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Application of Remote Sensing to Assess Land Ecological Sensitivity

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In this work, the Northern Guangdong region of China was taken as the study area. First, the ecological sensitivity of the Northern Guangdong Ecological Development Area was systematically assessed on the basis of remote sensing (RS) image data and multisource geographic information data. Then, the Criteria Importance Through Intercriteria Correlation (CRITIC) model was adopted to calculate the weight of each indicator. Finally, the spatial distribution of comprehensive ecological sensitivity in the Northern Guangdong region was obtained through the processing and analysis of geographic information data. According to the results, ecological sensitivity in the Northern Guangdong region shows significant spatial differentiation characteristics. Specifically, extreme-sensitivity and severe-sensitivity zones were mainly concentrated in the east and the northwest, whereas insensitive and mildly sensitive zones were mainly distributed in the southwest. The results of this study provide a scientific basis for ecological protection and management in the Northern Guangdong region, offering important references for the sustainable development of regional ecosystems and the delineation of ecological reserves.

1. Introduction

With the degradation of global ecosystems and the reduction of biodiversity, ecological sensitivity assessment in regional ecological protection and sustainable development has become increasingly important.[(1)] Land resources are the foundation of human survival and social development, and the rational use of land resources is a prerequisite for achieving sustainable urban development. The ecological sensitivity of land use refers to the adaptability of land eco-environmental factors to external pressures or changes on the premise of maintaining

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environmental quality. It is the basis for measuring the eco-environmental rationality of land use structure, layout, zoning, and management measures. Specifically, it reflects the sensitivity of a land ecosystem to natural or human disturbances in a specific area, as well as the severity and possibility of eco-environmental problems caused by these disturbances (such as soil erosion, desertification, and salinization). The ecological sensitivity analysis of land use provides an important basis for land use planning and layout. By assessing the environmental sensitivity of land use, the spatial scope of the planning area can be zoned and graded, to offer eco-environmental references for making scientific and rational land use plans. Exploring the ecological sensitivity of land use is of considerable significance for promoting the rational use of land resources, protecting the ecological environment, and achieving sustainable development.

Currently, studies in this field mostly assess the ecological security pattern of a region from the perspective of the importance of a single ecosystem service function or from a composite perspective that gives due consideration to ecological sensitivity. Overall, there is a lack of comprehensive consideration of the impacts of different types of landscape. The lack of rational correction also causes the ecological security pattern scheme to be very subjective and barely operational. Geographic spaces constitute a huge and complex system that involves multiple elements as well as their nonlinear interactions, with rich geographic phenomena, processes, and patterns.(2) Remote sensing (RS), developed to automatically extract land surface information of interest from RS data using image processing and computer technology, has been widely used in various aspects of Earth Science element perception and socio-economic research.(3,4) Therefore, in this study, we focused on analyzing ecological sensitivity in the demarcated study area using RS data and geographic information system (GIS) technology. The ecological sensitivity analysis of land use involves the efficient and accurate monitoring of land cover and land use, as well as their changes. Relying on sensors mounted on satellites, aircraft, and other platforms, RS technology obtains land surface information from different heights and angles to form high-resolution RS images.

These images, after preprocessing, feature extraction, classification, and other steps, can reveal key ecological parameters such as land use type, vegetation coverage, and soil moisture. In research on the ecological sensitivity of land use, RS technology can enable large-scale, rapid nondestructive monitoring, providing important data support for assessing the impact of land use change on the ecological environment. It can also be combined with GIS and model simulation to further analyze the spatial distribution, change trend, and driving mechanism of the ecological sensitivity of land use, laying a scientific foundation for land resource management and eco-environmental protection.

In this study, we focused on the Northern Guangdong region, a key ecological security barrier in Guangdong Province, China. The ecosystem stability of this region is of great importance for ensuring the sustainability of regional ecological security and ecosystem service functions. In this study, the ecological sensitivity of the Northern Guangdong Ecological Development Area was systematically assessed by combining RS image data with multisource data such as Digital Elevation Model (DEM) data, meteorological data, Normalized Difference Vegetation Index (NDVI) data, land use data, soil erosion data, and nighttime light data. The above data were then processed and analyzed using geographic information software ArcGIS

10,[5] and the weight of each indicator was calculated using the Criteria Importance Through Intercriteria Correlation (CRITIC) model[6] to obtain the spatial distribution of comprehensive ecological sensitivity in the Northern Guangdong region.

2. Materials and Methods

2.1 Study area

The Northern Guangdong Ecological Development Area was taken as the study area. The study area covers four prefecture-level cities in Guangdong Province, China, namely, Qingyuan, Shaoguan, Heyuan, and Meizhou (Fig. 1), which occupy a total area of 68900 km^2 (38% of the total land area of Guangdong Province, i.e., 179800 km^2) and have a total population of 15.59 million (12% of the total population of Guangdong Province, i.e., 126.84 million).

Natural resources, especially nonrenewable ones (such as water and soil resources), have the greatest impact on the population, that is, the richer the types and quantities of natural resources, the larger the population they can support. The study area is located in the mountainous region of Northern Guangdong, with abundant forest land resources and a forest coverage rate of more than 70%. It is an important ecological barrier and water source in Guangdong Province, China. In this study, by identifying the main factors affecting ecological sensitivity, we aimed to reveal the evolutionary mechanisms of ecosystems and explore the spatial optimization paths of land resources, offering references for the construction of ecological civilization and the sustainable development of ecological development areas.

2.2 Materials

(1) DEM

DEM is a model that enables the digital simulation of surface topography based on limited topographic elevation data.[1] The elevation data used in this study were obtained from Copernicus Global Digital Elevation Models GLO-30.[7] This dataset is derived from the

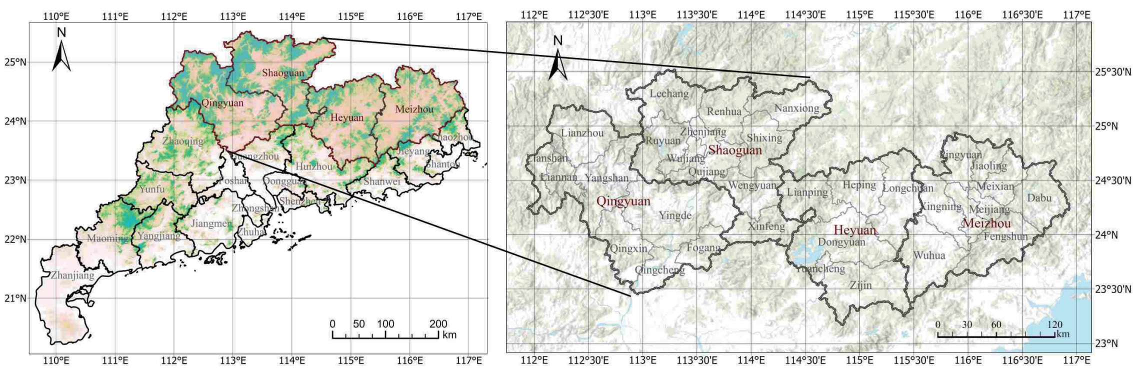

Fig. 1. (Color online) Geographic location of study area.

