parks and changed the location of an intervention park. This decision led to an imbalance in the number of control and intervention neighborhoods in our study. Another example was the postponement of the intervention due to the COVID-19 pandemic (particularly prior to vaccine availability). The postponement resulted in less follow-up time post-intervention. Because the intervention under study is an ecological rehabilitation, this has implications for plant maturation, biodiversity changes for avian, insect, and plant species, and ultimately the ways in which people use and benefit from restored spaces.

Changes in implementation of the intervention require research teams to be flexible in designing statistical analyses and can result in analyses not strictly following previously published protocols (7). Staying in communication and working closely with the intervention experts is essential, in order to pivot and make decisions that affect study design, staffing, and recruitment targets in real time. In practice, this means holding regular meetings and keeping accurate minutes from each meeting.

1.3. Examine privilege

It can be difficult for research teams to truly understand what is happening in communities of interest due to unintentional, implicit bias. Researchers and practitioners need to be open to realizing when they make missteps in the eyes of community members and mending situations with as much grace as possible. At times, the field staff on the research team may also exhibit privilege in the eyes of participants and residents in the nature-based intervention neighborhoods.

For example, our staff and participants faced safety and trust issues in both directions. At times, staff felt unsafe in certain parts of neighborhoods or working with particular participants. In fact, one neighborhood was ultimately deemed too unsafe for staff, and we did not conduct further recruitment after the first few weeks. We intentionally attempted to hire only staff who were Detroit residents, with the aim of ensuring that staff had contextual experience in Detroit neighborhoods and the realities of our participants' lives. While this was possible for most staff, we also had to hire some individuals who were from suburbs of the city. In many cases, we lost those staff members relatively quickly, as most did not feel comfortable in the environments where data were being collected. In the other direction, at times participants did not trust staff members upon their initial interaction. For most participants, this waned quickly through conversation. A Community Liaison can prove very useful in highlighting when optics are suboptimal or when privilege may be limiting the ability to successfully carry out the research and/or the intervention.

1.4. Create a unified vision

Exploring the outcomes of natural experiments is complex from an ecological conservation (29) and public health (30) perspective; thus, exploring both simultaneously results in amplified challenges. In urban environments, restoring ecosystem functioning is complex. For community buy in, ensuring that the research aims and the intervention prioritizes human benefits and considerations is essential. While many conservation groups are rightly focused on the benefits to biodiversity, the intervention is unlikely to succeed or endure time if community needs are not central to the intervention design and messaging.

2. Conclusion

Natural experiments offer a rigorous design, and perhaps the only realistic way to measure the co-benefits of nature-based interventions in communities. Because natural experiments happen under real-world conditions, they are inherently complex and involve multiple layers of perspectives, values, and trade-offs. So, natural experiments examining the nature-based interventions face challenges, which we report as four key recommendations for the research design, practice, and dissemination stages to bolster success. The key recommendations are (1) Engage community leadership, (2) Engage a transdisciplinary team and work closely; (3) Examine privilege; and (4) Create a unified vision. Despite these challenges, the rewards of conducting this complicated research may be far-reaching, including the genuine synergy of conservation biology, public health, and social science research to benefit both human and planetary health – a true "nature-based solution".

Data availability statement

The original contributions presented in the study are included in the article/supplementary materials, further inquiries can be directed to the corresponding author.

Author contributions

AP, KP, RB, TH, JG, and VA conceived of the manuscript. AP, KP, RB, and TH drafted the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Research progress on animal habitat constructions from the perspective of urban biodiversity improvement

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The accelerated urbanization process has caused problems such as habitat loss, isolation, and habitat quality decline, resulting in a sharp reduction in the richness and abundance of urban species. Constructing suitable habitat environmental conditions is the most direct and effective way to protect animals. In urban environment, habitat construction can be achieved by integrating species protection and landscape planning, which is also an important manifestation of biodiversity conservation at the ecosystem level. Understanding how to incorporate animal habitats into city plan and design is critical and urban planners would benefit from a review that holistically describes the steps and methods of animal habitat constructions. We conducted a review to highlight the animal habitats space resources and network structures. We synthesized the findings of research studies in the last 20 years to illuminate the investigation, assessment, planning and management of animal habitats. As habitat degradation and fragmentation in anthropogenic environments, our findings suggest city planners should consider ecological background investigation, habitat suitability assessment, habitat planning strategies and animal habitat management as four key steps of mitigation to alleviate these impacts. This study will provide a useful reference to improve animal survival quality and communication. Through this study, the consolidated research can aid in sustainable development and innovation to promote the ecological function of urban green space and the harmonious coexistence of humans and animals.

KEYWORDS

animal habitat, biodiversity, investigation, suitability assessment, planning strategy, management

1 Introduction

With the acceleration of urbanization, a large amount of land is used for development and construction (Fahrig, 2019). As a result, various ecological and environmental problems have emerged, such as biodiversity loss, landscape fragmentation, ecosystem services decline, and even regional or global environmental changes (Wu, 2010; Liang et al., 2019). The biodiversity crisis in modern cities is mainly due to the greater degree of habitat degradation and fragmentation (Haddad et al., 2015; Driscoll et al., 2013; Fahrig, 2003; Fischer and Lindenmayer, 2007; Laurance, 2018; Hilty et al., 2020). Habitat degradation means that animals do not have sufficient and high-quality habitat space

TABLE 1 Literature search keywords, 2000–2023. Each topic broadly categorized under ecological background investigation, habitat suitability assessment, habitat planning strategies, and animal habitat management and the keywords used for each topic to identify appropriate literature for the review.

Ecological background investigation	Habitat suitability assessment	Habitat planning strategies	Animal habitat management
Bird	habitat use	conservation	animal refuge
Mammal	species priority	attraction	monitoring
Amphibian	selection ratio	planting	recreation
Aquatic animals	habitat potential	networks	disturbance
Distribution	range	connectivity	interference
Diversity	model	restore	manipulation
Richness	suitability index	natural recovery	restoration
Environmental factors	grade	ecological corridors	ecological zonation
Variables	classification	landscape structure	adaptive management
Investigate	indicators	landscape composition	balance
Survey	habitat quality	landscape configuration	effect
Key species	simulation	habitat quality	vigilance
Selection	resistance surface	vegetation recovery	public participation
Preference	dispersal movement	man-made facility	
Urban wildlife	habitat source	nest cavity	
Urban animals	habitat patches	vest boxes	
Species occurrence	shape index		

(Thomas and Blakemore, 2007; Conrad et al., 2012). Habitat fragmentation means that the exchange of genes and individuals can be hindered by barriers created by fragmentation (Cheptou et al., 2017; Wang et al., 2020; Yang et al., 2021). Animal habitats constructions in urban areas are an effective approach because they can ensure the sufficient animal habitats, improve the quality of animal habitats and eliminate obstacles formed between habitat fragments (Pascual-Hortal and Saura, 2007; Albert et al., 2017; Schwarz et al., 2017; Russo and Holzer, 2021). The construction of animal habitats is not simply to increase the green area or improve the connectivity of patches, but to optimize the spatial layout through identifying suitable habitat sources and building a reasonable connectivity network based on understanding the habitat preferences of key species (Northrup et al., 2022), which will give full play to the ecological service function of urban green space as animal habitats.

At present, many scholars have conducted research on urban biodiversity and animal habitats, including key influencing factors (Soga and Koike, 2013; Gan, 2018) and distribution patterns (Farinha-Marques et al., 2017), scientific assessment methods (Wang et al., 2019), planning strategies (Xu and Shen, 2009; Ma et al., 2021; Su and Dai, 2021), design methods and management measures (Deng et al., 2015) and so on. Generally speaking, they focused on different scientific questions and how to integrate all the studies above is critical. The literature reviews on animal habitats constructions tend to be discipline-based and urban planners would benefit from a review that holistically describes the steps and methods of animal habitat constructions. We conducted this review of research to highlight the animal habitats space resources and network structures. We synthesized the findings of research studies in the last 20 years to illuminate the investigation, assessment, planning and management of animal habitats. Our study will provide a useful reference for urban planners and land managers so they can better carry out the ecological practices to strengthen the ecosystem services function of habitat in a metropolitan environment.

2 Methods

We reviewed papers published in international peer-reviewed journals of the Web of Science by using the topic "animal habitat construction" and consulting to the group composed of professionals working in Beijing Forestry University that have diverse ecological resource and zoological science backgrounds to summarize the content involved in the animal habitat constructions. These ideas were then consolidated into a scheme consisting of 4 key steps to restore and enhance the habitat functions in cities (Table 1). We broadly categorize these key steps as ecological background investigation, habitat suitability assessment, habitat planning strategies, and habitat management (Figure 1). The ecological background investigation includes animal resources survey and environmental resources survey. Habitat suitability assessment is based on the selection characteristics of species on environmental factors, comprehensively evaluates environmental factors, and finally obtains habitat suitability classification and spatial layout, including habitat patches assessment and connection evaluation. Habitat planning strategies can provide

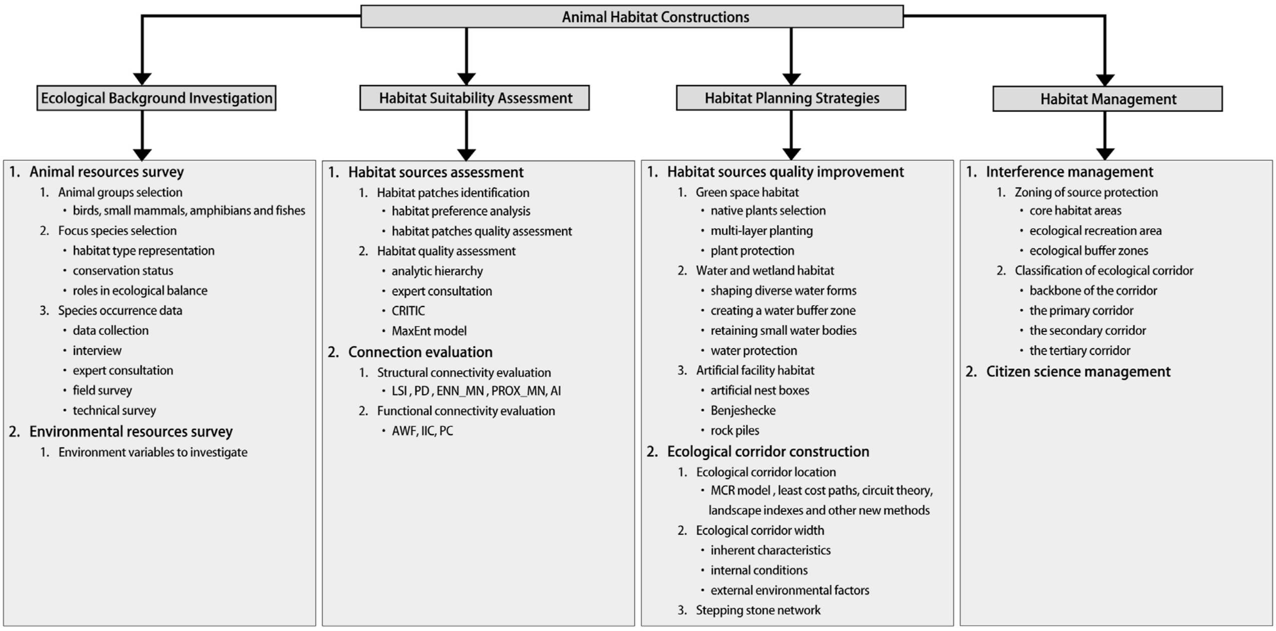

FIGURE 1
The four key steps of animal habitat constructions.

animals with effective living space and communication space according to the spatial pattern of habitat suitability assessment results, including the habitat patches quality improvement and the ecological corridor construction. Habitat patches should cover the main suitable habitat patches, and the area should be able to maintain the space requirements of a certain number of species. At the same time, patches should be integrated and connected to reduce fragmentation at the landscape level and enhance connectivity to facilitate regional population exchanges. Finally, habitat interference management and citizen science management should be carried out to ensure that habitats are rational and functional.

In total, we used 63 keywords in the Web of Science to identify pertinent literature for each step (Table 1). We limited our initial search to peer-reviewed articles, research studies, and other publications published after the year 2000. Earlier publications with significant findings that contributed to the review were later included. We also include a handful of recently published articles that were suggested by our peer reviewers. In an effort to address the literature review topic succinctly, we narrowed the pertinent papers down to a total of 240 papers across all 4 topics. Through this procedure, we were able to provide a reference for future land management decisions and highlight gaps in the literature.

3 Results

3.1 Ecological background investigation

3.1.1 Animal resources survey

3.1.1.1 Animal groups selection

Urban green spaces (Wolch et al., 2014; Li et al., 2017) is vital in providing suitable animal habitats. There are many types of urban animals, and their habitat requirements are also heterogeneous, leading to the assembly of different communities in different urban settings (Aronson et al., 2016).

First, birds, as one of the critical components of biodiversity, are an important element of the food chains (Hedblom and Murgui, 2017). Urban birds have been widely used as environmental bioindicators to assess habitat quality and environmental change (Herrera-Dueñas et al., 2014; Pollack et al., 2017; Bernat-Ponce et al., 2021). Second, small mammals, mainly as primary and secondary consumers in food chains, also play an important role in ecosystem cycles. They are sensitive to environmental changes, because their habitats in cities are often fragmented or replaced by human activities (Fernández and Simonetti, 2013; Łopucki and Kitowski, 2017). Their group size can reflect the quality of habitat and the degree of human disturbance, and they can also be selected as indicator groups of urban biodiversity. Third, amphibians are animals with both aquatic and terrestrial life forms (Cayuela et al., 2020). With a diversity of habitat requirements, they are highly susceptible to negative impacts from habitat conditions changes. In addition, amphibians have strong skin permeability, so they are extremely sensitive to ultraviolet rays, chemical fertilizers, pesticides, herbicides, etc. They can also be used as indicator groups for urban biodiversity. Fourth, mainly as upper organisms of the aquatic food chain, fishes have a significant impact on the existence and abundance of other populations (Hong et al., 2023). They are also sensitive to changes in the water environment and can be used as indicator groups for urban biodiversity (Tonkin et al., 2017; Lyon et al., 2019).

Therefore, this paper selects birds, small mammals, amphibians and fishes as representatives of animal groups. Their habitats and activity spaces cover forests, shrubs, grasslands and waters, which can represent urban habitat types more comprehensively.

TABLE 2 Animal species survey methods.

Method	Object	Description
Data collection	The name, population, distribution area and history of the species	The collection and organization of existing relevant materials. Normative reference documents and authoritative books, such as "The Fauna of China," and official website such as "https://www.animalfactsencyclopedia.com/" related to the species composition or special research aspects of the investigation area can be consulted
Interview	The name, distribution, quantity, use, and local utilization and protection of some species	Through interviews with local residents and objects identification, the effective information that is not disclosed to the outside can be obtained
Expert consultation	The name, distribution, quantity, use, and local utilization and protection of some species	The obtaining of information and advice on wildlife habitats by consulting experts with relevant knowledge and experience, with the aim of helping to protect habitats and wildlife
Field survey	The more accurate information on species distribution and movement	Based on the ground, focusing on species and environmental levels Duro et al. (2007), Zhu et al. (2015). And it is still the mainstream survey method of habitat resources, including transect method, sampling method, mark-recapture, trace counting, fence traps, artificial covering, and artificial shelters, etc.
Technical survey	The more accurate information, location and movement data of species	With the help of modern advanced technology, technical surveys have broken through the limitations of time and space, and reducing the impact on animals and their habitats Pimm et al. (2015). It can better serve wildlife monitoring and ecosystem research, including camera-trapping technology, voiceprint automatic recording, Global Positioning System (GPS) tracking technology, and DNA-barcode technology, etc., Xiao et al. (2020)

3.1.1.2 Focus species selection

In terms of habitat construction, it is not practical to monitor or survey every species. One or more species should be selected as typical indicators for habitat assessment and construction (Simberloff, 1998). Therefore, this paper adheres to the principle of focal species selection (Lambeck, 1997; Hess and King, 2002; Nicholson et al., 2013; Dondina et al., 2020). The selection differs from conservation biology, which is specific to endangered or protected species. While it is out of biological diversity enhancement, the focus species are selected based on their habitat type representation, conservation status, and role in ecological balance. By protecting the habitat required by the focal species, it extends to the most species protection in this group (Lindenmayer et al., 2014).

3.1.1.3 Species occurrence data

Through website or literature data collation, interviews, field surveys and other methods, we can obtain data on the types, quantities, distribution and activity patterns of existing animal species to understand the animal resources in the study area. The survey methods are shown in Table 2.

3.1.2 Environmental resources survey

An environmental resources survey obtains environmental data and clarifies habitat characteristics based on on-site investigation, map surveying, mapping, etc. Through literature reference (Arques et al., 2014; Bradfield et al., 2022; Callaghan et al., 2018; Cayuela et al., 2020; Churko et al., 2020; Curzel et al., 2021; Fahrig, 2003; Fidino et al., 2020; Fleury and Galetti, 2006; Gallo et al., 2017; Huang et al., 2021; Lerman et al., 2021; Matthies et al., 2017; Miller et al., 2022; Narango et al., 2017; Nielsen et al., 2014; Rico-Silva et al., 2021; Taylor et al., 2016; Yates et al., 1997), we determined the commonly used ecological variables around the species occurrence points, as shown in Table 3. In addition, we can calculate variance inflation factors for environmental variables (VIF, Quinn, and Keough, 2002) to avoid high multicollinearity affecting analysis results (Guisan and Zimmermann, 2000).