TerraSAR-X add-on for Digital Elevation Measurements (TanDEM-X) mission jointly operated by the Deutsches Zentrum für Luft-und Raumfahrt (DLR) and Airbus Defence and Space Europe. For this mission, two satellites, TerraSAR-X and TanDEM-X, were used to collect high-resolution X-band Synthetic Aperture Radar (SAR) data from 2011 to 2015. The data were then edited and processed to generate a global-scale DEM. In this study, data were processed using the Extract by Mask tool to obtain the DEM data of the study area, and slope and aspect analyses were performed in ArcGIS 10.5 [5] to obtain slope and aspect data.

(2) Meteorological data

The meteorological data used in this study, including annual average precipitation and temperature data, were extracted from the Climatic Research Unit gridded Time Series (CRUTS) dataset provided by the Tyndall Centre for Climate Change Research at the University of East Anglia, UK.[8] The CRUTS dataset is constructed on the basis of the data observed by meteorological stations worldwide, which are processed through interpolation and spatial analysis techniques to generate high-resolution gridded climate variable data. In this study, the data obtained were subjected to the Extract by Mask, Grid Computing, and Grid Resampling tools in ArcGIS 10.5, to acquire the gridded annual average precipitation and temperature data (with a resolution of 30 m) for the study area in 2020.

(3) NDVI

NDVI is an RS index that assesses the status of land vegetation by analyzing the reflection characteristics of light with different wavelengths from vegetation. Defined as the quotient of the difference in reflectivity between the NIR channel and the visible channel divided by the sum thereof, NDVI is often used to monitor vegetation growth.[9,10] In this study, Landsat 8 OLI and TIRS satellite digital products were downloaded from the Geospatial Data Cloud.[11] To better reflect the recent status of vegetation growth in the study area, we selected image data from September 2022. The image data were then processed through radiation correction, atmospheric correction, cloud detection and removal, and other preprocessing steps to calculate the NDVI data of the Northern Guangdong region with ENVI 5.4 (The Environment for Visualizing Images) (Broomfield, USA) software.

(4) Land use data

The land use data in this study were obtained from the China National Land Use/Cover Change (CNLUCC) Dataset[12] provided by the Resource and Environmental Science Data Platform of the Chinese Academy of Sciences.[13] This dataset uses RS imagery from Landsat satellites as the primary information source to construct the CNLUCC Dataset through manual visual interpretation. In this study, the data were processed using the Extract by Mask tool in ArcGIS 10.5 to acquire the land use data of the Northern Guangdong Ecological Development Area in 2020.

(5) Soil erosion data

The soil erosion data in this study were annual soil erosion data (with a resolution of 30 m) in China from 1990 to 2022, provided by the Science Data Bank.[3] This dataset is based on Google Earth Engine and includes soil erosion data in China from 1990 to 2022 [t/($hm^2 \cdot a$)] calculated from the Revised Universal Soil Loss Equation (RUSLE).[14] RUSLE consists of five factors, namely, the Cover and Management Factor (C), Soil Erodibility Factor (K), Slope

Length and Steepness Factor (LS), Rainfall Erosivity Factor (R), and Support Practice Factor (P). These five factors can be multiplied to obtain the soil erosion modulus. In this study, the data were processed using the Extract by Mask tool to acquire the gridded soil erosion data (with a resolution of 30 m) for the Northern Guangdong region.

(6) Nighttime light data

Nighttime light data reflect the spatial distribution and intensity of human activities, that is, the greater the nighttime light value, the higher the intensity of human activities, and the more serious the impact on the ecological environment. In this study, the annual nighttime light data for China in 2020 were obtained from the Resource and Environmental Science Data Platform.(12) They were derived from the NPP-VIIRS dataset based on observations by the Visible Infrared Imaging Radiometer Suite (VIIRS) aboard the Suomi National Polar-orbiting Partnership (SNPP) satellite. In this study, the nighttime light data of the Northern Guangdong region were obtained using the Extract by Mask tool.

(7) Other data

The water system and road data in this study were extracted from OpenStreetMap (OSM),(15) an open-source map data community to which users can contribute map data.(16) Vector data on water systems and roads can be downloaded from OSM and clipped for analysis. The species distribution and nature reserve data were obtained from the National Specimen Information Infrastructure.(17)

2.3 Methods

2.3.1 Construction of an indicator system

The topography of the Northern Guangdong region is dominated by mountains and hills, with large elevation differences and a slope range of 0–62°. This complex topography provides rich habitats for various ecosystems and biodiversity.(18) The Northern Guangdong region also has a subtropical evergreen broad-leaved forest system, which is the largest species gene pool in Guangdong Province. With a forest coverage rate of more than 70%, this region has formed a forest-based symbiotic ecosystem of animals and plants. In addition, this region is rich in wetland ecosystems and important water conservation areas. The mild climate of this region, characterized by warm and humid weather and abundant precipitation, is conducive to the growth and reproduction of organisms and provides a solid climatic foundation for ecosystem services.

To comprehensively assess the ecological sensitivity of the Northern Guangdong Ecological Development Area, we constructed an indicator system from the dimensions of topography, climate, natural resources, and human activities, following the principles of scientificity, feasibility, intelligibility, and integrity, based on the ecological characteristics of the Northern Guangdong region and the findings of related studies. The topographic dimension mainly consists of elevation, slope, and aspect, which reflect the impacts of topographic fluctuations and elevation differences on soil erosion, vegetation growth, and other ecological services in the Northern Guangdong region. Climate factors include annual average precipitation and temperature, which are closely related to vegetation growth cycles and ecosystem stability in the study area.

The natural resource dimension mainly includes indicators such as vegetation coverage, drainage density, species diversity, nature reserve density, land use type, and soil erosion, which directly reflect the ecological background of the study area. The dimension of human activities mainly includes two indicators, namely, road kernel density and nighttime light. Specifically, the use of roads produces noise, exhaust emissions, and fugitive dust, which directly impact the ecological environment. Roads also split wildlife habitats and obstruct animal migration, resulting in ecosystem fragmentation. Nighttime light directly reflects the intensity and density of human activities, that is, the greater the nighttime light value, the higher the intensity and density of human activities, and the more serious the impact on the ecological environment.(19)

Referring to the sensitivity standards given in the Interim Regulations on Division of Ecological Function Areas issued by the China Environmental Protection Administration and the findings of related studies, we graded the sensitivity of factors at five levels: 1 = Insensitive, 2 = Mild Sensitivity, 3 = Moderate Sensitivity, 4 = Severe Sensitivity, 5 = Extreme Sensitivity. That is, a region with a higher sensitivity level often has richer ecological resources and better ecological background and is more likely to be impacted and degraded by human development activities. Conversely, a region with a lower sensitivity level is less likely to be impacted and disturbed by human development activities. The indicator system and grading of ecological sensitivity are shown in Table 1.

2.3.2 CRITIC

The CRITIC method calculates weights by considering the standard deviation of each indicator and the correlation between indicators, thus avoiding inaccurate weight assignment caused by redundant information. It is an objective and rational method for determining the weights of multiple indicators, especially suitable for dealing with multi-attribute decision-making problems.(6)

The formula for calculating the amount of information of each indicator is as follows:

$$\sigma_j = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(X_{ij} - \overline{X_j}\right)^2}, \tag{1}$$

where σ_j denotes the standard deviation of the jth indicator and $\overline{X_j}$ denotes the mean of the jth indicator.

The matrix of correlation coefficients between all indicators can be calculated using the following formula:

$$r_{ij} = \frac{\sum_{k=1}^{n}\left(X_{ik} - \overline{X_i}\right)\left(X_{jk} - \overline{X_j}\right)}{\sqrt{\sum_{k=1}^{n}\left(X_{ik} - \overline{X_i}\right)^2 \sum_{k=1}^{n}\left(X_{jk} - \overline{X_j}\right)^2}}, \tag{2}$$

where r_{ij} denotes the correlation coefficient between the ith indicator and the jth indicator.

Table 1
Indicator system and grading of ecological sensitivity.

Dimension	ID	Name	Units	Insensitive	Mild sensitivity	Moderate sensitivity	Severe sensitivity	Extreme sensitivity
Topography	1	Elevation	m	<200	200–400	400–600	6000–800	>800
	2	Slope	°	<8	8–16	16–23	23–33	>33
	3	Aspect	—	Flat terrain and South	Southeast and Southwest	East and West	Northeast and Northwest	North
Climate	4	Temperature	℃	<18	18–19	19–20	20–22	>22
	5	Precipitation	mm	<1400	1400–1500	1500–1600	1600–1700	>1700
Resources and environment	6	Vegetation coverage	—	<0.2	0.2–0.4	0.4–0.6	0.6–0.8	>0.8
	7	Distance to water	m	>7500	5000–7500	3000–5000	1000–3000	<1000
	8	Species diversity	—	<0.11	0.11–0.28	0.28–0.48	0.48–0.78	>0.78
	9	Nature reserve density	—	<0.1	0.10–0.18	0.18–0.28	0.28–0.4	>0.4
	10	Land use	—	Construction land	Arable land	Grassland	Forest land and bare land	Water bodies
	11	Soil erosion	$t/(hm^2 \cdot a)$	<5	5–15	15–30	30–50	>50
Human activities	12	Distance to roads	m	>2500	1500–2500	1000–1500	500–1000	<500
	13	Nighttime light	—	<5	5–10	10–15	15–30	>30

The weight of each indicator can be comprehensively calculated on the basis of the amount of information and correlation using the following formula:

$$w_j = \frac{\sigma_j \cdot \sqrt{1 - \sum_{i=1, i \neq j}^{m} r_{ij}^2}}{\sum_{j=1}^{m} \sigma_j \cdot \sqrt{1 - \sum_{i=1, i \neq j}^{m} r_{ij}^2}}, \tag{3}$$

where w_j denotes the weight of the jth indicator, σ_j denotes the standard deviation of the jth indicator, and r_{ij} denotes the correlation coefficient between indicators.

2.3.3 Spatial autocorrelation analysis

Global Moran's I and Local Moran's I, as important indicators in spatial statistics, measure the spatial autocorrelation of geospatial data, i.e., the spatial distribution pattern of a geographic phenomenon or attribute. They are often used to detect whether spatial data exhibit an aggregated, discrete, or random distribution.

Specifically, Global Moran's I measures the overall spatial autocorrelation of attribute values across the whole study area. The value of this index reflects whether there is a global spatial aggregation or dispersion pattern in the data.

$$I = \frac{n}{W} \cdot \frac{\sum_{i=1}^{n} \sum_{j=1, j \neq i}^{n} w_{ij} \left(X_i - \bar{X} \right) \left(X_j - \bar{X} \right)}{\sum_{i=1}^{n} \left(X_i - \bar{X} \right)^2} \tag{4}$$

Here, n denotes the total number of spatial units, X_i and X_j denote the attribute values of the ith and jth spatial units, respectively, $\bar{X}$ denotes the mean attribute value, w_{ij} denotes the weight between the ith and jth spatial units, usually defined by spatial distance or adjacency, and W denotes the sum of all weights. "$I > 0$" indicates positive spatial autocorrelation, where the data exhibit an aggregated or similar distribution, "$I < 0$" indicates negative spatial autocorrelation, where the data exhibit a discrete or mutually exclusive distribution, and "$I = 0$" indicates the absence of spatial autocorrelation, where the data exhibit a random distribution.

Local Moran's I, on the other hand, measures spatial autocorrelation in a local area, i.e., the autocorrelation of a specific place or area. In contrast to Global Moran's I, Local Moran's I can reveal local hot spots (high-value aggregation areas) and cold spots (low-value aggregation areas) in spatial data.

$$I_i = \frac{\left(X_i - \bar{X} \right)}{S_0} \sum_{j \neq i} w_{ij} \left(X_j - \bar{X} \right) \tag{5}$$

Here, I_i denotes the Local Moran's I of the ith spatial unit, X_i denotes the attribute value of the ith spatial unit, $\bar{X}$ denotes the mean attribute value, w_{ij} denotes the weight between the ith and jth spatial units, and S_0 denotes a normalized constant.