3.2 Habitat suitability assessment

3.2.1 Habitat patches assessment

3.2.1.1 Habitat preference analysis

Establishing animal habitats requires information about where animals are, why they are there, and when they might be (Aarts et al., 2008). Habitat selection studies provide insights into resource selection at landscape scales and improve our understanding of potential drivers of animal distributions (McIntyre, 1997; Razgour et al., 2011). So habitat preferences analysis is critical to enhancing the biodiversity of urban fringes' green spaces. We can use SPSS for statistical analysis. For example, Pearson's chi-square test (independence test) is used to compare the relationship between the specific location and the land category. Multiple correlations or regression analyses based on the generalized linear model (GLM) are used to compare the relationship between the environmental variables (such as green patch size and side length) and species richness.

According to IUCN Habitats Classification Scheme and land cover map (Lumbierres et al., 2022; IUCN, 2023), from the perspective of landscape planning and design in urban areas, we can divide the habitats of urban animals into three types:

(1) Green space habitat: it has a certain canopy coverage, mainly covered by trees, shrubs and grassland;
(2) Water and wetland habitat: it mainly includes lakes, ponds, streams, ditches, etc., and the vegetation is mostly aquatic plants such as reeds and irises;
(3) Artificial facility habitat: it is artificially placed some animal auxiliary facilities to help animals rebuild their habitat.

TABLE 3 Common environment variables to investigate.

Variable type	Variable name	Description
Plant	Coverage of tree layer	Primary habitats, breeding, feeding, resting, hibernation
	Coverage of shrub layer	Primary habitats, breeding, feeding, resting, hibernation
	Coverage of herb layer	Secondary habitats, permeability for amphibians
	Fallen leaf mulch	Good shelter and heat storage
	Diversity of tree layer	Availability of space and resources
	Diversity of shrub layer	Food source (flower, fruit, seeds) and good shelter
	Richness of tree layer	Availability of space and resources
	Richness of shrub layer	Food source (flower, fruit, seeds) and good shelter
	Richness of ground cover	Food source (flower, seeds)
	Average tree diameter at breast height	Nesting site
	Vegetation Height	Influences the diversity of niches but also the availability of light
	NDVI	Primary productivity
	Nearest distance to forest	Access to terrestrial habitats
Water	Soil moisture variability	Physiological importance for amphibians
	Nearest distance to water	Access to Breeding, feeding, aquatic habitats
	Nearest distance to rock-rubble-sandy ground	Habitats of importance for amphibians
	water body area	Aquatic habitats for waterfowl, warder birds and amphibians
Terrain	Slope	Steeper slopes can obstruct movement for certain species
	Aspect	Sunny or shady slopes will affect the growth and development of species
Others	Traffic volume	Increased mortality
	Urbanization proxy (density of buildings)	Loss, degradation and fragmentation of habitats
	Nearest distance to road	Multiple negative effects (mortality, noise)

3.2.1.2 Habitat patches quality assessment

According to the results of species habitat preference analysis, the most important factors were selected as dominant habitat selection factors. ArcGIS can be used to preprocess data and build related spatial layers. Then weights are assigned to each factor, and in the current studies, analytic hierarchy, expert consultation and CRITIC are practical methods (Dong et al., 2013; Maleki et al., 2016; Yang et al., 2022). Finally, by overlaying factor layers using ArcGIS software, we can evaluate the animal habitats' suitability. If the habitat suitability index is high, the regional biodiversity is equally high.

In addition, we can also choose simulation model to evaluate the quality of habitat patches. The Maximum Entropy Model (MaxEnt), based on the maximum entropy principle and niche theory, is a modeling method that uses mathematical models to induce or simulate the ecological niche requirements of species based on their specific living environment (Phillips et al., 2006). It is currently an effective tool for predicting and evaluating the spatial distribution pattern of suitable habitats for species. This model has a low requirement for the independence of data and can achieve high prediction accuracy even with a small number of distribution points (Pearson et al., 2007; Chen et al., 2012). Researches have shown that the MaxEnt model has significant advantages in terms of accuracy and convenience compared to many niche models (Elith et al., 2006; Gogol-Prokurat, 2011; Xu et al., 2015).

3.2.2 Habitat connection evaluation

Landscape connectivity refers to the degree to which landscape influences the movement of species between habitat patches, including structural connectivity and functional connectivity.

3.2.2.1 Structural connectivity evaluation

In terms of structural connectivity evaluation, MSPA is used to identify regions with significant connectivity from the pixel level (Wang and Pei, 2020; Rincón et al., 2021). Because habitats are landscape entities with considerable range and landscape characteristics, some quantitative information can be provided based on landscape indicators, such as fragmentation and proximity on the landscape spatial patterns (Zhang and Wang, 2006; Cui et al., 2020; Huang et al., 2022), which could be an important basis for connectivity assessment. Therefore, we can use Fragstats software and select the metrics including LSI (landscape shape index), PD (patch density), ENN_MN (mean euclidean nearest-neighbor distance), PROX_MN (mean proximity index), AI (aggregation index) (Zhang and Wang, 2006; Zhao et al., 2019; Cui et al., 2020; Huang et al., 2021).

3.2.2.2 Functional connectivity evaluation

However, the focus of recent studies has shifted from structural connectivity, and not only the spatial habitats arrangement, but also the functional connection of real biological movements and processes (Albert et al., 2017; Matos et al., 2019; Laliberté and St-Laurent, 2020). Graph theory is a technical approach for analyzing the functional connectivity and ecological conservation (Urban et al., 2009; Zetterberg et al., 2010; Clauzel et al., 2018). It presents habitat patches in the form of nodes (Urban et al., 2009; Galpern et al., 2011), and it is the most common and straightforward used method for measuring and assessing various aspects of habitat connectivity (Minor and Urban, 2008; Zhang, 2017). In graph theory, topological metrics introduced by network analysis methods are often used to evaluate functional connectivity (Huang et al., 2021b), simulating the relationships between network nodes (Nogués and Cabarga-Varona, 2014). Network analysis metrics include network ring Path α, the mean number of connections β, the ratio of the number of possible connections γ, and the network density φ (Cook, 2002; Zhao et al., 2019; Huang et al., 2021b). In the application, we can use the Conefor software (http://www.conefor.org/) (Saura and Torné, 2009), and the following metrics are commonly selected, including the area-weighted flux (AWF), the overall connectivity index (IIC) and the possible connectivity index (PC), etc. (Matos et al., 2019; Cui et al., 2020; Guo et al., 2020; Huang et al., 2021b). Among all kinds of connectivity indices, the Integral Index of Connectivity (IIC) and COHESION are the most popular and suitable indices for evaluating landscape connectivity (Saura and Pascual-Hortal, 2007; Zhang et al., 2019). The cohesion index measures the structural connectivity of a landscape (Zhang, 2017), and the IIC index is one of the best binary indices for functional connectivity analysis (Saura Santiago and lucía, 2008; Mahmoudzadeh et al., 2022).

Finally, the scientific combination of the two methods can effectively evaluate the structural and functional connectivity of habitats.

3.3 Habitat planning strategies

3.3.1 Habitat patches quality improvement

The existence of a habitat patch by itself does not fully guarantee higher species richness and abundance (Watling and Donnelly, 2006; Lee and Rhim, 2017). The environment within a habitat patch is critical to improving the habitat quality (Laidlaw, 2000; Prevedello and Vieira, 2010). Habitat quality indicates the capacity of an ecosystem to deliver the resources and conditions needed for wildlife and is a crucial determinant of biodiversity (Hall et al., 1997; Terrado et al., 2016; Aznarez et al., 2022). According to the physiological characteristics and habitat preferences of species, more favorable conditions should be created, and the stability of ecological habitat structure should be enhanced, mainly including the improvement of the quality of green space habitat, water and wetland habitat, and artificial facility habitat.

3.3.1.1 Green space habitat

Mixed woodland with trees, shrubs and grass has a complex plant community structure, which can provide a variety of habitats for animals. Plant flowers, fruits, and seeds of plants are also important food sources for animals. For example, birds like to jump between trees to find food, hedgehogs tend to move in bushes, and frogs need the abundant grass to shade. Therefore, green space habitat should avoid increasing the density of single plant species and planting structure, which would result in biotic homogenization. Such habitat cannot support the needs of various animals (McKinney, 2002; McKinney, 2006; Choudaj and Wankhade, 2022).

① Native plants selection

The current studies (Potgieter et al., 2017; Potgieter et al., 2019; Langmaier and Lapin, 2020; Choudaj and Wankhade, 2022) find that increase in the richness and diversity of native species increased the richness and diversity of animals. In the same case, a decline in the richness of animals as an increase in the density of exotic plants. Exotic species can replace native species and lead to loss of local biodiversity (Florianová and Münzbergová, 2017). In particular, they can destroy native habitats, limit biodiversity by reducing breeding, nesting and foraging space, and alter prey-predator relationships. This is because exotic plants do not satisfy the local habitat selection mechanism and do not have the structure adaptation. While native plants require little maintenance so that they can save money and water. They are less sensitive to local weather and rarely invasive so that they are a better food source for native animals (Mohammad et al., 2013). At the same time, tall native plants with thick trunks and dense foliage, are also good places for animals to hide from natural enemies and build nests. Therefore, native plants are the preferred plant types for restoring natural habitats.

② Multi-layer planting

Vegetation composition is a major factor in animal habitat selection in urban environments. Building a multi-layer plant community structure with an "arbor-shrub-herb" transition can provide animals with various ecological niches and positively impact animal habitats.

(1) Arbor forest layer

Maintain the forest core area. A large area of forest core area is important. Many previous studies have shown that populations persist longer in larger patches of suitable habitats than in smaller patches (Stacey and Taper, 1992; Capizzi et al., 2003; Jorge, 2008). Because these species require large areas of woodland to establish breeding grounds, build nests and raise young. In urban environments with high human influence, the minimum size of a circular forest is 3.1 ha and that of a square forest is 4.5 ha. The forest cores are not only essential for protecting habitat, but also play a vital role in dispersing seeds, maintaining populations and gene pools, and sustaining life cycles (Cho et al., 2021).

Keep the fallen and dead leaves. The rich vegetation cover of woodlands will shed a large amount of litter in autumn and winter, and a particular area of fallen and dead leaves should be reserved, with some small stones used to form caves or gaps. It can provide refuge for frogs, and the soil layer under the fallen leaves is relatively cool and humid, which is beneficial for frogs to dig and live and keep their bodies moist. The fallen and dead leaves is also an excellent habitat choice for arthropods and molluscs, and can be food of birds, small mammals and amphibians.

Preserve the dead and fallen trees. People often like to remove old trees, including dead branches. Because their poor health affects the aesthetics of the landscape, but these trees are important for nature conservation because the removal of old dead trees will exacerbate forest degradation and cause ecological imbalance, and they are also suitable habitats and shelters for animals (Oleksa and Gawronski, 2006; Oleksa et al., 2013; Horák, 2017). For example, the larvae of termites and certain beetles feed on broken branches and low tree branches, and they can become food for animals such as birds, hedgehogs, and squirrels (Fergus, 2019). Hollows of various sizes may form in dead or aged tree trunks and branches, which are valuable homes for wildlife. Many birds and mammals use burrows for nesting, rearing young, resting in cold or stormy weather to store food, hiding from predators, or hibernating.

For over-dense woodlands, the gaps are equally important. Because the gaps between the woodlands can not only provide a resting place for flying birds, but also allow sunlight shine directly on the ground, promoting the growth of low-level shrubs and grasses (Niu et al., 2021). The plant community has sufficient growth and natural succession space. Their wide leaves and dense branches can protect young animals from predation, as well as, flower buds and berries and attracted insects are also a good source of food for them.

(2) Shrub layer

The shrubs and grasslands mainly distribute on the edge of woodlands and open spaces, steep slopes of mountains, and demolished plots with poor soil (Niu et al., 2022), it is necessary to reduce intervention and create a natural community of multi-layered shrubs with different densities and heights.

Appropriately increasing the number of fruit-bearing tree species in early spring and winter (Zhou et al., 2018; Niu et al., 2022), and more functional plants such as jujube (*Ziziphus jujuba*), hairy cherry (*Prunus tomentosa*), Vitex (*Vitex negundo*), large flowered vetch (*Vicia bungei*), etc. are supposed to be planted. Their nuts, berries, and insects that spread pollen and nectar in the forest are important food sources for birds, small mammals and amphibians (Sulaiman et al., 2013; Bergner et al., 2015).

Planting low shrubs with clump-like plants and dense branches and leaves is an excellent place for animals to build nests and avoid natural enemies (Rhim et al., 2015). Scattered stones are piled up around the shrubs, and the surrounding soil environment is loosened, which can create the shaded and moist terrestrial environment for amphibians to hide and overwinter.

(3) grassland layer

The grassland is a significant habitat for insects. Thus it is also an important predation area for insectivorous birds, herbivorous seed birds, small mammals and amphibians (Murgui, 2009; Pithon et al., 2021). A variety of grass species should be selected. The common types are cool-season grasses and warm-season grasses. Warm-season grasses have stiffer stalks that are less likely to be overwhelmed by snow, providing shelter in winter and nesting space in spring. However, the warm-season grasses germinate late in early spring, but the cool-season grasses can be planted as food supplements and temporary shelters for small mammals and amphibians before the warm-season grasses starting to grow or after the dormancy period (Wang, 2021). In addition, wild flower seeds can also be sown to increase the richness of the grassland further.

The grassland habitat with variable micro-topography can produce different light, water and soil conditions locally, and promote the generation of differences in plant communities, which is conducive to enhancing the richness of animals. The large flat lawns should be avoided. On the contrary, micro-terrain design can be used to create belt-shaped valley spaces and shallow pits on the ground, where rainwater can gather to form various seasonal water bodies such as puddles and streams. Studies have shown that frogs and toads such as philodendron have a high hatching rate in seasonal water bodies at a depth of 3–4 cm (Lin et al., 2018).

(4) Aquatic and wet plants layer

For wet plants in the water, from the shore to the water, it is advisable to follow the plant mix of "terrestrial trees, shrubs and grasses - wet plants - emergent plants - floating plants - submerged plants." Water-resistant reeds or multi-branched shrubs are planted in nearshore mud pools to provide breeding places for birds. The growth of emergent plants provides hiding space for amphibians and small mammals to breed and feed. The floating and submerged plants can become food for plankton and aquatic insects, eventually food sources for amphibians. The overall water area should maintain a relatively large aquatic vegetation coverage, providing a large hiding space and a sufficient area of resting spots for birds and amphibians, as well as (Babbitt and Tarr, 2002; Hartel et al., 2007) preventing amphibians from being exposed to excessive ultraviolet rays after landing (Wu et al., 2011). However, the vegetation cannot completely cover the surface of the pond, because the complete coverage of vegetation reduces the water temperature and dissolved oxygen concentration, leading to a reduction in the number of algae and epiphytes in the water, thereby reducing the food source and foraging success rate of amphibian larvae (Skelly et al., 2002; Maerz et al., 2005; Thurgate and Pechmann, 2007).

③ Plant protection

The plant protection for habitats can determine whether habitat patches quality has achieved the target, and intervene or modify the strategies based on long-term monitoring results to maintain the interests of the site. First, from the perspective of protecting animal food sources, nest sites, shelters and large-scale non-directional insect removal operations should be avoided in near-naturalized habitats, and tree holes should not be blocked. Excessive pruning should only be done on necessary roads (Yang et al., 2023). A low-disturbance method should be adopted to protect the self-growing ground cover plants, simulating the form and community structure of natural secondary forests, shrubs and grasslands (Xian et al., 2020; Zhou et al., 2018). Second, the healthy growth of plants is an important basis for ensuring the stability of animal habitats. The monitoring content of vegetation growth includes whether the branches are strong, whether the leaves are whole in color, whether there are dead and diseased leaves, etc (Yin et al., 2017). The plants with weak growth should be updated and replaced in time.

3.3.1.2 Water and wetland habitat

Water is the most important habitat type for animals to survive, as well as humans. All animals require the consumption of water to survive and reproduce. And they prefer to choose the area close to the water source as their habitat (Zhang et al., 2017). Therefore, the design of water bodies and their surrounding environment is particularly important.

① Shaping diverse water forms

Firstly, water bodies with irregular shorelines attract more wildlife. Creating diverse water forms such as rivers, lakes, islands, beaches, pits, and ponds, as well as different slopes and water depths of river banks, can create rich water environments and water landscapes to increase the diversity of water habitats (Lin et al., 2016). Secondly, the larger the water body area is, the more likely it is to support more plants and wildlife. However, when the water area exceeds a certain level, it is advisable to build islands, which are essential habitats and stops for wetland birds (Li et al., 2014; Yuan et al., 2021). Thirdly, the water body slope is also a significant habitat space. During the low water level period, a larger area of land will be exposed above the water surface, showing a mud-like shape and providing a substrate for the germination and growth of wetland plants. For most wetlands, a slope of 1:10 is suitable (Fergus, 2019; Wang, 2021). A gentle slope can make it easier for amphibians to enter and exit the wetland and make it easier for mammals to drink water (Huang et al., 2018). In order to increase diversity, different slopes can be designed in other wetland areas, but most slopes should be natural and gentle (Fergus, 2019).

② Creating a water buffer zone

The hard river banks should be naturalized, and the near-water area should be transformed into the grass and scrub habitats to restore the aquatic ecosystem by reducing erosion and stabilizing the revetment. First of all, grass, wildflowers, shrubs and trees are planted on both sides of the water body as a buffer zone. The width of the buffer zone can be set between 7 and 15 m or even wider, which can intercept runoff, control soil particles, chemicals, pollutants, etc. from entering the wetland, and protect the wetland from the sediment or pollutants of surface runoff (Fergus, 2019). Secondly, the buffer zone can also be used as a moving corridor and breeding area for wild animals, especially to create extremely favorable habitat conditions for wild waterfowl animals, and some mammals also like to move in the riparian zone (Fergus, 2019). Thirdly, a certain buffer area of exposed mudflats is needed. Because this type of shoreline can effectively meet the avoidance needs of small and medium-sized frogs during the day (Li, 2018; Lin et al., 2018). In winter, amphibians can also dig holes in the mud pool sediments for hibernation.

③ Retaining small water bodies

Small water bodies, such as ponds, make up a large proportion of the global freshwater surface (Downing et al., 2006). Given their ubiquity and variability in habitat types, ponds are considered “key systems for biodiversity conservation” (Oertli, 2018) and support greater diversity than similarly sized rivers and lakes. Because they can serve as shelters and corridor/stepping stone connectors (Le Viol et al., 2012; Maynou et al., 2017; Davies et al., 2008). Evidence from urban small water ponds suggests that they support a remarkable diversity as a miniature life network (Bishop et al., 2000; Le Viol et al., 2009; Hammer et al., 2012; Hassall and Anderson, 2015; Hill et al., 2017; Meland et al., 2020). Thus, retaining small water ponds can maintain or promote regional biodiversity by providing additional habitat. At the same time, you can put stones and sunken wood in the pond to attract amphibians to breed, and to attract birds to stop and rest.

④ Water protection

Animals usually use water bodies as the main space for feeding and drinking, and some birds and amphibians use aquatic plants and other materials for nesting on the water’s surface. Therefore, conservation methods such as salvaging aquatic plants and spraying pesticides in the park to keep the water clean should not be completely applied. Instead, pollution discharge should be controlled from the source, and the degree of manual management should be reduced. The self-purification ability of the water body should be restored to maintain the integrity of the aquatic ecosystem.

In addition, numerous studies indicate that regular management of ponds is critical to maintaining their biodiversity conservation function (Briers, 2014; Hassall and Anderson, 2015; Holtmann et al., 2018). Fish stocking, eutrophication, and woody overgrowth should be avoided in these ponds. The connectivity of the existing stormwater network can be improved by creating new ponds, which can be built from water bodies that can serve as stepping stones. General stormwater pond management strategies include maintaining ponds during early successional stages to facilitate the emergence of pioneer habitat specialists (Holtmann et al., 2018) through sludge prevention of terrestrialization and logging of woody plants along shorelines to provide sunny microhabitats. These practices also increase the macrophyte diversity and enhance the aerobic decomposition processes to counteract eutrophication (Sayer et al., 2012; Deacon and Samways, 2021). In addition, they conform to a reconciliation ecology since they help maintain the ponds’ technical function (Šigutová et al., 2022).

3.3.1.3 Artificial facility habitat

Another method to help mitigate habitat loss from urbanization is to use artificial structures to create new refuges and attraction facilities for animals. Humans can temporarily provide a range of different types of facilities, such as nest boxes, bat boxes, insect hotels, toad houses, etc. (Gaston et al., 2005; Davies et al., 2009), to introduce or translocate species, and monitor species abundance and distribution (Beyer and Goldingay, 2006; Williams et al., 2013; Goldingay et al., 2020). Obviously, any facility’s physical structure should meet the focal species’ requirements.

① Artificial nest boxes

Artificial nest boxes are built for animals, allowing animals to rest, reproduce or avoid natural enemies. For small mammals such as hedgehogs, they prefer to build nests in hedgerows and woodlands (Haigh et al., 2012; Bearman-Brown et al., 2020), because the nests built under the shelter of the ground can reduce the risk of detection by predators (Evans et al., 2002), and also protect them from adverse weather conditions, such as reducing rain, wind and direct sunlight (Jackson and Green, 2000). At the same time, hedgehogs are sensitive to changes in the microclimate inside the nest: high levels of humidity can cause the decay of nesting materials (Morris, 1973), the presence of parasites (Heeb et al., 2000) and impaired evaporative heat mechanisms in animals (McComb et al., 2022). During their hibernation, low temperatures in the nest would accelerate individual heat loss and lead to rapid depletion of fat stores (Soivio et al., 1968; Jansen, 2004; Gazzard and Baker, 2022). Therefore, when setting up artificial nest boxes, the leaves of broad-leaved trees are preferred because they can be "woven" to form a layered structure, which is believed to maintain the temperature inside the nest and gas transfer (Gazzard and Baker, 2022). Second, nests are placed in sheltered places, such as under shrub cover. The distance between nests varies between 2–323 m (Jensen, 2004; Yarnell et al., 2019). Third, bedding materials such as leaves, hay, or shredded newspaper inside the nest box had a significant positive effect on resting but a (non-significant) negative effect on reproduction. This is because females with dependent young are susceptible during breeding. Pregnant females may interpret the presence of bedding if their nest is disturbed as an indication of other hedgehogs, and the mother may abandon the breeding nest or kill the young (Gazzard and Baker, 2022).

For the design of artificial nest boxes for birds, the shape and size need to be determined in conjunction with the size of the target bird. The materials generally use wood, clay, etc., which are functional and durable. The served birds are secondary-cavity nester birds that use existing caves as nest sites. The nest box style and layout area should be determined according to the ecological habits of the species. For example, the nest boxes of Beijing swifts and barn swallows are arranged on building facades, and the nest boxes of mandarin ducks and woodpeckers are hung on tall trees.

② Dead hedges

Dead hedges are piled up with stones, branches, etc. to form a small porous ecological environment. The interior is filled with soil with seeds, and thorny vines are planted to protect the plants in the pile from herbivores. Dead hedges are equivalent to a kind of "artificial bushes," which can be set up in open areas lacking hidden spots and understory spaces lacking bushes, providing shelter for birds and small animals. The common size is 6 m*6 m wide and 1.2–2.4 m high. It consists of a three-layer structure: the substrate layer, the middle layer and the top layer. The substrate layer is made of wood, wood stones and plants arranged in a grid, or the stones are arranged in a triangular shape. The middle layer is made of small pieces of branches and sticks stacked repeatedly, and the top layer is covered with thorny vines or branches. Dead hedges should be arranged at a distance of 10–45 m so that nearby animals can quickly reach and use them (Wang, 2021).

③ Rock piles

Rocks add important cracks, cavities, and other structures to habitats that provide cover for animals. Rock squirrels are especially fond of rock structures. They are good at climbing and jumping on undulating rocks. In natural environments, rock squirrels also eat, rest or groom on rocks. Weasels and hedgehogs also roost and breed in caves or rock piles. Placing rock mounds in scrubland, fences, or wetland revetments can create a very important structural element for habitats, which can also be supplemented by planting some food-producing vines or shrubs between the rocks (Fergus, 2019). Some amphibians like to hide in aquatic cave environments. Stone slabs can be built in places with sufficient water sources to create dark and hidden spaces, such as caves and rock crevices, which are convenient for amphibians to survive and reproduce.

3.3.2 Ecological corridor construction

3.3.2.1 Ecological corridor location

Ecological corridors (ECs) have been identified as one conservation tool to provide linkages or restore connections between isolated ecological spaces in human-modified landscapes (Matthews, 2008) to solve ecological fragmentation problems and maintain biodiversity. Methods for constructing ecological corridors include minimum cumulative resistance (MCR) models (Pirnat, 2000; Dong et al., 2020; Xiao et al., 2020), least cost paths (LCP) (Adriansen et al., 2003; Zhang et al., 2019; Morandi et al., 2020), circuit theory (McRae et al., 2008; Song and Qin, 2016) or landscape indexes (Xiao et al., 2020). A small number of studies have developed new tools, such as Moreno et al. (2020), by applying GIS, GPS and the Normalized Difference Vegetation Index (NDVI) derived from Santinel-2 to determine vegetation cover, chlorophyll activity and plant vigor to identify the potential of green corridor. Many studies (Rudd et al., 2002; Kong et al., 2010; Yang et al., 2017; Zhang et al., 2019; Zhao et al., 2019) applied the Gravity Models to simulate the interactions between nodes connected by corridors, whereby the priority of these corridors could be determined.

3.3.2.2 Ecological corridor width

The ecological corridor is not a line but a strip space containing the ecological land along the central line. Although there are several methods to determine the location of ecological corridors, in practice, the width of ecological corridors still needs to be improved. Their boundaries are often subjectively identified or estimated (Avon and Bergès, 2016; Liang et al., 2018; Dong et al., 2020). According to the research of Shen and Wang (2022), five indicators are selected from the following three dimensions as the key factors that significantly affect the width of ecological corridor construction (Table 4). 1) The inherent characteristics of ecological corridors, including path length and the capacity of connecting important ecological spaces; 2) The internal conditions of the ecological corridor, including the number of ecological spaces and the ecological functions on the path; 3) The external environmental factors of the ecological corridor, including the land use types along the path.

In addition to being affected by the above indicators, the appropriate width of the ecological corridor should be limited to a certain range. According to the landscape ecology, ecological corridors with widths>12 m and with tree, shrub, and grass structures are considered to have ecological significance. These qualities are also necessary for species living within

TABLE 4 Impact index system of the width of urban ecological corridors (Shen and Wang, 2022).

Evaluation base (Identified key attributes)	First-level index	Second-level index	Description and influencing way	Quantification methods
Length Connectivity	Inherit feature	Structure: Path length	The length of the potential path, positively correlated with its width	MCR model
		Function: Ability to connect important ecological spaces	The functional importance/connectivity, positively correlated with its width	Gravity model
Patch Composition	Internal condition	Structure: Number of ecological spaces on the path	The degree of the fragmentation of ecological spaces on the path, positively correlated with its width	MCR model
		Function: Ecological function of ecological spaces on the path	The overall capacity of multi- ecosystem services provided by ecological spaces on path, positively correlated with its width	MESC index
Matrix barrier	External environment	Function and structure: Land-use pattern along the path	The cumulative ecological resistance of surrounding land uses, negatively correlated with its width	MCR model

them (Shen and Wang, 2022). Therefore, 12 m is the minimum effective width of the ecological corridor. Generally speaking, the wider the ecological corridor is, the better the internal habitat quality is, and the greater the overall ecological benefits. However, the corridor cannot be as wide as possible, due to the consideration of land use, cost economy, and species spanning range. According to the studies on ecological corridor planning and design (Zhu et al., 2005; Teng et al., 2010; Zhang et al., 2017; Xiao et al., 2020), we found that 1,000 m is an appropriate width for ecological corridor planning within the urban-rural gradient in China. Therefore, in this paper, the width of the ecological corridor can be between 12 m and 1,000 m.

3.3.2.3 Stepping stone network

Stepping stones are small habitat patches that have crucial ecological linkage functions. Although these landscape patches are small and have weak ecological functions, they can serve as transfer stations for biological migration and become an important part of the ecological corridor network (Baum et al., 2004). According to the range of potential ecological corridors, we can use ArcGIS's "overlap" tool to screen the stepping stones in buffer zones of habitat sources and potential corridors. Then, the stepping-stone network can be built with the Build Network and Map Linkages tools in Linkage Mapper (Zhang and Song, 2020). The network simulates biological communication between important habitats and stepping stones. Finally, the stepping stone network is embedded in the ecological corridor network to form a multi-level network structure. This network structure delineates the connections between landscape patches in the area (Wang et al., 2022).

3.4 Animal habitat management

Nowadays, most habitat designs are difficult to play a substantive role or exert ecological benefits in the long run. An important reason is the lack of habitat management, which requires the joint efforts of the whole society. Habitat management can monitor and give feedback on the rationality of habitat construction, help designers or managers improve the habitat environment, and provide more experience for future biological protection work. In the study, it is divided into two parts.

3.4.1 Interference management

The urban environment is the home where humans and animals live together. But human activities may cause disturbances in many species' predation, foraging, and mating activities (Bateman and Fleming, 2014; Mikula et al., 2018; Gallo et al., 2019). Previous studies have found that many animals tend to avoid human interaction and prefer habitats with lower human population densities (George and Crooks, 2006; Gehrt et al., 2009). Therefore, we need to control the type and intensity of people's activities.

3.4.1.1 Zoning of source protection

In general, the "one-size-fits-all" approach of the functional positioning leads to little practical significance. Depending on the species and environmental factors in the area, the functional orientation of the habitat should also vary. The precedence principle (Minor and Urban, 2008; Liang et al., 2018) is used to identify priority areas for animal habitat conservation, as described below. With large amounts of human infiltration into natural green areas, protection in the form of protected areas alone cannot be fully effective (Nori et al., 2015). The presence of sufficiently wide buffer zones and the concentration of pedestrian traffic is proven to be more effective in protecting urban biodiversity.

In order to balance the needs of animal habitats and human activities, it is necessary to delineate areas with different development intensities. According to the evaluation results of habitat suitability, 1) Set the area with concentrated distribution of animals and high suitability in the habitat network as the core habitat areas. The core habitat areas provide suitable habitat conditions for the survival and reproduction of animals. At the same time, it is also the core area of animal protection and strictly restricts construction and interference from human activities; 2) Set up areas with low animal distribution density, low habitat suitability and non-moving paths as ecological recreation areas. Based on the low intensity of recreational activities and damage to the ecological background, various recreational services should be created as much as possible to balance ecological habitat protection and recreational

TABLE 5 Projects types and contents of citizen science management (McKinley et al., 2017).

Management type	Public participation
Species management	Providing information on species abundance, distribution, phenology, and behavior
Ecosystem services management	Providing resource valuation; mapping ecosystem services
Invasive species control	Providing real-time monitoring (an early-alert system)
Pollution detection and enforcement	Providing information on water and air quality

functions. 3) The ecological buffer zones between the core habitat areas and the ecological recreation areas buffer the interference of human activities in the core habitat area. It is the primary place for urban residents to observe, experience nature, and carry out popular science education.

3.4.1.2 Classification of ecological corridor

① Determine the backbone of the corridor

The corridors most frequently used by animals were calculated using the kernel density model (Teng et al., 2011) and identified as backbone corridors, constituting the ecological corridor network. The kernel density distribution is a spatial analysis method. It calculates the distribution density of event points in the adjacent space, which can directly reflect the aggregation or discrete distribution characteristics of point groups (Yang et al., 2022). The kernel density analysis provides information about the density of each corridor, with larger values indicating the most likely path animals would have traveled, and it is used to estimate the distribution and habitat range of animals (Worton, 1989; Feberg, 2007; Li et al., 2010; Teng et al., 2011).

② Corridors classification

Corridors are classified according to objectives of city planning and the balance of ecological protection and economic development. This is necessary to adapt ecological corridors to limited land and financial resources. Referring to the definition of corridor classification and the trend of diffusion of animals between corridor nodes (Yang et al., 2022), corridors are divided into three levels to correspond to three ecological security levels: primary corridors, secondary corridors, and tertiary corridors. 1) The primary corridor has the largest core density and the widest width, connecting many important large-scale ecological spaces, most of which are located in areas with fewer human activities and disturbances. It also assumes diverse functions for ecosystem services, such as shaping the landscape, connecting the source of habitat and adjusting the microclimate. 2) The secondary corridor has the second highest core density and broader width, which connects stepping stones. 3) The tertiary corridor has the most negligible core density and the narrowest width. It connects more ecological spaces in the green space on the edge of the city and can be built as traffic green belts or scenic trails. The ecological culverts, ecological overpasses and other structures can be used to guide the safe migration of species on both sides of the road to prevent interruption of landscape flow and ecosystem service flow. It can also be combined with leisure greenways or short-distance leisure places for urban residents.

3.4.2 Citizen science management

Citizen science is led by scientists in academic, government, nonprofit, or commercial organizations and is conducted jointly by professional scientists and paid technicians or students (Nichols and Williams, 2006; Sullivan et al., 2009; McCormick, 2012; Hemmi and Graham, 2014; McKinley et al., 2017). Volunteers help to generate scientific information for conservation scientists, natural resource and environmental managers, and other decision-makers. Or stimulate public input and participation in natural resource and environmental management and policy-making. Citizen science has emerged as a powerful tool for addressing many of the challenges environmentalists face (McKinley et al., 2017; Table 5). For example, citizen science is being used to understand the effectiveness of urban wildlife habitats (Mowry et al., 2021) by collecting big data from citizen scientists. These data can be used to implement adaptive management in response to uncertainty caused by environmental changes, improved sampling methods, and species adaptation (Richardson et al., 2020). We advocate adopting an adaptive management strategy, establishing a long-term data network, and revising management plans annually based on modeling results. With the latest species and environmental information, policymakers can adjust their management strategies, remain flexible, and respond to changes in the urban environment and the species they monitor.