3. Results

3.1 Single-factor sensitivity analysis

Mountains and hills are widely distributed in the Northern Guangdong region, where the overall elevation gradually declines from north to south. As shown in Fig. 2, elevation-sensitive factors exhibit the distribution characteristics of higher values in the north and lower values in the south. Extreme-sensitivity and severe-sensitivity zones were most widely distributed, accounting for 66.70% of the total area, and they were mainly concentrated in the north and west of Shaoguan and the north of Qingyuan. Mild-sensitivity and insensitive zones were sparsely distributed, accounting for 9.24 and 5.65% of the total area, respectively. The distribution characteristics of slope-sensitive factors were highly correlated with those of elevation-sensitive factors, i.e., the slope sensitivity level was lower in zones with low elevation but higher in zones with high elevation. Specifically, high-sensitivity zones were most widely distributed, accounting for 29.67%, while insensitive zones accounted for the least, at 6.2% of the total area. Aspect-sensitive factors were affected by slope orientation, so they did not exhibit significant spatial differentiation characteristics such as elevation-sensitive or slope-sensitive factors. In terms of sensitivity levels, aspect-sensitive factors displayed an alternating distribution of

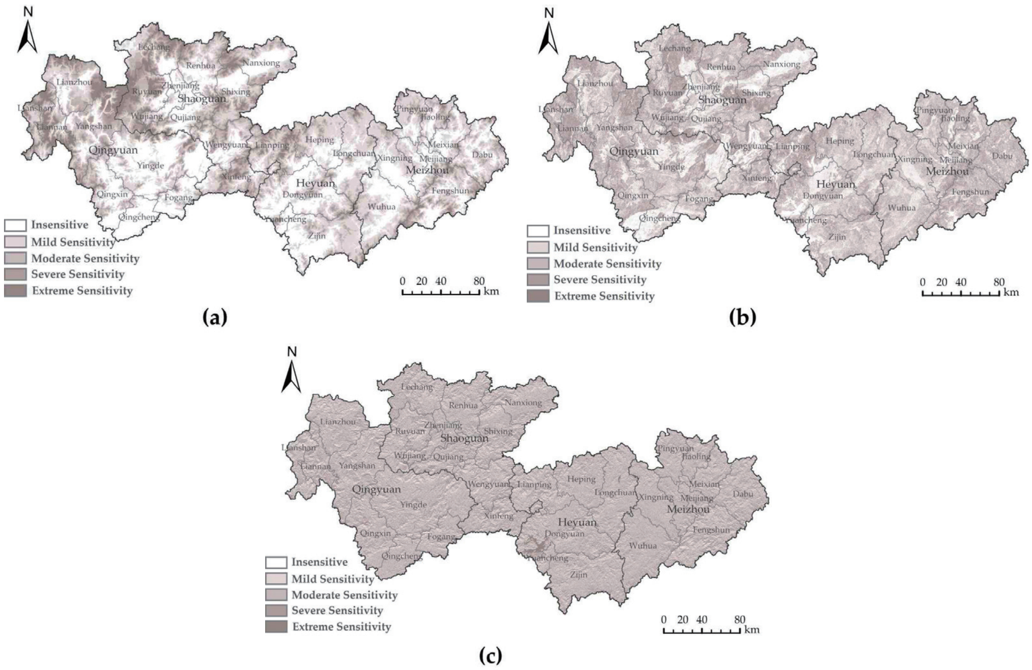

Fig. 2. (Color online) Topographic sensitivity analysis map. Ecological sensitivity distribution maps of (a) elevation-sensitive, (b) slope-sensitive, and (c) aspect-sensitive factors.

different sensitivity levels. In terms of proportion, mild-sensitivity zones were most widely distributed, accounting for 25.04%, followed by severe-sensitivity zones with a proportion of 24.67%.

Figure 3 shows the spatial distribution of climate sensitivity assessment factors in the Northern Guangdong region. It is clear that temperature was mainly affected by elevation and latitude. The higher the elevation, the lower the temperature; the closer the latitude is to the south, the higher the temperature. Accordingly, temperature sensitivity exhibited significant spatial differentiation characteristics from north to south, and the spatial distribution pattern of temperature-sensitive factors was similar to that of elevation-sensitive factors, i.e., higher in the north and lower in the south. In terms of proportion, mild-sensitivity zones were most widely distributed, accounting for 44.79% of the total area, followed by insensitive zones with a proportion of 26.59%. Because of its mild climate and low temperature fluctuations, the overall temperature sensitivity in the Northern Guangdong region was relatively stable. Overall, the spatial distribution pattern of precipitation-sensitive factors exhibited characteristics of higher values in the east and lower values in the west. Extreme-sensitivity and high-sensitivity zones were mainly distributed in Meizhou and northern Shaoguan, while insensitive zones were mainly found in western Heyuan and southern Shaoguan. In terms of proportion, mild-sensitivity zones were still most widely distributed, accounting for 35.59% of the total area, followed by moderate-sensitivity zones with a proportion of 25.56%. Extreme-sensitivity zones accounted for the least, at 7.57% of the total area.

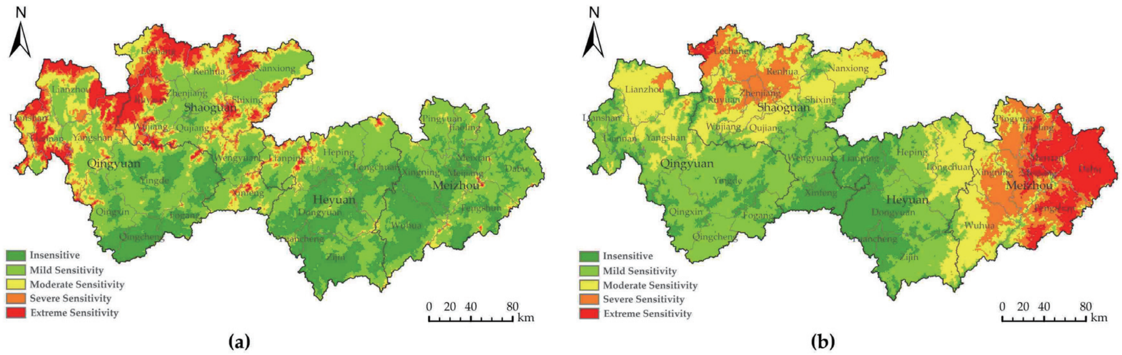

Fig. 3. (Color online) Climate sensitivity analysis map. Ecological sensitivity distribution maps of (a) temperature-sensitive and (b) precipitation-sensitive factors.

Figure 4 shows the spatial distribution of natural resource sensitivity. The Northern Guangdong region is rich in forest resources and has a high vegetation coverage, so it is more susceptible to human activities and has a high ecological sensitivity. From the perspective of the spatial distribution of vegetation coverage-sensitive factors, extreme-sensitivity zones were widespread in the Northern Guangdong region, while insensitive zones were mainly distributed in highly urbanized areas and near water bodies in the four cities of Northern Guangdong. In terms of proportion, extreme-sensitivity zones were most widely distributed, accounting for 51.24% of the total area, followed by severe-sensitivity zones with a proportion of 42.74%. By contrast, mild-sensitivity and insensitive zones accounted for only 1.17% of the total area. In this sense, sound ecological protection plans should be developed for the future development of the Northern Guangdong region to avoid damage to existing vegetation by overexploitation. The spatial distribution characteristics of soil erosion sensitivity were opposite to those of vegetation coverage sensitivity, i.e., in the former case, high-sensitivity and extreme-sensitivity zones were sparsely distributed, while insensitive zones were widely distributed.