4 Conclusion

Constructing suitable habitat environmental conditions is the most direct and effective way to protect animals. In this paper, we synthesized research from a variety of environmental fields and consolidated the findings to act as a reference for future planning, management, and policymaking in city. This paper has three implications for the construction and research of urban animal habitats. 1) In terms of resources investigation, various methods are used to obtain data, such as data collection, interview, expert consultation, field survey and technical survey. The accuracy and richness of multi-source data can provide reliable basic support. 2) In terms of evaluation and planning, the hotspots of animal distribution and the suitable patches evaluated by the model can be combined to delineate the specific spatial range of source areas and ecological corridors. The habitat characteristics of animals' preferences are an important basis for habitat construction. And on the basis of satisfying the green coverage and the plants ecological function, highlighting the dominant position of animals in green space is the critical way to ensure the success of habitat construction. 3) Finally, in terms of habitat management, by encouraging positive human intervention and avoiding negative behaviors, the balance between humans and animals can be realized to achieve the maximum function and sustainability.

Overall, our review has highlighted the 4 key steps of animal habitat constructions throughout recent literature to create a blueprint for future development and management. However, to incorporate these benefits into urban green space, further researches are needed to construction methods. For example, regions can use their own multi-source data to draw habitat maps, explore and evaluate the suitable habitat region by combining geographic information systems and biodiversity research, which can provide scientific basis for biodiversity protection and urban ecological planning. Besides the important habitat sources under centralized protection, we also need to pay attention to small and micro green spaces, brownfields and green roofs, etc., and actively call on community residents to share the responsibility for daily management and maintenance. In addition, the current literature focuses on the scientific research of a single species or a single animal group. And each species is part of the ecosystem and there are fluidity and integrity in the ecological cycle. Future research studies need to consider the ecological relationship between species and explore the construction models and methods of urban composite habitats from the perspective of integrating multiple species.

Author contributions

ZL and HY conceived the idea. QC and ZW collected the data. ZL and YW wrote the manuscript with input from HY. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Centring localised indigenous concepts of wellbeing in urban nature-based solutions for climate change adaptation: case-studies from Aotearoa New Zealand and the Cook Islands

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Nature-based solutions (NbS) offer significant potential for climate change adaptation and resilience. NbS strengthen biodiversity and ecosystems, and premise approaches that centre human wellbeing. But understandings and models of wellbeing differ and continue to evolve. This paper reviews wellbeing models and thinking from Aotearoa New Zealand, with focus on *Te Ao Māori* (the Māori world and worldview) as well as other Indigenous models of wellbeing from wider *Te Moana-nui-a-Kiwa* Oceania. We highlight how holistic understandings of human-ecology-climate connections are fundamental for the wellbeing of Indigenous peoples of *Te Moana-nui-a-Kiwa* Oceania and that they should underpin NbS approaches in the region. We profile case study experience from Aotearoa New Zealand and the Cook Islands emerging out of the Nature-based Urban design for Wellbeing and Adaptation in Oceania (NUWAO) research project, that aims to develop nature-based urban design solutions, rooted in Indigenous knowledges that support climate change adaptation and wellbeing. We show that there is great potential for nature-based urban adaptation agendas to be more effective if linked closely to Indigenous ecological knowledge and understandings of wellbeing.

KEYWORDS

wellbeing, adaptation, nature-based solutions, Aotearoa New Zealand, Cook Islands, Indigenous people

1 Introduction

Climate change is the most significant health issue of our times (Costello et al., 2009; Smith et al., 2014; World Health Organisation, 2021). Climate change results in direct impacts on human health, including deaths, illness and injury due to extreme weather events. In addition, significant indirect impacts are mediated by a complex and powerful interplay of social, ecological, and economic factors. These indirect impacts of climate change on human health include: shifting patterns of infectious disease; air pollution; freshwater contamination; impacts on the built environment from sea level rise and storm events; forced migration; conflict over scarce resources; increasing food insecurity; and (possible) economic collapse (McIver et al., 2016; Tukuitonga and Vivili, 2021; Romanello et al., 2022). Emerging research also highlights the deleterious effects of climate change on mental health (Gibson et al., 2020; Tiatia et al., 2022).

The health impacts of climate change, and in particular the harm caused by the increased frequency and intensity of storm events linked to climate change, have heightened the need to provide urgent solutions that protect communities and enhance resilience (Romanello et al., 2022). In *Te Moana-nui-a-Kiwa* Oceania, including Aotearoa New Zealand (Figure 1), recent events (such as damaging floods and cyclones affecting Aotearoa New Zealand in January and February 2023, and Vanuatu in February and March 2023) have highlighted the urgent need to adapt to climate change (Ministry for the Environment, 2022). Using nature-based solutions (NbS) is one way of doing this.

NbS are actions to protect, conserve, restore, and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems, which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human wellbeing, ecosystem services and resilience and biodiversity benefits (Cohen-Shacham et al., 2016). This definition emphasises that the overall aim of NbS approaches is to generate multiple societal, cultural, health and economic co-benefits for people while conserving, regenerating, or restoring ecological and biodiversity health (IUCN, 2023). Understanding that the health of ecosystems, and the biodiversity within them, is essential for human survival, while leveraging the patterns and functions of social-ecological systems and ecosystem services across and within interconnected landscapes, ocean ecologies and socio-cultural contexts, is crucial to the successful design and implementation of NbS (Cohen-Shacham et al., 2016). Working with nature, rather than against it or without it, often leads to more effective, economical and culturally appropriate responses to societal challenges while at the same time conserving or restoring biodiversity (Pedersen Zari et al., 2022).

Central to this paper is the principle that for the Indigenous communities of *Te Moana-nui-a-Kiwa* Oceania impacted by climate change, localised understandings of wellbeing, or "placing wellbeing" (Panelli and Tipa, 2007; Tiatia-Seath et al., 2020) must inform a full assessment of impact and potential responses, including NbS. In short, nuanced and contextualised understandings of wellbeing must be central to Indigenous-led and focused adaptation efforts (Kiddle et al., 2021). It is also vital to understand that relationships between people, the land, ocean,

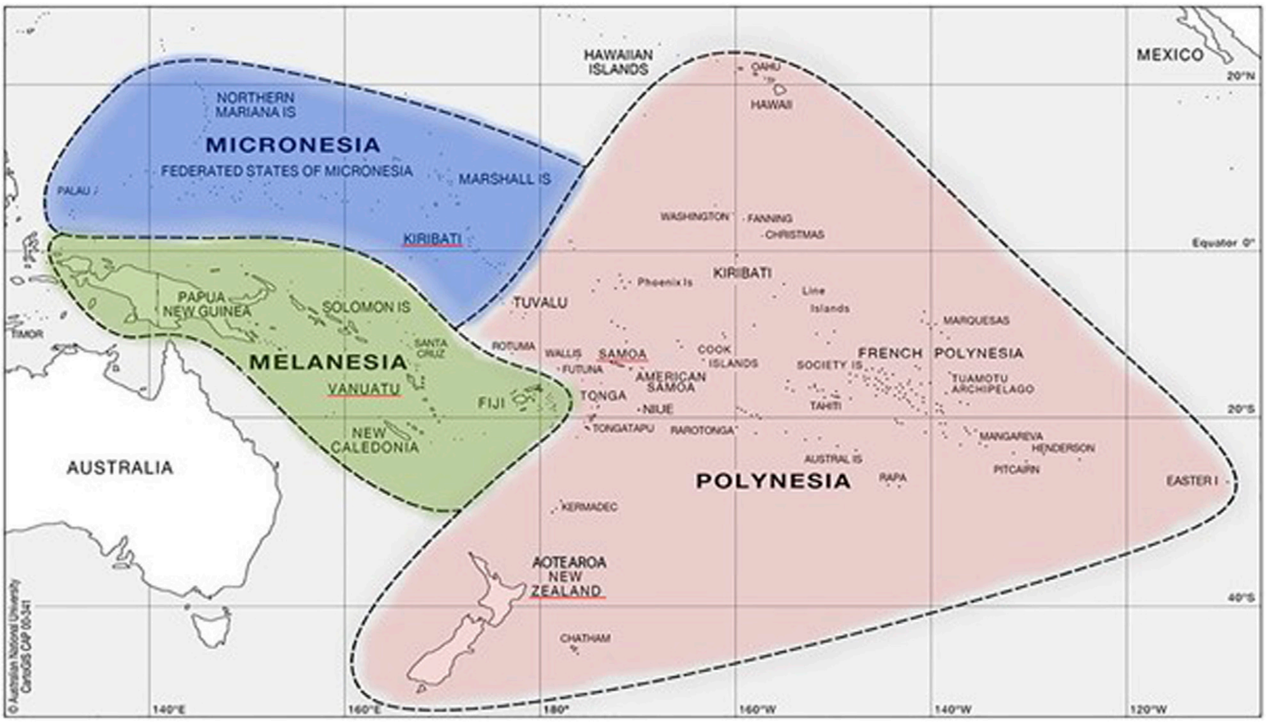

FIGURE 1
Regions of *Te Moana-nui-a-Kiwa* Oceania. Source: Adapted from Australian National University (CC License).

mountains, rivers, forest, animals and so on are different in *Te Moana-nui-a-Kiwa* Oceania than in other parts of the world. For example, in *Te Ao Māori* (Māori world and worldview), genealogy at its most profound, includes a more-than-human lineage and kinship. Māori are literally related to certain mountains, rivers, and bodies of water which are seen as living entities in their own right (expanded upon in Section 3) (Yates, et al., 2023). This means to intervene in, regenerate, manipulate, or work with "nature" has very real spiritual connotations and potentially social justice outcomes related to wellbeing, particularly for Indigenous peoples. Understanding this, at least in the context of *Te Moana-nui-a-Kiwa* Oceania, will ensure that NbS are contextualised and support fundamental values, and thus will be more likely to be successful in terms of ecological and climate outcomes, but also holistic human wellbeing. Internationally agreed definitions and practices of NbS are useful, but these must be locally contextualised in different parts of the world to fit with differing worldviews, particularly related to human-nature relationships. Without such contextualisation, NbS run the risk of undermining local or Indigenous notions of human and ecological wellbeing, worldviews, and social justice agendas. Climate adaptation and NbS should not become a tool of neo-colonisation of spaces or ideas, even if unintentional.

This article reviews Indigenous wellbeing models from Aotearoa New Zealand and wider Oceania; and in doing so brings attention to the important role of NbS and NbS approaches that centre human wellbeing, and the need for a more nuanced *Te Moana-nui-a-Kiwa* Oceania approach to NbS. The article presents the summarised findings of a literature review and critically links Indigenous wellbeing models, climate impacts, and social justice factors within the context of *Te Moana-nui-a-Kiwa* Oceania. It then presents key findings from two Indigenous knowledge-driven explorations of climate change adaptation through urban built environment design, one in Aotearoa New Zealand, and one in the Cook Islands, that have emerged out of Nature-based Urban design for Wellbeing and Adaptation in Oceania (NUWAO) research; a project funded by the New Zealand government through the Royal Society of New Zealand, that aims to develop nature-based urban design solutions, driven by Indigenous knowledges that support climate change adaptation and individual and community wellbeing in diverse urban settings in *Te Moana-nui-a-Kiwa* Oceania. NUWAO focuses on urban NbS because there has been less attention on urban NbS in the region (Kiddle et al., 2021), and because globally most people live in cities now meaning urban areas are where climate change impacts are more likely to be experienced (Pedersen Zari et al., 2022). In Aotearoa New Zealand approximately 87% of the general population and 85% of Māori live in urban centers, the result of a rapid urbanisation process in the 20th century (Ryks et al., 2019). In nearly every Pacific island nation urban population growth rates now exceed national population growth rates (Kiddle et al., 2021), and some of the world's highest urbanisation rates exist, particularly in the western nations of *Te Moana-nui-a-Kiwa* Oceania (often termed "Melanesia"), while to the north urbanisation rates are approaching 70% (in areas referred to as "Micronesia") (Kiddle et al., 2021).

An important part of decolonising research practices is to make the positionality of researchers apparent (Tuhiwai Smith, 2012; Latai-Niusulu et al., 2020). In light of this, authors of this article include Indigenous Māori (Indigenous peoples of Aotearoa New Zealand) and Cook Island researchers and designers, as well as those who are *Pākehā* (New Zealanders of European descent), all of whom are involved in research related to NUWAO. Further details about the positionality of each author and the NUWAO project are available at www.nuwao.org.nz.

2 Indigenous health and climate change

Climate change poses a significant threat to the health and wellbeing of Indigenous people globally (United Nations, 2016), including Māori in Aotearoa New Zealand and Pacific communities across *Te Moana-nui-a-Kiwa* Oceania. The health impacts of climate change are progressively becoming realised (Royal Society Te Aparangi, 2017) and will be felt disproportionately across vulnerable groups and those already enduring poorer health outcomes (Jones et al., 2014), including Māori and Pacific communities. In the Pacific islands of *Te Moana-nui-a-Kiwa* Oceania, Indigenous people are at the frontline of climate change impacts. The nations of the Pacific have unique and diverse island and marine ecosystems and cultures that are facing significant impacts from changes to climate (Nurse et al., 2014; Alam et al., 2022). These changes directly threaten the health of Pacific islanders, as well as economic and social development. Across *Te Moana-nui-a-Kiwa* Oceania increasing extreme weather events, especially cyclones, floods and droughts, are also displacing populations, causing injury and psychological trauma (Gibson et al., 2020; Tiatia et al., 2022). Indirectly, human health is threatened because of negative climate change impacts on the health of ecosystems that fundamentally underpin human wellbeing, the health of which is considered by many Indigenous peoples in Oceania to be indivisible from human wellbeing.

Communities of *Te Moana-nui-a-Kiwa* Oceania live in diverse contexts but face a number of common challenges. These include: a tendency to live in geographical locations that are particularly prone to the impacts of climate change (UNESCAP, 2019); high dependence on land and ocean ecologies for basic needs and economic security (for example, food, shelter, medicines, and fuel); and experience of economic deprivation as well as social and political marginalisation (Bailey-Winiata, 2021), that has often, but not in all nations of the Pacific, been exacerbated by complex histories and on-going realities of colonisation. Climate change will likely increase existing social and health inequalities, both between and within nations (Woodward and Porter, 2016; Levy et al., 2017), with traditionally marginalised Indigenous populations likely to be impacted disproportionally. This is concerning because the response to climate change thus far has generally adhered to western hegemonic understandings of health and ecological systems (Jones et al., 2014). We contend that Indigenous-focused and led approaches are needed, including those centring wellbeing and working with nature to effectively adapt to climate change (Kiddle et al., 2021).

3 Indigenous models of wellbeing from Oceania

Definitions and models of wellbeing are fluid and evolving. The Organisation for Economic Co-operation and Development (OECD) and the United Nations highlight the importance of individual and communal wellbeing in people's development (Yates et al., 2022). Yet, wellbeing as articulated and measured in typical western metrics tends to be individualistic. In contrast, a common thread running through the world's diverse Indigenous populations is the collective nature of wellbeing (Durie, 1994). Indigenous concepts of wellbeing tend to be broader and more holistic and, particularly, recognise the interconnected relationships of people with ecosystems and biodiversity, especially related to ancestral lands, oceans and waterways, which Indigenous peoples often depend upon for their collective flourishing (Durie, 1985; United Nations, 2011). Recognition of the interconnected relationships of people with the living world is also consistent with an ecosystem services framework, which is often used to address health and wellbeing outcomes internationally including in the *Te Moana-nui-a-Kiwa* Oceania region (McFarlane et al., 2019).

In the context of NbS, a defining feature of indigeneity is the intrinsic relationship between humankind and the natural environment, with Indigenous cultures paying deliberate attention to the responsibilities these relationships generate and giving active expression to them in all aspects of life. In short, Indigenous ontologies position humans as inseparable from the Earth and its living ecologies (Redvers et al., 2020). For example, in Aotearoa New Zealand, in *Te Ao Māori* (Māori world/worldview), humans have *Whakapapa* (genealogical/kinship) relationships with many aspects of the natural world, including *Papatūānuku* (the earth mother), as well as specific mountains, rivers, waterways and even plants. People are literally related to the land. *Whakataukī* (proverbs) illustrate the holistic kinship relationship Māori have with the environment. For example, a common *Whakataukī* is: *Ka ora te wai, Ka ora te whenua. Ka ora te whenua, Ka ora te tangata* (If the water is healthy, the land will be nourished. If the land is nourished, the people will be provided for). Another is: *Ko au te whenua, te whenua ko au, Ko au te awa, te awa ko au* (I am the land, the land is me. I am the river, the river is me). In Kiribati, people refer to the sea as their mother ocean (Anterea, cited in Xuande and Yuting, 2021). In Samoa, the word for earth, *Ele'ele,* also translates to blood, highlighting that the integral part of being or existing is the land (Powell and Fraser, 1892; Vaai, 2019). Holistic health, wellbeing, and identity is therefore inherently connected to the eco-sphere in the region. This relational ontology is fundamentally of Te Moana-nui-a-kiwa and is at the foundation of Oceanic understandings of the world. This highlights that working with nature in the region potentially holds very different meaning and significance than in other parts of the world.

3.1 Māori wellbeing

In Aotearoa New Zealand Māori have a holistic and interconnected relationship with *Te Taiao* (the living world, nature) (Mead, 2003; Hikuroa, 2017). The traditional knowledge base, *Mātauranga Māori* (Māori knowledge), has developed over many millennia (and continues to), including centuries in Aotearoa following Polynesian settlement likely in the thirteenth century (Anderson et al., 2015). *Mātauranga Māori* includes a multifaceted endeavour to apply knowledge and understanding of *Te Taiao* following a systemic methodology based on evidence, culture, values and worldview (McAllister et al., 2019).

An early and influential model of Māori wellbeing in Aotearoa New Zealand is *Te Whare Tapa Whā*, originating in a meeting of Māori health workers in 1982 and later refined and presented by leading Māori health advocate Professor Mason Durie in 1984 (Durie, 1985 & 1994). *Te Whare Tapa Whā* models Māori health as the four walls of a whare (house), with all four walls necessary to ensure symmetry and balance of the individual and community. The four walls, or dimensions of Māori wellbeing in the model, are: *Taha Tinana* (physical health); *Taha Wairua* (spiritual health); *Taha Hinengaro* (mental health); and *Taha Whānau* (family health). The model represents the concept that should any of these dimensions be missing or harmed in some way, a person, or a collective, may become unwell. Overall, the model looks to incorporate a traditional Māori approach which takes the view that the spiritual dimension (often missing in modern health approaches), family, and the balance of the mind are as important as the physical manifestations of illness (Durie, 1994). Many representations of *Te Whare Tapa Whā* also show the four walls of the whare resting on the *Whenua* (ground or land, also placenta), showing the foundation of the holistic model of health to be itself dependent on the health of the *Whenua* (Moewaka Barnes and McCreanor, 2019).

Taha Wairua is very important in *Te Ao Māori* and is a significant and integral part of Māori wellbeing. *Taha Wairua* provides a spiritual link that is interwoven through *Whānau* (family) and the environment to ensure health and wellbeing. Durie (1994) emphasises that the spiritual world for Māori extends to relationships with the environment. For example, *Whenua* (the land), *Awa* (rivers), and *Maunga* (mountains) have a spiritual importance, and their significance is often immortalised in *Pūrākau* (stories), *Waiata* (songs), *Mōteatea* (laments), *Kōrero Tuku Iho* (oral tradition) and *Whaikōrero* (formal oratory). Thus, *Taha Wairua* is deeply affected when Māori experience a lack of access to ancestral lands which is regarded by *Kaumātua* (tribal elders) as a sign of poor health (Thom and Grimes, 2022).

Te Whare Tapa Whā was followed in 1985 by Rangimārie Rose Pere's model of Māori wellbeing, *Te Wheke*, based on the eight tentacles of an octopus. *Te Wheke* models all aspects of Māori life and health as interconnected, enabling an inclusion of family, spirituality and ancestors. This model extended past the four dimensions as established by Durie to eight dimensions of wellbeing—adding *Mana Ake* (the unique qualities of each individual and family to create positive identity), *Mauri* (the life-sustaining principle in all people, elements of the living world, and objects), *Ha a koro ma a kuri ma* (breath of life from ancestors), and *Whatumanawa* (the open and healthy expression of emotion) (Love, 2004). The collective *Waiora*, or the total wellbeing for the individual and family, is gained from a combination of these dimensions, and is represented in the model as the eyes of the octopus. In *Te Wheke* each tentacle of the octopus represents aspects of a person's life that need to be supported in order to sustain balance and wholeness (ibid).

In 1988 the New Zealand Royal Commission on Social Policy[1], in *Ngā Pou Mana*, presented a model of Māori wellbeing in which the foundations of social policy and social wellbeing were presented as four supports, or four interrelated prerequisites: *Mana* (prestige, authority, control, power, influence, status, and charisma); cultural integrity; a sound economic base; and a sense of confidence and continuity. *Ngā Pou Mana* also outlined four factors considered to be fundamental to social wellbeing for Māori, specifically: *Whanaungatanga* (the importance of the family), *Taonga Tuku Iho* (cultural heritage), *Te Ao Tūroa/Te Taiao* (the natural environment) and *Tūrangawaewae* (the land base; a place of belonging, standing and identity). The *Ngā Pou Mana* model's point of difference to earlier work in Aotearoa New Zealand was an unequivocal emphasis on linkages between Māori and the environment. Reference to *Te Ao Tūroa* paid homage to the number of Waitangi Tribunal[2] claims throughout the 1980 s responding to the modification and pollution of culturally significant waterways in Aotearoa New Zealand (Derby, 2023). The explicit attention to *Te Ao Turoa* seeks to emphasise that Māori wellbeing is affected not just by access to, or quantity of, natural resources, but also their state or condition. Therefore, experiences like the loss of land (through colonisation), pollution affecting traditional areas of food gathering, and the depletion of "natural resources," are all destabilising factors on health and wellbeing and debase spiritual and cultural values (Royal Commission on Social Policy, 1988; Thom and Grimes, 2022). This makes sense when, as discussed earlier, Māori understand their kinship relationship with, and responsibility to, the natural world recognising rivers and mountains, for example, as living ancestors. The natural environment is not simply resource for exploitation. The connection between spirituality, ecological health, and physical health for Māori makes links to negative health and wellbeing outcomes associated with colonisation, the accelerated deforestation transformation of the Aotearoa New Zealand landscape, and rapid urbanisation of the 20th century clearer. Like many other Indigenous populations these social justice impacts combine to make land access, tenure, and management as an aspect of adaptation to climate change more complex (Ryks et al., 2019; Aslany and Brincat, 2021).

3.2 Pacific peoples' wellbeing

Historically the western world has looked to define the wellbeing of Pacific peoples from a eurocentric perspective. However, Pacific peoples have their own ways of describing what wellbeing means to them (Tanguay, 2014). For example, spirituality is central to Pacific ways of life and is prominent in traditional understandings and models of Pacific wellbeing (Pulotu-Endemann, 2001). Indeed, leading Pacific theologian Reverend Upolu Lumā Vaii describes a "Pacific eco-relational spirituality" as the essence to life and wellbeing, such that there is "no wellbeing of the individual without the wellbeing of the whole" (Vaii, 2019, p. 7).

An important model of Pacific wellbeing developed in the Aotearoa New Zealand context is the *Fonofale* model of wellbeing for Pacific peoples, originally developed by Fuimaono Karl Pulotu-Endemann in the early 2000 s (Pulotu-Endemann, 2001). Here the configuration of the Samoan fale (house with open sides and traditionally a thatched roof) represents various interconnected concepts that are central to the wellbeing of Pacific peoples: (i) the roof—"culture"—as the overarching component, under which all other elements important for Pacific peoples are maintained: (ii) "family" as the foundation; and (iii) the four posts of "physical," "spiritual," "mental" and "other" sustaining the link between family and culture. The *Fonofale* model, like *Te Whare Tapa Whā*, also shows the interconnectedness of all elements, as influenced by the environment, time, and context (Thomsen et al., 2018).

More recent work on Pacific wellbeing commissioned by the Aotearoa New Zealand Treasury (Thomsen et al., 2018) looked to inform ongoing refinements to the Living Standards Framework, first introduced in 2011 to the Aotearoa New Zealand public sector to model and measure multidimensional wellbeing and, overall, drive a wellbeing focus in public policy. This work was informed by the *Fonofale* model as described above and recommended that "any framework for describing and understanding Pacific peoples must highlight family as the dominant relationship that Pacific peoples acquire from birth, and highlight the key influence that culture plays in the social, human, and physical capital stocks of Pacific Aotearoa New Zealanders" (ibid, p. i). The work recommended four initial indicators for Pacific peoples' wellbeing for inclusion in the Living Standards Framework: "family resilience;" "Pacific connectedness and belonging;" "religious centrality and embeddedness;" and "cultural recognition."

Within the Pacific island nations and territories, Vanuatu has been a regional leader in both measuring wellbeing and embedding a wellbeing focus within public policy making. The "Alternative Indicators of Wellbeing for Melanesia" initiative, for example, begun in 2010, defined through extensive research three distinct domains of wellbeing particularly relevant for wellbeing and happiness in Vanuatu: access to customary land and natural resources; traditional knowledge and practice; and community vitality (Malvatumauri National Council of Chiefs, 2012). Vanuatu's approach has been focused on subjective wellbeing, or happiness. Centred around the question *"what do you need in order to have a good life?,"* key results highlight that people living on customary land, participating in traditional ceremonial activities, and those who are active members of their community, are, on average, happier in Vanuatu. The deeper and more nuanced understandings of wellbeing created through this work in Vanuatu have flowed through into national development planning. For example, for the first time, policies around traditional medicine and healing practices, traditional knowledge,

1 Established to examine social conditions in Aotearoa New Zealand and recommend policies that would result in a more just and fair society.

2 A permanent commission of inquiry in Aotearoa New Zealand that makes recommendations on claims brought by Māori relating to Crown actions which breach the promises made in *Te Tiriti o Waitangi* (the *Te Reo Māori* version of the Treaty of Waitangi)—Aotearoa New Zealand's founding document.

access to traditional wealth items, access to customary land, and use of Indigenous languages have been included in the 2016–2030 Vanuatu National Sustainable Development Plan (NSDP) (Department of Strategic Policy, Planning and Aid Coordination, 2017).

The environmental context is typically prominent in Pacific models of wellbeing. For example, in the Cook Islands, *Pito'enua* (health and wellbeing) encompasses five dimensions: *Kopapa* (physical wellbeing); *Tu Manako* (mental and emotional wellbeing); *Vaerua* (spiritual wellbeing); *Kopu Tangata* (social wellbeing); and *Aorangi* (total environment), with the latter meaning how an individual is shaped by society and the environment (Scheyvens et al., 2023a). In addition, the Tokelauan *Te Vaka Atafaga* model of wellbeing positions wellbeing as a *Vaka* (voyaging canoe) within the ocean, which acts as its environmental context. For example, if the sea is rough, or the wind is too strong, these things will affect the wellbeing of those on the *Vaka* (Kupa, 2009). Environmental wellbeing is also central to the "Frangipani Framework of Pacific Wellbeing," which draws from recent work exploring the wellbeing of Pacific peoples from communities in Samoa, Fiji, Vanuatu, and Cook Islands. Here Pacific wellbeing is modelled into spiritual, mental, physical, financial and social domains (the petals of the frangipani flower) and environmental wellbeing (how the health of the environment and access to land and other environmental resources has an impact on human wellbeing) is modelled as the trunk and roots of the frangipani tree (Scheyvens et al., 2023b & 2023c).

In considering the importance of traditional spiritual beliefs on wellbeing in *Te Moana-nui-a-Kiwa* Oceania, the impacts of western colonialism must be taken into account. As a phenomenon accompanying colonisation, the conversion of most Oceanic peoples to Christianity is of particular significance (Vaai, 2019). The overwhelming majority of adult inhabitants of most Pacific island countries consider themselves Christian, with the exception of the non-indigenous population of Fiji, who include Hindu and Muslim peoples totalling just over one-third of the population (Fiji Bureau of Statistics, 2023). Even in Aotearoa New Zealand, where adherence to any religious faith has declined significantly in the last 2 decades, approximately two-thirds of Māori declared themselves as Christian in the 2018 census, a significantly higher proportion than in the overall population (which is approximately 40%) (Statistics New Zealand, 2019).

Overall, wellbeing understandings, from the Pacific islands of *Te Moana-nui-a-Kiwa* Oceania and from Pacific communities within Aotearoa New Zealand, highlight how wellbeing for Pacific peoples is communal, linked closely to the spiritual world, and is influenced by relationships with island and ocean environments, and the ecosystem services that these environments provide. At the same time, Pacific models of wellbeing are also place-based; highlighting how contextualised and nuanced understandings of wellbeing are required in a unique, and very diverse, oceanic region.

4 Nature-based solutions and wellbeing in urban design

The links between connection to nature and human wellbeing are well documented and numerous and range from physiological benefits to psychological ones that are both overt and easily to comprehend through to ones which occur on a subconscious basis (Gillis and Gatersleben, 2015; Soderlund and Newman, 2015; Aerts et al., 2018). Evidence exists of positive physical benefits such as reduced blood pressure and cortisol levels, increased parasympathetic nervous system activity, and reduction in overall stress; increased immunity; and increased cognitive ability (Berman et al., 2008; Tyrväinen et al., 2014). Evidence of psychological benefits include: positively modified behaviour, particularly in terms of social interaction and reduced violence; decreased rates of depression; increased ability to concentrate; increased happiness; and increased social cohesion (Kuo and Sullivan, 2001; Mayer and Frantz, 2004; Hartig et al., 2014; Cohen-Cline et al., 2015).

NbS typically involve working with vegetation, water, and biodiversity, so can therefore have numerous positive impacts on human individual health (as well as more technical benefits related to climate change adaptation; for example, flood mitigation). This means that the design of urban nature-based interventions can more strategically consider the causes of health and wellbeing (rather than just the causes of disease). For example, the spatial design and materiality of buildings and their facades, as well as public works of art and soundscapes, and the experiences of these in linked urban spaces impacts on experiences of human-nature relationship in cities (Pedersen Zari, 2019). Specific cultural interpretations of nature and human-nature relationships, as well as the inclusion of specific native or cultural keystone plant species are also highly important, particularly in the context of Indigenous communities (Rodgers et al., 2023). This means that the quality and variety of opportunities for human-nature relationships in urban contexts and how spatial experiences are linked through time and cultural values is likely to be important in the creation of NbS that result in human wellbeing in general, and Indigenous wellbeing specifically. This is in contrast to simply understanding the success or value of NbS as, for example, a measurable quantity of trees or the size of urban green space. Effective urban NbS are arguably more complex and holistic than simply the amount of biomass or greenspace in a city.

Although literature shows that experiencing and valuing nature-human relationships differs between various cultural groups (Sangha et al., 2018), and certainly this is true in *Te Moana-nui-a-Kiwa* Oceania, to date most examples of NbS do not consider in depth how cultural diversity and the differences between the preferences or needs of various groups of people can be more effectively explored and integrated into design practice. Exploration of this is an opportunity for design-led research focused on NbS in *Te Moana-nui-a-Kiwa* Oceania (and in other parts of the world). Such NbS design could be an important contributor to a more holistic notion of ecological urban sustainability or regeneration that takes into account cultural relationships to land and ocean. This is of great importance for safeguarding both the physical and psychological wellbeing of individuals and communities in the coming decades as humanity increasingly becomes urbanised and removed from outdoor environments, while concurrently people must learn how to create, adapt, and live in urban environments in a greatly changed ecological and climatic context. It is also vital in social-justice oriented understandings of climate change adaptation interventions which is important in the diverse and complicated colonisation contexts of *Te Moana-nui-a-Kiwa* Oceania.

Building from this understanding of a more holistic and locally contextualised kind of NbS for the wellbeing of Indigenous peoples, we now profile two case-study examples from *Te Moana-nui-a-Kiwa* Oceania (from Aotearoa New Zealand and the Cook Islands) that have emerged from the NUWAO research project.

4.1 Case study: *Te Awa Kairangi* (Lower Hutt, Wellington), Aotearoa New Zealand—Pūrākau

Research by Holman-Wharehoka (2023), who holds both *Māori* and *Pākehā Whakapapa*, looked to investigate the relationship between the built environment and climate change from a *Te Ao Māori* perspective, and to propose alternative ways to approach climate change adaptation planning by/with Māori. Key research aims were: to investigate how Māori wellbeing could be better reflected in climate adaptation design; and to investigate how the built environment can better reflect the reciprocal relationship that Māori have with *Te Taiao*. The concepts of sustainable engineering systems directly connect the built environment to *Te Taiao*, however the sector typically looks at non-human ecosystems purely for practical benefits or as a resource for humans. A *Te Ao Māori* perspective is more holistic and comes from lived experience and connection to *Wāhi* (place). The particular *Wāhi*/case study discussed in this research was *Waiwhetū (Waiwhetū* Stream*)*, in *Te Awa Kairangi* (Lower Hutt); a setting that highlights the way the built environment over the past 180 years has colonised and degraded the wellbeing of the *Awa* and therefore has challenged the ability that Māori of *Waiwhetū* have to be *Kaitiaki* (guardians) of their *Awa*.