In terms of proportion, insensitive zones accounted for 86.92% of the total area, while severe-sensitivity and extreme-sensitivity zones accounted for 1.55 and 1.66%, respectively. When it came to land use-sensitive factors, severe-sensitivity zones were most widely distributed, accounting for 73.13% of the total area, while extreme-sensitivity and insensitive zones were sparsely distributed, accounting for 1.82 and 2.10%, respectively. The overall spatial distribution of water system sensitivity was characterized by higher values in the south and lower values in the north, and extreme-sensitivity zones were mainly concentrated in the south of the Northern Guangdong region. In terms of proportion, the distribution of different sensitivity levels was relatively balanced. Mild-sensitivity zones accounted for the lowest proportion of 15.29% of the total area, while severe-sensitivity zones accounted for the highest proportion of 26.89%. The spatial distribution of species sensitivity was characterized by higher values in the west and lower values in the east, and extreme-sensitivity zones were mainly distributed in Ruyuan and Lechang of Shaoguan. In terms of proportion, insensitive zones were most widely distributed, accounting for 38.28%, followed by mild-sensitivity zones, accounting for 31.30%, while extreme-sensitivity zones accounted for the lowest proportion of 4.20%. The spatial distribution

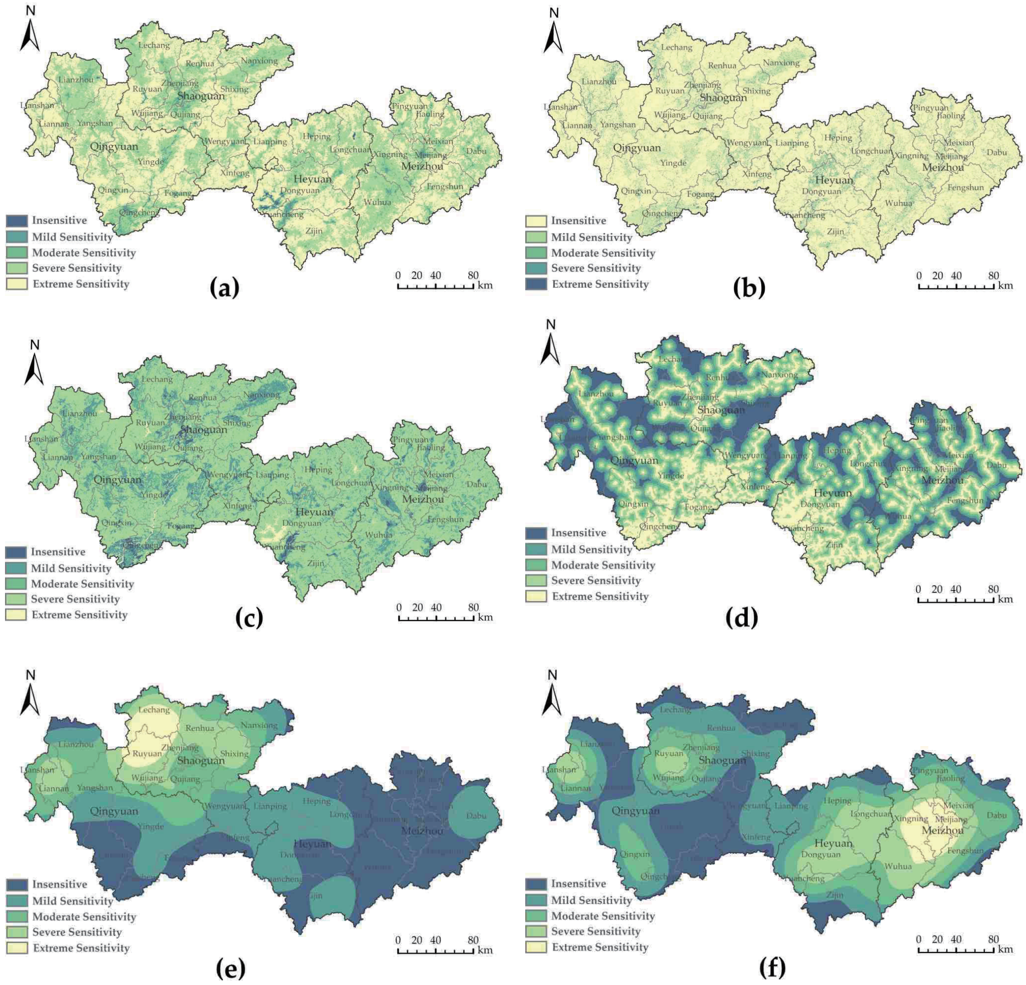

Fig. 4. (Color online) Natural resource sensitivity analysis map. Ecological sensitivity distribution maps of (a) vegetation coverage, (b) water system, (c) species diversity, (d) nature reserve density, (e) land use, and (f) soil erosion factors.

of reserve sensitivity was characterized by higher values in the east and lower values in the west, and extreme-sensitivity zones were mainly concentrated in Meijiang, Meixian, and Xingning of Meizhou. In terms of proportion, mild-sensitivity zones accounted for the highest proportion of 32.25% of the total area, while extreme-sensitivity zones accounted for the lowest proportion of 4.64%.

Figure 5 shows the spatial distribution of human disturbance sensitivity. The high-sensitivity areas of nighttime light were mainly concentrated in highly urbanized areas. A region with a higher nighttime light value has more intensive human activities and, consequently, a weaker ecological background, so the impact of future human activities on its ecological value is smaller. Conversely, a region with a lower nighttime light value has fewer human activities and, consequently, a stronger ecological background, so the impact of future human activities on its ecological value is greater. As an ecological reserve, the Northern Guangdong region has a

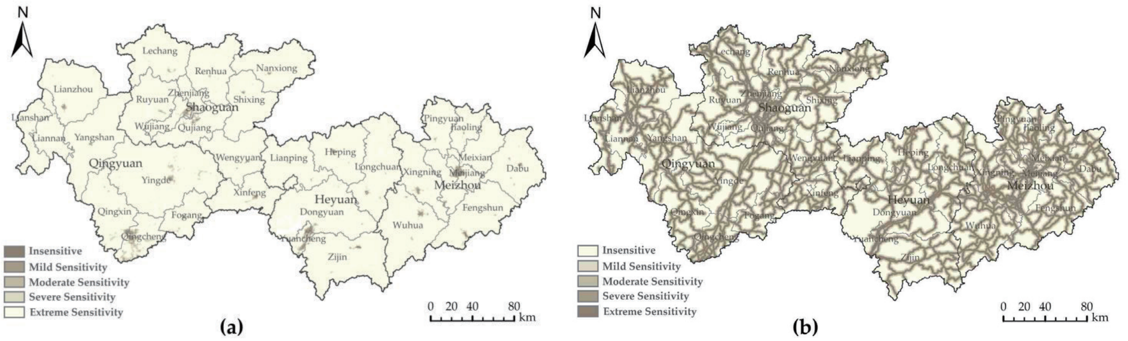

Fig. 5. (Color online) Human activity sensitivity analysis map. Ecological sensitivity distribution maps of (a) road and (b) nighttime light factors.

strong ecological background, and its extreme-sensitivity zones accounted for 97.90% of the total area. In future development, we should be alert to the potentially destructive impact of human activities on nature. Road-sensitive factors were mainly affected by the layout of the road network. In this study, we mainly analyzed expressways, national roads, provincial roads, county roads, and railways, all of which have a significant impact on nature. The results showed that insensitive zones accounted for the highest proportion of 37.44%, while moderate-sensitivity and severe-sensitivity zones accounted for 11.77 and 14.26%, respectively.