The central research methodology, founded in principles of a *Kaupapa Māori* framework (a by Māori, for Māori, with Māori approach) (Tuhiwai Smith, 2012), involved using *Pūrākau* (traditional Māori oral stories) to understand traditional knowledge in relation to dealing with extreme climate-related events such as flooding. Key findings of both literature review and interviews indicated that the writing of new *Pūrākau*, created to fit today's context of time, society and climate, could embody a *Kaupapa Māori* approach to climate adaptation understanding and planning, drawing on *Mātuaranga Māori,* that would better reflect cultural values and therefore support wellbeing. This makes sense in the context of understanding that traditional knowledge is constantly evolving. The final aim of the research was therefore to explore the role of new *Pūrākau* as a way to begin design for climate adaptation in the built environment, including devising a new *Pūrākau* in collaboration with authors Te Kahureremoa Taumata and Khali-Meari Materoa to tell the story of the river's changes in a first person narrative with the river as the central voice.

For Māori, everything is connected in a spiritual, mental, social, and physical sense. Central to the research was the understanding that *Whenua, Awa, Wāhi Tapu* (sacred sites) and Māori wellbeing are inseparable from *Te Taiao* (which includes climate). The *Te Whare Tapa Whā* model (Durie, 1995) provided a central conceptual framework for the research; highlighting the importance and interconnectedness of spiritual, mental, physical and family wellbeing for Māori, as well as *Whenua*, for "it is clear that without our land and roots to understand where we come from, we would be out of balance" (Holman-Wharehoka, 2023, p. 13).

The *Pūrākau* that was developed begins with an ode to *Ranginui* (the sky father), recognising the source of the *Wai* (water), that it is gifted from *Ranginui* to *Pukeatua*, the *Maunga* that *Waiwhetū whakapapa* to. The meaning of the name *Waiwhetū* is described in the *Pūrākau*; *Wai,* being water, and *Whetū,* being the stars, meaning the *Awa* is named for its ability to reflect the stars. The *Pūrākau* then describes the *Awa* in a pre-colonisation context, how big and deep it used to be, and that it was once a highway for Māori that would take *Waka* (Māori canoe) from the ocean into the *Whenua*. The *Pūrākau* then begins to discuss the emergence of *Pākehā* settlement and development, showing a noticeable shift in societal life and therefore a negative shift in the health of the *Awa*, and in turn the wellbeing of *Waiwhetū Māori* (Māori who *whakapapa* to *Waiwhetū*). The culverting of the *Awa* for urban development, with portions now hidden in underground pipes, is described. Overall, the *Pūrākau* intended to elucidate what it would feel like, from the perspective of the *Awa*, to go through this tremendous shift of life, from being nurtured to becoming desecrated. The *Pūrākau* ends with the following lines:

He taonga te wai Water is sacred

I whakarereā A treasure abandoned

Mā wai rā e taurima te ipukarea? Who will take care of the source?

Ko wai koe? Who are you? (You are water)

(Holman-Wharehoka, 2023, p. 95).

The degradation and lack of acknowledgement of the role the *Awa* plays for Māori are made manifest in the *Pūrākau* as consequences and impacts of climate change. The *Pūrākau* shows that if we want to ensure that the *Awa* can help to mitigate impacts such as floods, we need to return *Mana* (prestige and authority) to our *Wai*. The research is groundbreaking in the field of architectural science because it demonstrates how traditional knowledge and practice can be used to convey human-nature relationships and cultural values that in turn help to determine appropriate climate change adaptation strategies and ways of working with nature. It centers Māori worldview and priorities in urban design and planning, and makes it clear that the health of ecologies (in this case the *Awa*), climate, and people are not able to be separated and should be considered as interconnected parts of *Te Taiao* when trying to understand past, current and future conditions, and in relation to designing new interventions.

Within the context of today's climate crisis, adaptation methods, including NbS, continue to develop and evolve. There is space within this development for Māori voices and *Mātauranga* to be at the centre of the conversation and decision making. A key finding of the research is that *Mātauranga* comes from and is used/given by Māori. It is not simply another formula for industry or government to "use;" it is a lived knowledge system that requires correct *Tikanga* (appropriate Māori customary practices and behaviours), guided by *Kawa* (governing protocol and policy).

4.2 Case study: Rarotonga, Cook Islands—Enhancing *Oraanga Meitaki* through regenerative design

Mataroa's research (2023) explored how *Kuki Airani* (Cook Islands) values can enable architecture that enhances the *Oraanga Meitaki* (wellbeing, health, and vitality) of *Te Aorangi* (the environment) and existing ecosystems. The research had four key aims: (i) to investigate how *Kuki Airani* values can reshape methods of designing architecture; (ii) to explore how *Kuki Airani* methods of design can contribute to the health and wellbeing of *Kuki Airani Tangata* (the community of the Cook Islands) and *Te Aorangi*; (iii) to understand the *Kuki Airani* relationship between wellbeing, *Te Aorangi*, and architecture; and (iv) to empower *Kuki Airani Tangata* (people) to apply their knowledge in architectural responses to climate change.

The research site was in Rarotonga, the largest of the Cook Islands. In recognition of the genealogical connections that *Kuki Airani* share with *Te Aorangi*, the selected site belongs to the researcher's *Kopu Tangata* (family). Located in the western district of *Arorangi*, the site lies next to the shore and beneath the *Maunga* (mountain) of *Raemaru*. This area faces many challenges such as storm surges, cyclones, increasing sea temperatures and surface run-off. Despite a trend towards purely technical responses to the impacts of climate change seen in many nations of the Pacific where European or Australasian aid money is the basis of much climate adaptation infrastructure works (such as the building of sea walls for example), traditional knowledge concerning living with the *Enua* (land) and *Moana* (ocean) has been passed down from generation to generation, allowing *Airani Tangata* to adapt to many of these challenges. As a means to reiterate the importance of 'working with' nature and Indigenous knowledges, recognising conceptions of wellbeing in the Pacific, rather than a "doing to" method (a technical only lens), prioritisation of this traditional *Kuki Airani* knowledge was a key aim of the research. *Kuki Airani* cultural values and traditional knowledge shaped a design process that worked with nature to adapt to climate change and began to address many of these challenges.

As discussed, wellbeing in Pacific contexts refers to more than just the individual. The Rarotonga research centered wellbeing as a concept that radiates out to all other existing life forms, or the essence of being (Ministry of Social Development, 2012; Feek and Kepa Brian Morgan, 2013; Mahi Maioro Professionals, 2021). As discussed by Tavioni (2018), Atua (Gods) can manifest in many aspects, such as seasons, *Maunga* and *Moana*, demonstrating how every component of *Te Aorangi* shares a life force and requires consideration when designing in *Te Moana-nui-a-Kiwa* Oceania. The research understood wellbeing as *Oraanga Meitaki* and it was explored as the spiritual, physical, and emotional wellness of all life forces, from *Tangata* (people), to the *Atua* (god/s), and existing ecosystems of *Te Aorangi* (Ministry of Social Development, 2012). *Oraanga Meitaki* resonates with the intergenerational responsibility that *Kuki Airani* share in protecting, preserving and caring for their homeland, and enables connections to be made between the design of space and *Oraanga Meitaki*.

Climate adaptation in urban contexts within the Pacific is often approached with a Eurocentric perspective, separating environmental and climate impacts from human occupation and economic potential. While sustainable design frameworks have been utilised within Rarotonga, there is an urgent need to prioritise local values, traditional knowledge and regenerative design strategies over the commonly accepted standards of sustainability in architectural discourse (Mataroa, 2023). A shift towards improving the *Oraanga Meitaki* of *Te Aorangi* demands simultaneous consideration of the spiritual, emotional, and physical impacts of a design. The unique contribution of this research is the development of the *Te Aorangi* framework; conceived to address design issues in Rarotonga by identifying connections between the *Atua*, *Tangata* and *Te Aorangi*. Derived from cultural *Tivaevae* (a traditional Kuki Airani tapestry) values, the framework sought to enhance the *Oraanga Meitaki* of spaces and challenged the current perception of what architecture can and should achieve. Prioritisation of *Oraanga Meitaki* within the framework can result in architectural solutions that improve and enhance the ecological landscape of *Te Aorangi*, as opposed to merely sustaining current degraded levels.

Through a decolonisation lens, the research explored how *Kuki Airani* values can empower *Tangata* to reclaim their approach to climate adaptation by re-shaping the architectural processes of designing environmentally responsive architecture in Rarotonga. Overall, a shift towards holistic, context-specific architectural processes in Rarotonga would enhance the *Oraanga Meitaki* of *Te Aorangi*, existing ecologies, and hence the *Oraanga Meitaki* of *Kuki Airani Tangata*, and also ensure that *Peu Kuki Airani* (the culture of the Cook Islands) is celebrated and preserved for future generations. The design-led research demonstrated that by using Indigenous knowledge and understandings of human-nature relationships personified as *Atua*, as a means to generate a regenerative architectural design framework, and resulting designs for a community centre (Figures 2, 3), both the processes and outcomes of design can centre Indigenous values and priorities while having adaptation and wellbeing outcomes.

5 Discussion

The urgent need to adapt to climate change is clear and is of great importance in Oceania, where some of the most globally vulnerable peoples in relation to the impacts of climate change reside, and where human wellbeing is disproportionately affected. NbS could and in some places in *Te Moana-nui-a-Kiwa* Oceania do already play a key role, enabling multiple co-benefits to evolve that focus on revitalising ecological health, and (if designed well) improving wellbeing. The next step in creating effective NbS, we argue, is to make sure that they contribute to culturally appropriate and just climate adaptation, leading to outcomes that support cultural values and self-determination for Indigenous people (Kiddle et al., 2021; Latai-Niusulu et al., 2022). Without this key cultural lens at the forefront of design and planning, adaptation is not supporting "a good life" and could lead to further marginalisation of Indigenous peoples. In short, NbS need to be localised not only in terms of ecological and climatic site conditions, but also cultural knowledge and values to be effective.

Ideas and worldviews related to human-nature relationships influence the design of NbS. It is clear that Indigenous peoples of *Te Moana-nui-a-Kiwa* Oceania have different relationships with nature compared to each other, but holistic concepts of ecological-human

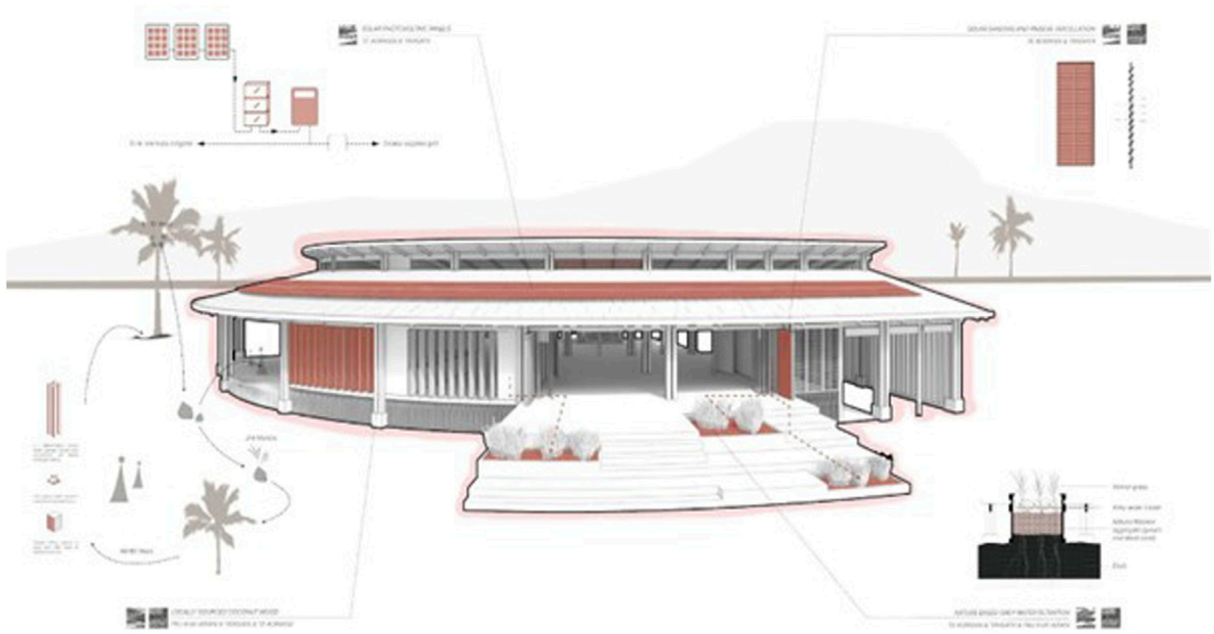

FIGURE 2
Design for a Community Centre in Rarotonga derived through te aorangi framework (Source: Mataroa, 2023).

FIGURE 3
Design for a Community Centre in Rarotonga derived through Te Aorangi framework (Source: Mataroa, 2023).

roles, values, and relationships differ hugely when compared to typical European or North American ideas about how people and nature can or should interact. This is where many "standardisations" of NbS terms and processes come from however. This means there is a clear need to reassess how NbS fit into a wider local agenda of wellbeing, particularly for Indigenous peoples, and in the case of this research, Indigenous peoples of *Te Moana-nui-a-Kiwa* Oceania. Without this framework of reference NbS can become accidental vehicles of neo-colonisation and actually undermine wellbeing for Indigenous people.

Overall, as for other Indigenous peoples globally, in *Te Moana-nui-a-Kiwa* Oceania, Indigenous wellbeing tends to be holistic, relational and collective in nature. Indigenous people tend to have broader, more holistic approaches to wellbeing that centre the environment, spirituality, and the connectedness of all; or what is known in Aotearoa New Zealand as collective *Waiora.* Indigenous worldviews and cosmologies position humans as inseparable from the Earth and often oceans and/or from ecosystems. Ecological and climate wellbeing are not separable. This understanding of a kind of life force that binds all living aspects of the world (including rivers, oceans, mountains, forests and other "entities" not often acknowledged as being alive in western science) has varying names in Oceania including: *Mauri* (Aotearoa New Zealand), *Mo'ui* (Tonga), *Mauli* (Hawaii) and *Oraanaga Meitaki* (Cook Islands) (Krupa, 1996). The *Mauri* of rivers has been recognised in Aotearoa New Zealand for example, through granting of legal personhood to the Whanganui River as a means of *Te Ao Māori*-centred care for and management of the ecologies associated with these entities (in this case the river) that better reflects their meaning and *Mana* (Charpleix, 2018). In short, wellbeing for Indigenous peoples is not considered in isolation, but rather in the broader context that the individual sits within. As we have shown, there are many models of wellbeing in *Te Moana-nui-a-Kiwa* Oceania that differ (but often are linked) that can and should influence urban and built environment design and climate change adaptation planning and interventions. How then can the design of NbS acknowledge, celebrate and work with such an understanding of the living world in order to centre local wellbeing? Our findings, including the examples provided by the tow case studies, indicate that it is not just the technical measurable outcomes of NbS that determine their compatibility with this worldview, but the overall frameworks of relational understanding, and the processes undertaken to arrive at and evolve NbS that are important.

The influence of colonisation, and resulting wide adherence to Christian perspectives and values in the Pacific, is significant and important to discuss in this context because there is potentially tension between climate action and some religious doctrines. For example, and in particular, the Judaeo-Christian tradition of human uniqueness compared to all other species and consequent licence of human dominion over nature, as expressed in parts of the Bible, has often been seen as leading to environmental devastation (White, 1967). There is now, however, strong and diverse involvement of Christians and people of other faiths involved in climate change and resilience responses in *Te Moana-nui-a-Kiwa* Oceania (Creegan and Shepherd, 2018; Purdie, 2022). Luetz and Nunn (2020) describe how climate change decision-making in Pacific Island nations is more likely to be influenced by tradition and local practice (including the highly-respected teachings of religious leaders) than by science.

In juxtaposition to the religious belief of human dominion over nature, a significant stream in religious thinking that is often termed "eco-theology" (Deane-Drummond, 2008) has arisen. Eco-theology can be seen as a form of constructive theology that focuses on the interrelationships of religion and nature, particularly in the light of environmental concerns. As such, eco-theology has drawn significant thinking from the concepts of traditional ecological knowledge, especially in terms of the intrinsic and holistic relationship between humankind and the natural environment. Nunn et al. (2016), surveying a large sample of University of South Pacific students, found that nearly 90% of respondents reported feeling part of Nature, having a personal connection with the natural environment, and thought their welfare was linked to Nature. Participants had spiritual values that explained their feelings of connectedness to Nature. In theological as well as cultural framing this relationship of oneness with nature also leads towards holistic wellbeing (Mayer and Frantz, 2004; Tomlinson, 2019; Vaai, 2019; Whitburn et al., 2020; Barragan-Jason et al., 2022) while addressing colonial and neo-colonial paradigms (Pacific Conference of Churches, 2001).

Pacific peoples' understandings of wellbeing and identity are grounded in relationships and collectivism (Lautua, 2023). In Aotearoa New Zealand, the relationships between *Whenua*, *Maunga*, *Ngāhere* (forests) and *Atua* are life-affirming (Pomare-Peta, 2022). Gelves-Gómez and Brincat (2021) discuss similar holistic concepts associated with the Fijian word *Vanua* (territory, place) and relate these concepts to wellbeing, quoting (Ravuvu (1987): "For to live well in this world *and* in the other world, one has to live according to *Vanua* beliefs and values. . .." Fihaki (2022) and Pomare-Patea (ibid) also consider that both the recognition of the concept of stewardship in the Bible, and the subsequent actions of stewardship, bring increased *Hauora* (health). In the Judeao-Christian tradition those actions of stewardship, including climate adaptation, are often collectively called "Creation care." As such, there have been calls for the inclusion of faith-based approaches and opportunities in climate adaptation and wellbeing, that go beyond the secular. Luetz and Nunn (2020), for example, describe how current climate responses in *Moana-nui-a-Kiwa* Oceania Oceania have been hindered by previous technocratic approaches rooted in a secular and binary view of humans in nature, and quote Hulme (2017), summarising his international reviews, exhorting that "climate policies need to tap into intrinsic, deeply-held values and motives if cultural innovation and change are to be lasting and effective."

6 Conclusion

Climate change is the most significant health and wellbeing issue of our times, with Indigenous people disproportionately affected. NbS play a key role in adapting to climate change; bringing multiple co-benefits and critically focusing on revitalising ecological health. Culturally appropriate NbS also need to be informed by localised understandings of wellbeing. As we have discussed, for the Indigenous people of *Te Moana-nui-a-Kiwa* Oceania Oceania, these understandings are many, but are linked by centring human-ecological relationships and connections, spirituality, and the connectedness of all.

The two case studies discussed in this article illustrate the importance of appropriate research methods, design frameworks and design that forefront Indigenous values, knowledge, and wellbeing in the creation of NbS that centre local practices of wellbeing. More consciously considering worldview and cultural values during (co) designing processes will make these adaptation strategies, including NbS, more locally relevant, effective, and likely to have positive wellbeing outcomes for interconnected socio-ecological systems. There is a clear need for standardisations of NbS terms, methods, and evaluation frameworks to be flexible enough to be relevant to specific localised contexts, particularly where Indigenous peoples reside. There is need for further research on the intersection of spiritual and religious beliefs and models of human wellbeing in *Te Moana-nui-a-Kiwa* Oceania, as also noted by Gelves-Gómez and Brincat (2021).

The case studies highlight that working with nature in the context of *Te Moana-nui-a-Kiwa* Oceania is not simply a technical exercise, but a deeply meaningful, potentially spiritual, and certainly a political act in the context of decolonisation and re-Indigenisation. People seeking to employ NbS in *Te Moana-nui-a-Kiwa* Oceania should be aware of this in planning, design, and participatory processes, overall design goals and outcomes, and ongoing maintenance planning. The further development of a framework to guide NbS work in *Moana-nui-a-Kiwa* Oceania will be the subject of ongoing research. The motivation and positionality behind NbS design for climate adaptation that centres worldview-driven local ideas and practices of wellbeing is of vital importance to effectiveness in the *Te Moana-nui-a-Kiwa* Oceania context and should be made transparent by funders, designers and planners, managers, and other actors involved in design for climate adaptation.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by the Victoria University of Wellington Human Ethics Committee. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

SM: Conceptualization, Investigation, Writing–original draft. M-t-oH-W: Investigation, Writing–original draft. JM: Investigation, Writing–original draft. GK: Investigation, Writing–original draft, Conceptualization, Writing–review and editing. MP: Funding acquisition, Supervision, Writing–original draft, Writing–review and editing. PB: Writing–original draft, Writing–review and editing. SB: Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Glossary

Māori	English translation
Aotearoa	Literally "the land of the long white cloud;" the common Te Reo Māori name for New Zealand
Atua	God/s
Awa	River/s, stream, waterway
Hauora	Health
Kawa	Governing protocol and policy
Kaupapa Māori	Research that is by Māori, for Māori and with a Māori approach, with a Māori topic and agenda, engaging Māori customary practices (*Tikanga*) principles (*Kawa*) and values (Tuhiwai Smith, 2012)
Kōrero Tuku Iho	Māori oral tradition
Mana	Prestige, authority, control, power, influence, status, charisma
Māori	Indigenous people of Aotearoa New Zealand, (also *māori* - normal, ordinary, natural, usual, common)
Mātauranga Māori	Indigenous Māori knowledge
Maunga	Mountain/s
Mauri	Life force, life essence, life-field, the ephemeral. Life force that binds all living aspects of the world (including rivers, oceans, mountains, forests and other "entities" not often acknowledged as being alive in western science)
Mōteatea	Lament, chant
Ngāhere	Forest/s, bush
Pākehā	New Zealanders of non-māori, usually European descent
Papatūānuku	The earth mother
Pukeatua	The Maunga/mountain at the top of the Waiwhetū Stream catchment
Pūrākau	Traditional oral Māori stories—these stories hold important knowledge, names and relationships to place/s, kinship stories
Ranginui	The sky father
Taonga Tuku Iho	Māori cultural heritage
Te Ao Māori	The Māori world and world view
Te Ao Tu̅roa/Te Taiao	The natural environment
Te Moana-nui-a-Kiwa	The great ocean of Kiwa, the Pacific Ocean, Oceania
Te Reo Māori	The Māori language
Te Taiao	The living world, nature, the eco-sphere, planetary living systems including climate
Te Tiriti o Waitangi	The Treaty of Waitangi—importantly the Te Reo Māori version of the Treaty—signed by the British Crown and Rangatira Māori (Māori chiefs, leaders), the founding document of Aotearoa New Zealand.
Tikanga	Appropriate Māori customary practices and behaviours
Tūrangawaewae	The land base; a place of belonging, standing and identity—A place to stand
Waiata	Song/s
Wāhi	Place
Wāhi Tapu	Sacred site/s
Wai	Water, liquid
Waiora	The total wellbeing for the individual and family, also health
Waiwhetū	Waiwhetū Stream, Lower Hutt, Wellington, NZ—*Wai*, being water, and *Whetū*, being the stars, named for its ability to reflect the stars
Whakataukī	Māori proverbs
Whakapapa	Genealogy, lineage. Also the kinship of human and non-human encompassing the complex relations between people and the land
Whaikōrero	Formal oratory
Whānau	Family, close kinship group

Whanaungatanga	Sense of connection, relationships, the importance of the family
Whenua	The earth, ground or land; also placenta
Te Whare Tapa Whā	A model of Māori wellbeing in Aotearoa New Zealand (Durie, 1995)
Taha Tinana	Physical health (one of the four walls of Te Whare Tapa Whā)
Taha Wairua	Spiritual health (one of the four walls of Te Whare Tapa Whā)
Taha Hinengaro	Mental health (one of the four walls of Te Whare Tapa Whā)
Taha Whānau	Family health (one of the four walls of Te Whare Tapa Whā)
Te Wheke	A Model of Māori Wellbeing (Love, 2004)
Mana Ake	The unique qualities of each individual and family to create positive identity (from Te Wheke: Model of Māori Wellbeing)
Mauri	The life-sustaining principle in all people, elements of the living world, and objects (from Te Wheke: Model of Māori Wellbeing)
Ha a koro ma a kuri ma	Breath of life from ancestors (from Te Wheke: Model of Māori Wellbeing)
Whatumanawa	The open and healthy expression of emotion (from Te Wheke: Model of Māori Wellbeing)
Kuki Airani (Cook Island) Māori	**English translation**
Aorangi	Total environment
Airani Tangata	Island people
Arorangi	District on western side of the island of Rarotonga
Atua	God/s
Enua	Land
Kopapa	Physical wellbeing
Kopu Tangata	Family, social wellbeing
Kuki Airani	Cook Islands
Kuki Airani tangata	The people, the community of the Cook Islands
Maunga	Mountain/s
Moana	Ocean
Oraanga Meitaki	Wellbeing, health, and vitality - life force that binds all living aspects of the world (including rivers, oceans, mountains, forests and other 'entities' not often acknowledged as being alive in western science)
Peu Kuki Airani	The culture of the Cook Islands
Pito'enua	Health and Wellbeing
Raemaru	Maunga (mountain) of Raemaru in Rarotonga
Tangata	People
Te Aorangi	The environment
Tu Manako	Mental and emotional wellbeing
Vaerua	Spiritual wellbeing
Other terms	**English translation**
Ele'ele	Samoan—Earth
Fonofale	Samoan—House of support, Model of wellbeing for Pacific peoples (Pulotu-Endemann, 2001)
Te Vaka Atafaga	Tokelauan model of wellbeing (Kupa, 2009)
Vaka	Tokelauan—voyaging canoe
Mo'ui	Tongan - life force that binds all living aspects of the world (including rivers, oceans, mountains, forests and other "entities" not often acknowledged as being alive in western science)
Mauli	Hawaiian—life force that binds all living aspects of the world (including rivers, oceans, mountains, forests and other "entities" not often acknowledged as being alive in western science)
Vanua	Fijian—Land, territory, place. Land one is identified with, confederation of clans

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Research progress and prospects of urban resilience in the perspective of climate change

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The natural hazards caused by climate change have a significant impact on the production and life of urban residents, enhancing urban resilience is an important way to cope with climate disasters and ensure the safety of urban systems. Based on the "urban resilience" research relevant literature, the paper applies bibliometric analysis software to reveal the research hotspots and evolution trends of urban resilience in the perspective of climate change. The results indicate that the main research contents can be summarized into four aspects: i) influencing factors of urban resilience; ii) evaluation index and method of urban resilience; iii) the impact of climate change on urban resilience; iv) Enhancing urban resilience in response to climate change. Finally, potential directions for future research on urban resilience were proposed, multi-dimensional research on urban resilience should be carried out from aspects of theoretical development, urban planning based on resilience mechanisms should be carried out from the perspective of planning practice, and innovation and reform should be carried out in policy implementation and urban management. Accurately understanding the conceptual connotation and construction mechanism of urban resilience is a crucial premise for climate mitigation and adaptation. Relevant research conclusions can provide useful reference for theoretical research and spatial planning of resilient cities.

KEYWORDS

urban resilience, climate change, urban system, nature-based solutions, sustainable development

1 Introduction

The global urbanization rate has exceeded 50% on average, and the number and density of urban population are rising every day. Cities are the centers of economic activities and innovation, as well as the main sources of energy consumption and greenhouse gas emissions (Kennedy et al., 2014; Zhao et al., 2020). The changes in urban development around the world will have a huge impact on global sustainable development after the novel coronavirus pneumonia (COVID-19). With the continuous deepening of urbanization, more and more people gather in cities, and the economic and population agglomeration function of cities are more prominent. At the same time, meteorological disasters caused by extreme climate have become the main types of disasters threatening the security of urban space. The impact of climate change on cities has become increasingly significant. On the one hand, urban areas consume more energy and emit more greenhouse gases, which is the main cause of climate change; On the other hand, densely populated urban areas are extremely vulnerable to climate change, especially for the region's "most disadvantaged populations" (Klein et al., 2003; Hunt and Watkiss, 2011). Climate change has exacerbated existing urban problems and made cities more vulnerable (Adger et al., 2003; Tyler and Moench, 2012). Under the background of global climate change, various uncertain risks such as extreme climate and natural disasters have posed an important obstacle on human living environments and urban sustainable development. How to enhance the resilience of urban system has become a new problem for cities. Therefore, it is necessary to explore how to build a future city that can effectively resist the crisis and be inclusive by enhancing urban resilience.

The increase of extreme weather disasters caused by climate change continues to threaten the safety of human settlements and ecological security. Floods and droughts, food and water shortages, and climate disaster events adversely affect future urban land structure, infrastructure construction, as well as the life, welfare, and property of residents (Abel et al., 2011). Enhancing urban resilience is an important initiative to effectively avoid the loss of life and property caused by climate risks and to improve the wellbeing of society. In recent years, "urban resilience" has received a lot of attention in the field of urban planning and social governance (Ribeiro and Goncalves, 2019; Tong, 2021). Urban resilience is a new approach to urban risk management, it focuses on improving the ability of self-organization, functional coordination, and adaptability to uncertainties of the urban system (Ahern, 2011; Shao and Xu, 2015), pays attention to the plasticity of changes in natural and human factors (Xu et al., 2018), and pursues the concept of sustainable development of human and environmental systems. It can be seen that how cities can operate normally and maintain resilience in the face of increasing risks and challenges (Cai et al., 2012), and building climate resilient city has become a new project that needs to be studied urgently.

Urban resilience has become a new analysis tool and research perspective in the field of urban sustainable development and global environmental change (Li and Zhang, 2011; Zheng et al., 2018). In order to effectively reduce the damage caused by climate disasters to human economy and society, urban resilience can contribute to ecosystem resilience and human wellbeing through ecosystem services (Demuzere et al., 2014), thus is considered a widely adopted and effective approach for climate change mitigation and adaptation, while driving economic development and improving social wellbeing. City is a complex and diverse system, vulnerable to the impact of natural disasters. The Intergovernmental Panel on Climate Change (IPCC) pointed out that global warming has made extreme weather more frequent in various regions, and "climate-resilient pathway" as an important development strategy for mitigating and adapting to climate crisis (Denton et al., 2014). In addition to coping with climate risks, urban resilience also focuses on strengthening the city's overall anti-risk capabilities. In the face of risks or disturbances, cities can adapt and recover to the original state, and they can also predict, anticipate and prevent the risks and disturbances of climate change in advance (Moser and Boykoff, 2013; Maru et al., 2014; Meerow et al., 2016; Shaker et al., 2019), which emphasizes the initiative and learning capacity of urban systems. Scientific diagnosis of climate risks and design of urban system development path according to different types of risks and adaptation goals (Tyler and Moench, 2012), which is an important branch of urban resilience. On the basis of sustainable development of cities from the perspective of climate change, this paper summarizes the progress of urban resilience, systematically sorts out the basic concepts and main research topics of urban resilience, and proposes the future development direction according to the current research trends, so as to provide support for the comprehensive research of multi-factor, multi-level and multi-objective urban resilience in the future. It provides reference for improving the ability of cities to cope with uncertainty and urban sustainable development research.

2 Materials and methods

2.1 Definition and scope

Climate change refers to the change of climate state caused by natural internal processes or external forcing, as well as the continuous change of atmospheric composition or land use by human activities. Climate change brings various problems, such as sea level rise due to global warming, and changes in the climate environment that make extreme weather such as droughts, floods, hail, storms and high temperatures frequent, which have a significant impact on human survival and activities (Jabareen, 2013). Urban resilience reflects the ability of urban systems to adapt and recover from risks such as natural disasters and major social events. Coping with natural disasters caused by climate change is one of the most important directions for building resilient cities, focusing on the long-term impact of urban systems on climate change processes and the comprehensive response to extreme climate disasters (Barbarossa et al., 2018).

2.2 Data sources

In order to explore the research progress and hotspots of urban resilience, the relevant literature data in this paper are from the core databases of "Web of Science" (WoS) and "China National Knowledge Infrastructure" (CNKI). We searched the literature database for topics (including subject, title or keywords) with "Urban Resilience + Climate Change" or "Resilient City + Climate Change", and other keywords or concepts related to resilience, such as "green infrastructure", "Climate change and disasters", "climate change impact"; The time span of literature retrieval was set from 2003 to 2022 (the retrieval time was February 2023); According to the above retrieval conditions, the advanced search method of WoS and CNKI database was used to cover all the literature as far as possible, and a data set of 1635 literatures related to urban resilience from 2003 to 2022 was preliminarily obtained. Therefore, a document-screening task was carried out manually, by further reading the title and abstract of the literature, the irrelevant literature was eliminated, and 559 valid literatures were retained.

2.3 Research methodology

Based on the "urban resilience" research related documents collected in WoS and CNKI core database from 2003 to 2022, this paper uses CiteSpace and VOSviewer two kinds of bibliometric software to analysis and knowledge visualization of the above datasets. The analysis function of CiteSpace can process the literature data with keyword co-occurrence and literature co-citation. The literature with strong co-citation is clustered by different algorithms, combined with data information such as high-frequency keyword matrix and highly cited literature, and then the literature clusters are named with nominal terms extracted from titles, abstracts or keywords. Through the induction method of co-occurrence clustering and high-frequency words analysis of keywords in domestic and foreign literatures, the hot topics of urban resilience research were analyzed, and the research hotspots and frontier issues of urban resilience were grasped based on keyword frequency map. The visual bibliometric analysis of literature was conducted by VOSviewer software to reveal main content of the literature. With the help of qualitative bibliometric analysis, the research hotspots, evolution trends and characteristics of urban resilience research can be obtained. The distribution structure, quantity change and correlation of literatures were conducted on the existing literature dataset and co-occurrence network of keywords, for better grasping the main research content and evolutionary relationship in current research.

3 Results and evolution trends

3.1 Research hotspots

Keywords are the author's concise summary of the main idea of the article, which can reflect the hot topics in the research field. The VOSviewer software was used to statistic high-frequency keywords in the literature, and the frontier hotspots of urban resilience research were analyzed by visual clustering map. According to the keyword clustering map, resilience, urban resilience, vulnerability, sustainability, adaptation, risk, systems, governance, ecosystem services, challenges, infrastructure and green infrastructure are the keywords most frequently used by scholars in the study area of urban resilience.