3.2 Comprehensive sensitivity analysis

In this study, a 1000 × 1000 m^2 sampling matrix was constructed using ArcGIS 10.5. The sensitivity levels of 13 factors were sampled into the sampling point matrix using the “Multi-Value Extraction to Points” tool, and the sampling results were exported via the “Table to Excel” function and introduced into the CRITIC model to calculate the weights of indicators in the study area. As a multi-indicator method that comprehensively considers the variability and conflict of indicators, the CRITIC weighting method provides the relative importance of each indicator in the overall assessment system. The calculation results are shown in Fig. 6.

According to the results calculated by the CRITIC weighting method, the weight assignment of each indicator reflects its amount of information in the assessment system and its contribution to the final assessment results. Specifically, the road and water system sensitivities had the highest weights of 12.79 and 11.81%, respectively, indicating their significant impacts on the comprehensive ecological sensitivity. This is because they have a direct bearing on hydrological cycles, the biodiversity conservation of ecosystems, and the disturbance degree of human activities. Nature reserve density, precipitation, and aspect factors had relatively high weights of 8.85, 8.84, and 8.78%, respectively, indicating that topographic features and precipitation conditions are equally important in the study area. These factors are usually closely related to soil erosion and other environmental problems. On the basis of the results calculated by the CRITIC weighting method, we performed an overlay analysis on the 13 indicators to obtain the spatial distribution of the comprehensive ecological sensitivity in the study area, as shown in Fig. 7(a).

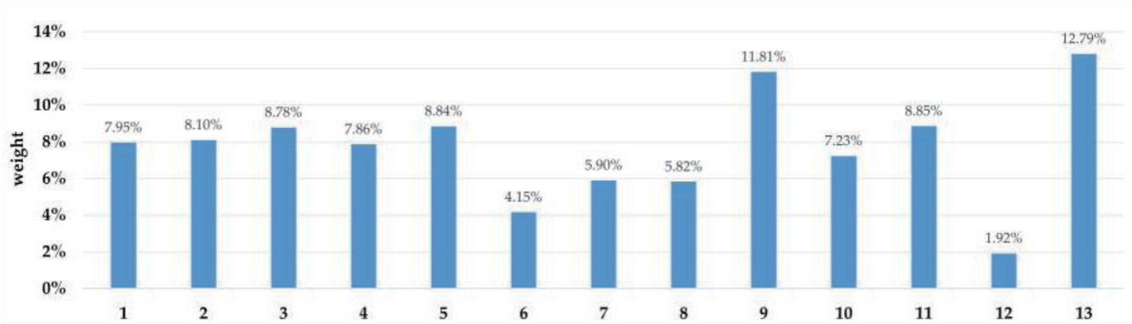

Fig. 6. (Color online) Human activity sensitivity analysis map: 1. elevation, 2. slope, 3. aspect, 4. temperature, 5. precipitation, 6. vegetation coverage, 7. distance to water, 8. species diversity, 9. nature reserve density, 10. land use, 11. soil erosion, 12. distance to roads, and 13. nighttime light.

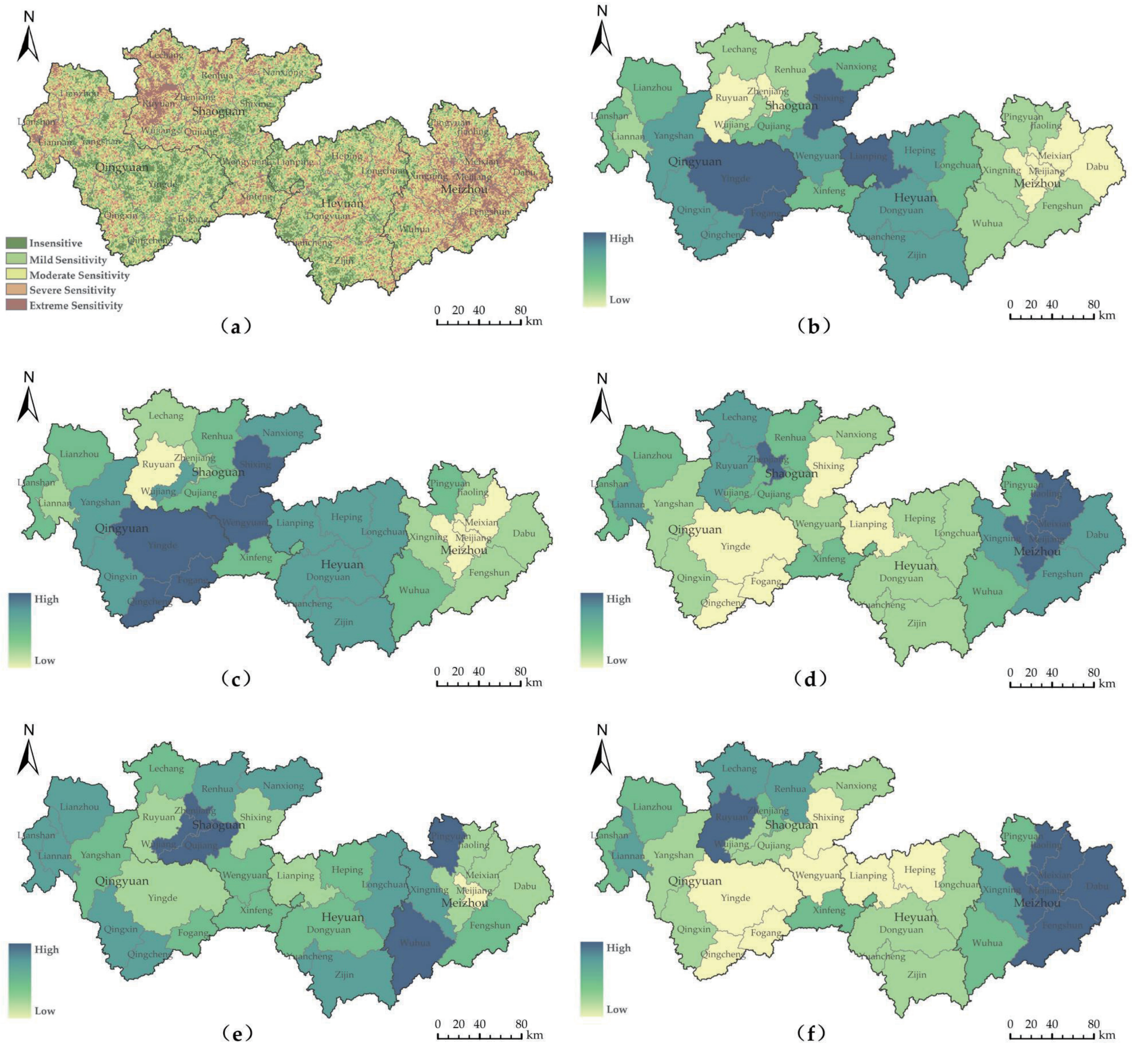

Fig. 7. (Color online) Human activity sensitivity analysis map: distribution maps of (a) comprehensive ecological sensitivity and cities with high proportions of (b) insensitive, (c) mild-sensitivity, (d) moderate-sensitivity, (e) high-sensitivity, and (f) extreme-sensitivity zones.

From the perspective of the spatial distribution of the comprehensive ecological sensitivity in the Northern Guangdong region, extreme-sensitivity and severe-sensitivity zones were mainly distributed in the east and northwest, while insensitive and mild-sensitivity zones were mainly concentrated in the southwest. In terms of proportion, moderate-sensitivity zones accounted for the highest proportion of 28.61% of the total area, followed by mild-sensitivity and severe-sensitivity zones with proportions of 26.80 and 22.76%, respectively, while extreme-sensitivity zones had the lowest proportion of 9.6%. It is clear that the comprehensive ecological sensitivity of the Northern Guangdong region ranges between mild and severe sensitivities, with extreme cases being rare. This means that the overall ecological stability of this region is good. However, in future development, we should be cautious about the impact of human activities on ecosystems, so as to protect extreme-sensitivity zones from damage by development activities.

To facilitate administrative units in taking effective and targeted ecological management measures, we adopted districts and counties as the basic units to calculate the proportion of each type of ecological sensitivity zone. The calculation results are shown in Figs. 7(b)–7(f). The areas with a high proportion of insensitive zones mainly included Yingde, Fogang, Lianping, and Shixing. Insensitive zones were mainly characterized by flat topography, advanced development, and low drainage density. Human development activities carried out in insensitive zones had a slight impact on ecosystems. The spatial distribution of cities with a high proportion of mild-sensitivity zones was similar to that of cities with a high proportion of insensitive zones, and they were mainly concentrated in the southwest of Northern Guangdong. Starting from moderate sensitivity, the areas with higher proportions shifted to the east. Extreme-sensitivity zones were mainly concentrated in eastern cities in the Northern Guangdong region, including Meijiang, Meixian, Jiaoling, and Fengshun. The areas with a high proportion of extreme-sensitivity zones had an excellent ecological background and abundant natural resources, and currently, they are only slightly affected by human development activities. Therefore, in future development, measures should be taken to strictly delineate ecological redlines and constrain development bottom lines. Before development, development suitability and resource carrying capacity assessments should be conducted to avoid the adverse impacts of development activities on the ecological environment in these areas. For areas where ecosystems have been destroyed or impacted, we should actively launch special ecological restoration and management projects, effectively establish an ecological monitoring and assessment system, dynamically monitor changes in the ecological environment, and promptly take corresponding ecological management measures.

3.3 Spatial correlation test on ecological sensitivity

In this study, the proportions of different levels of ecological sensitivity in each district/county were exported in .shp format, and their spatial aggregation characteristics were calculated using GeoDa 1.22 (Fig. 8). According to the calculation results of Global Moran's I, except for the areas with a high proportion of moderate-sensitivity zones, the other four types of areas showed a strong spatial correlation. It can be seen from the scatter plot that the scatter points were mainly distributed in the first and third quadrants. This indicates that cities with high

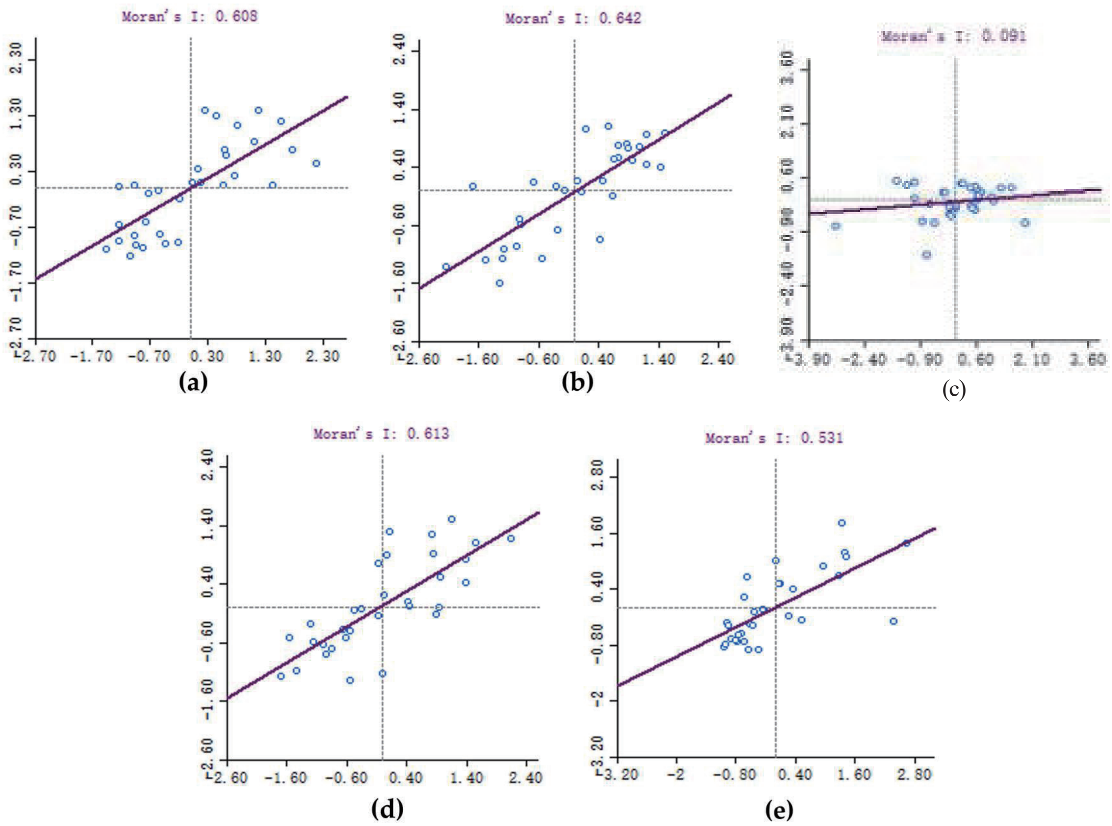

Fig. 8. (Color online) Scatter plot of proportions of different types of ecological sensitivity zones. Global Moran's I of cities with high proportions of (a) insensitive, (b) mild-sensitivity, (c) moderate-sensitivity, (d) high-sensitivity, and (e) extreme-sensitivity zones.

proportions of insensitive, mild-sensitivity, severe-sensitivity, and extreme-sensitivity zones were mainly characterized by high-high and low-low clusters.