The hot topics in the research field of urban resilience were displayed by using the co-occurrence function of the visualization software VOSviewer. We searched all keywords in the literature, high-frequency keywords were screened out, and a co-word knowledge graph is generated according to the core keywords (Figure 1). Combined with relevant literatures, four hot topics in the current international research on urban resilience were summarized: ecosystem resilience, infrastructure resilience, governance resilience, and urban sustainable transformation. From the major clusters recognized by Citespace, five topics were identified after reviewing the highly co-cited document in the clustering diagram. These topics were named as "urban heatwave and high temperature," "urban waterlogging and flood," "sea-level rise," "forest wildfire," and "Nature-based Solutions (NbS)", respectively.

3.2 Evolution trends

The concept of resilience has experienced three stages of evolution from engineering resilience (Berkes and Folke, 1998), ecological resilience to more complex social-ecological resilience (Carpenter et al., 2001; Folke, 2006). According to the sequence change of high-frequency co-occurrence keywords (Figure 2), the study of urban resilience has undergone a transformation from large-scale space to small-scale space. From the resilience of social ecosystems to resilient cities and resilient infrastructure, the spatial scale of resilience has gradually focused on cities and their internal spaces. More resilience studies of different types of small-scale spaces will become a useful supplement to the macro-and meso-scale studies of regions and cities.

From the perspective of research fields and hotspots, the research on "urban resilience" has shown a trend towards a multidisciplinary field. The previous related papers mainly focused on the resilience and vulnerability of social ecosystems, including resilience to specific disasters, how to deal with urban risks has been a worldwide concern for a long time. The research direction has gradually expanded to resilient cities, sponge cities, green infrastructure, etc. It can be seen that the overall evolution trend of "urban resilience" research is its corresponding planning strategies, governance measures, evaluation methods and so on. In recent years, many studies have extensively explored the role of nature-based solutions in addressing climate change and natural disasters. Nature-based solutions enhance urban resilience in terms of both urban planning and infrastructure to address climate change mitigation and adaptation (He et al., 2023).

3.3 Main research content

In order to withstand the risks of climate change, urban systems need to have the ability to update, restructure and adapt. Enhancing urban resilience has become the best approach to urban sustainable development to effectively cope with various impacts or changes and reduce the vulnerability and uncertainty of the development process.

(1) Influencing factors of urban resilience

From the basic elements of urban composition, land use, economic development, housing, transportation, disaster and infrastructure plans affect the resilience of a city. Economic, social, and institutional factors influence urban resilience, and the level of urban economy determines the resilience of urban economic development and is the dominant factor affecting post-disaster economic resilience (Zhou et al., 2019). Climate change poses systemic and complex problems for urban planning and management at multiple levels and scales, which are difficult to be solved by traditional linear methods (Carter et al., 2015) and need to deal with problems at different levels from more dimensions. Policy intervention and institutional management play a lasting role in improving urban resilience and regional transformation (Dawley et al., 2010). Infrastructure plays an important role in ensuring sustainable urban development (Paul and Charles, 2012), reasonable urban spatial form can not only reduce the frequency and intensity of extreme climate disasters, but also enhance the

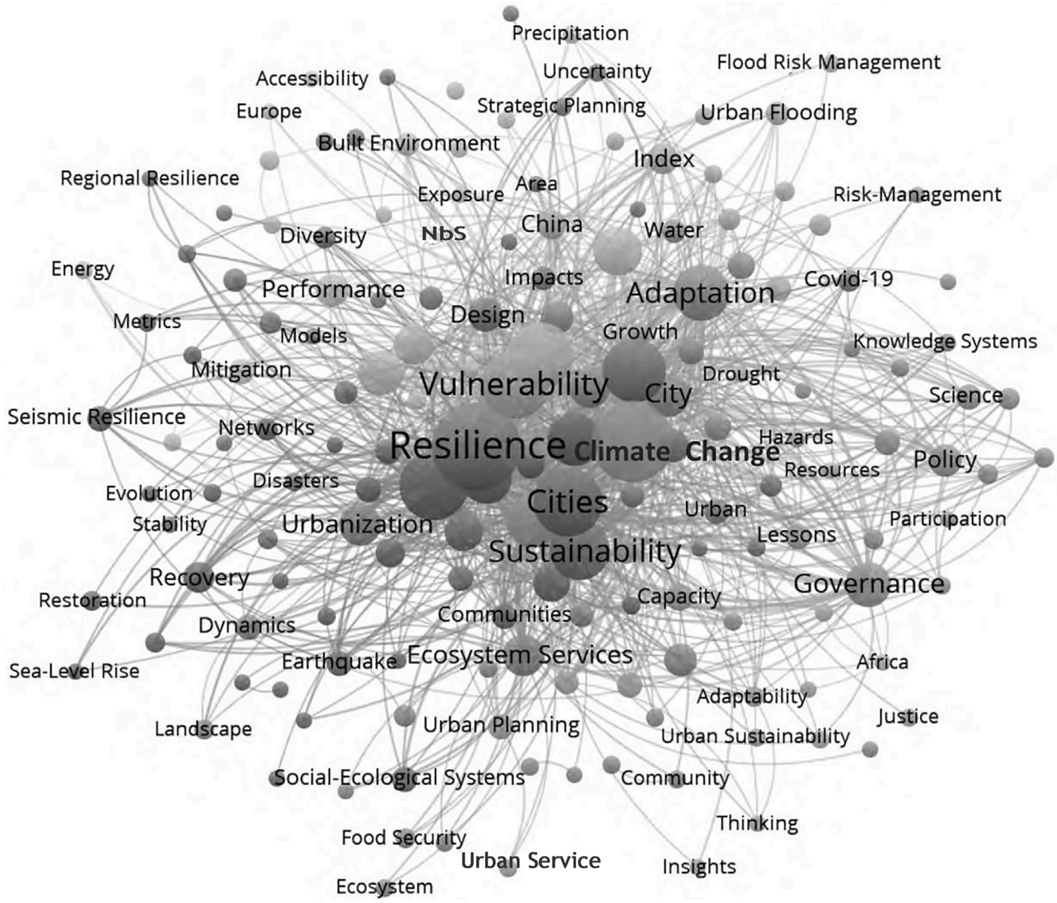

FIGURE 1
Network analysis of keyword co-occurrence.

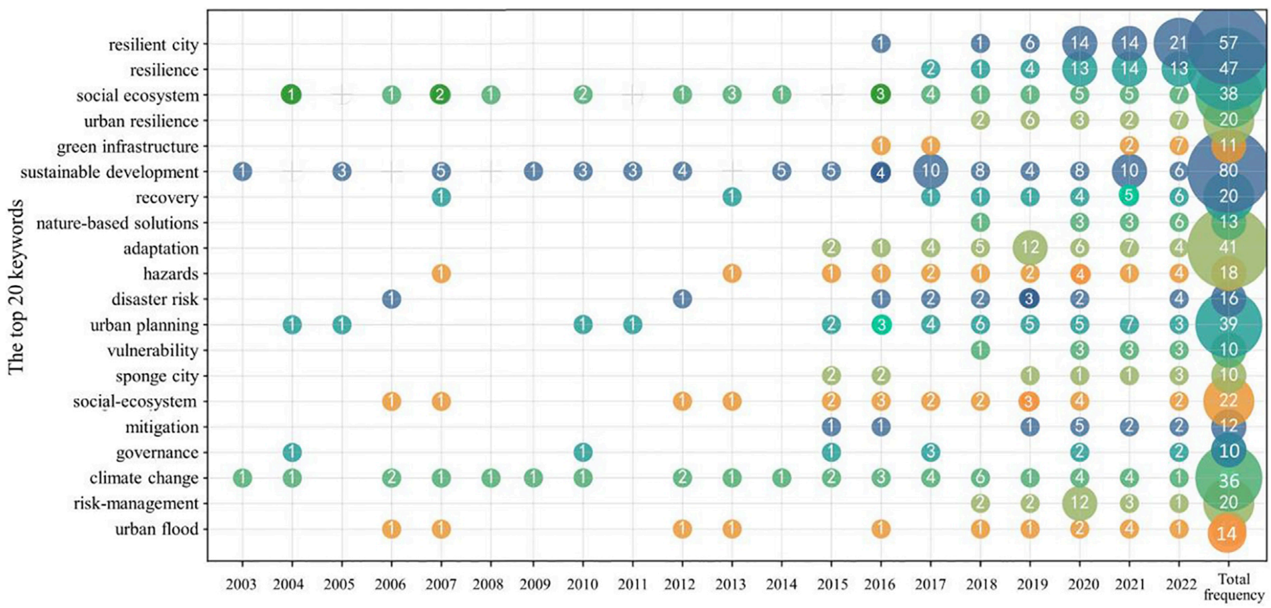

FIGURE 2
Sequence changes of the top 20 keywords in 2003-2022.

system resilience and adapt to climate change (Feng et al., 2020). Urban ecological environment aims to achieve specific goals such as maintaining biodiversity, reducing flood risk, alleviating heat island effect and safeguarding human settlement environment (Chad et al., 2018).

(2) Evaluation index and method of urban resilience

The main content of quantitative research on urban resilience is to construct an evaluation index system for resilience assessment, or to construct an economic or mathematical model (Sherrieb et al., 2010) for static resilience evaluation or analysis of influencing factors, in order to provide a basis for quantitative decision-making. Geographical location has an important effect on the distribution of spatial difference in urban disaster resilience, remote sensing models can assess the spatial heterogeneity and quantitative characterization of spatio-temporal evolution of urban resilience (Li and Zhai, 2017); Aiming at the goal of resilient community action, the evaluation index system of urban community resilience was preliminarily constructed from five dimensions of infrastructure, society, economy, institution and nature (Joerin et al., 2012); Assessing urban resilience through network resilience evaluation of network efficiency, diversity, and connectivity (Peng et al., 2018). Therefore, to better achieve urban resilience, the combined effects of physical, social, and natural factors need to be incorporated into the assessment of adaptive planning policies. However, how to evaluate the implementation effect of adaptive measures from multiple perspectives such as social, economic and ecological perspectives still needs more research and exploration (Han and Peng, 2019).

(3) The impact of climate change on urban resilience

Cities' response to climate risks depends on infrastructure standards, resource quality endowments and investment in environmental governance (Highfield et al., 2014; Han et al., 2021). Climate change is having a great impact on the space for human survival and activities, a series of natural disasters related to climate change have seriously threatened economic development, infrastructure operation, human health, and the safety of citizens' lives and property (Satterthwaite, 2013; Papa et al., 2015). This requires urban and regional development, especially in the layout of productive forces, urban and rural infrastructure construction and major project planning, to fully consider the requirements of adapting to climate change (Barbarossa et al., 2018). In the context of extreme weather occurs frequently, the risk uncertainty faced by cities has increased. Under the background of increasing uncertainty of disasters and risks, the concept of resilient city is further recognized and concerned by the academic community, and is considered as an important indicator and collaborative process of sustainable development (Magis, 2010; Ahern, 2011; Leichenko, 2011). Enhancing urban resilience is not only a strategic choice, but also a new paradigm of urban development in the context of climate change.

(4) Enhancing urban resilience in response to climate change

Numerous studies have presented strategies and practices to enhance urban resilience in various aspects from macroscopic urban morphological planning and microscopic spatial design (Wang and Zang, 2017), covering urban stormwater and water system resilience planning and design (Zhou and Li, 2017; Li et al., 2019; Zhang et al., 2019), delta urban planning (Dai et al., 2017; Dai et al., 2019), and island planning and design (Wang et al., 2017; Bosselmann et al., 2019; Chen et al., 2019; Tu, 2019). Furthermore, the combination of grey and green infrastructures can reduce the reliance on the overall urban drainage system, urban woodland and sunken green spaces can effectively store and detain rainwater (Ahern, 2011; Casal-Campos et al., 2015; Meerow and Newell, 2017). Spatial planning has been widely accepted as an effective strategy responding to climate change and city safety problems caused by climate change and extreme weather events. Since spatial elements should be rationally distributed in land use and urban development regulations, to reduce the impact of climate disasters on cities, major infrastructure and important urban space needs to avoid climate-sensitive areas. In the process of building resilient cities to cope with climate change, the content of climate change adaptation should be incorporated into spatial planning, and a climate adaptation strategy featuring government-led and public participation should be formed in the planning system (Markolf et al., 2018).

4 Conclusion and future directions

Based on the perspective of climate change, this study tries to analyze the research hotspot, main research content, and the future directions of urban resilience. The high-frequency co-occurring words with urban resilience involve resilient city, vulnerability, sustainability, risk adaptation, system governance, ecosystem services, challenges, infrastructure construction, green infrastructure, reflecting the research hotspot in different stages. According to the existing literature, urban resilience construction is a comprehensive improvement of society, economy, ecology, infrastructure, and governance level. Urban resilience is enhanced through multiple means such as urban planning, infrastructure construction and maintenance, and institutional mechanism optimization, so that cities can integrating nature-based solutions for urban resilience to cope with extreme weather, and improve the resilience of cities to climate change.

The trend of climate change is inevitable, and urban resilience research has weaknesses in disaster prevention planning, resilience and spatial integration, and regional linkage. Adaptive measures should be taken as early as possible to reduce disaster risk and promote sustainable urban development. The current research progress mainly focuses on the mitigation and adaptation of urban resilience to climate change, as well as nature-based solutions to enhance urban resilience to reduce disaster risk. With the intensification of climate change, the frequency and intensity of extreme weather and climate events such as floods, droughts and high temperatures will also increase. It is particularly important to understand the sensitivity and vulnerability of urban systems to these changes. On this basis, a flexible and effective urban resilience planning program can be developed, taking into account social, economic and environmental interests.

Climate change brings various negative effects to human daily life and production, and thus poses a threat to sustainable urban development. Urban resilience is a hot topic on how urban space responds to natural disasters caused by climate change. The United Nations Human Settlements Programme (UN-Habitat) identified urban disaster risk management, urban economy and society, resilient infrastructure and basic services, urban planning and environment, and urban governance as five pillars of urban resilience. Based on the analysis of the current research progress and predicament of urban resilience, the authors assume that more attention should be given to the following aspects:

1) Conduct multi-perspective systematic study on urban resilience. Faced with complex urban systems, future research on urban resilience needs to conduct a holistic evaluation of the interaction between urban systems and climate change. New technologies such as big data crawlers, sensor technology, digital image recognition, and interdisciplinary modeling methods can support resilience planning. Strengthen dynamic observation and research on human, logistics and information flows by means of emerging technologies, so as to improve the city's prediction and preparation for unknown risks. Planning for the construction of resilient urban infrastructure often includes nature-based solutions that can have a positive impact on the social and natural environment. Nature-based solutions for urban resilience are means of sustainable development with social, economic, and environmental benefits.
2) Planning and design city based on resilience mechanism. With the aggravation of climate change, it is urgent to improve the adaptability of cities in spatial planning system regarding resilience planning and risk reduction. The urban resilience mechanism covers the development process of the urban system and the whole life cycle. It emphasizes the systematic construction of planning techniques, construction standards, social governance and public participation to comprehensively enhance the structural adaptability of urban system, so as to enhance the overall resilience of the city. In planning and design practice, the resilience planning strategy of climate mitigation and adaptation is incorporated into the planning system, so as to promote achievement the goal of urban resilience to climate change.
3) Innovation and reform of urban governance and management system. In order to form a virtuous cycle of resilient urban construction, the institutional method of feedback mechanism is established from the effects and influencing factors of urban resilience practice. Explore the establishment of a resilience infrastructure project library and encourage the application of science and technology to promote the development and pilot of resilience projects. Innovate financing channels and public-private partnership models, increase investment in urban resilience construction, and guide more social capital to invest in resilient infrastructure. Governments and financial institutions can further explore the ecological paths of urban resilience construction that combines resilient infrastructure with nature-based solutions.

Author contributions

WW and HW were in charge of designing the experiments and writing the manuscript. HW, XH, and HH were in charge of revising the manuscript. HW was in charge of project administration. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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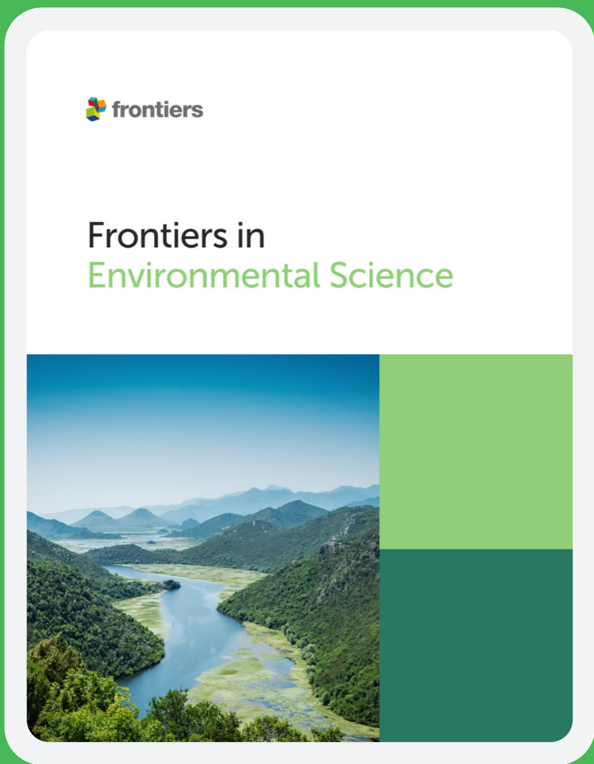

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