On the basis of Global Moran's I values, the Local Moran's I values of different types of ecological sensitivity zones were further calculated. According to Fig. 9, the areas with high proportions of mild-sensitivity and insensitive zones were mainly concentrated in the southwest, including Yingde, Wengyuan, Xinfeng, and Lianping. Such areas have intensive human activities and a fragile ecological background, and the impact of future development activities on ecosystems is expected to be minimal.

For such areas, moderate development can be carried out according to local conditions to improve resource utilization efficiency. Urban renewal and renovation projects can be launched to improve the ecological service functions of cities, enhance their sustainable development capacity, and promote the coordination of ecological and economic developments. Cities with high proportions of severe-sensitivity and extreme-sensitivity zones were mainly concentrated in the east of the Northern Guangdong region, including Dapu, Fengshun, Meijiang, and Meixian. For such agglomerated areas, local regulations or special laws should be adopted to explicitly prohibit environmentally destructive development activities and strictly control industrial pollution, resource overexploitation, and other harmful activities. Regional ecological

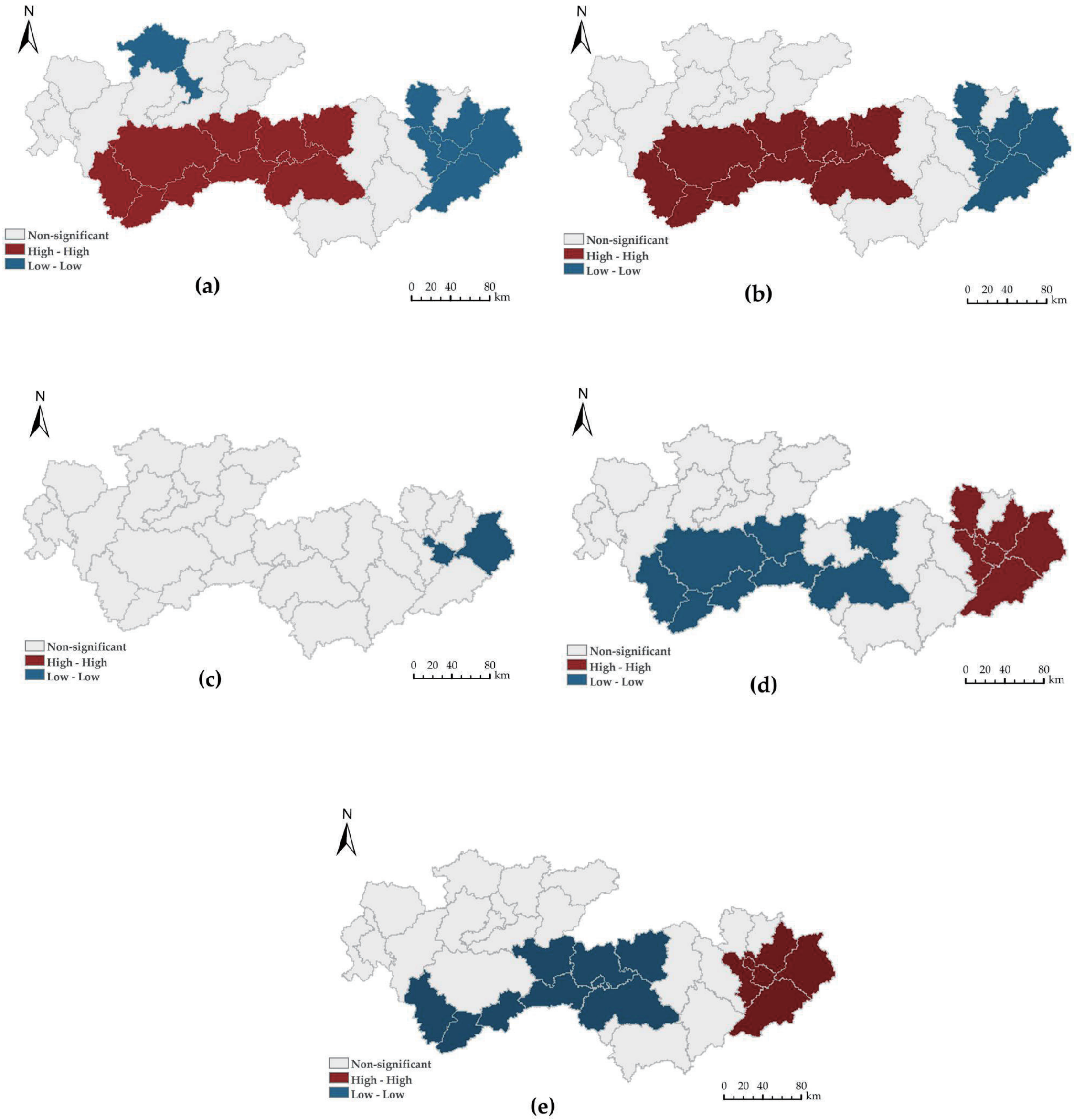

Fig. 9. (Color online) Cluster maps of different types of ecological sensitivity zones. Cluster maps of cities with high proportions of (a) insensitive, (b) mild-sensitivity, (c) moderate-sensitivity, (d) high-sensitivity, and (e) extreme-sensitivity zones.

protection plans should be prepared to establish cross-administrative ecological protection cooperation, coordinate the comprehensive needs of regional ecological, economic, and social developments, support regional economic development and transformation through ecological compensation mechanisms, and promote the development of eco-friendly industries.

4. Discussion

There are a variety of ecosystem types in the Northern Guangdong region, including mountains, forests, wetlands, and rivers. This region is characterized by a complex topography, a wide distribution of mountains and hills, and significant changes in elevation. It is an important ecological barrier in Guangdong Province, and its ecosystem stability plays a key role in the ecological security of the entire province.[20] Compared with the Pearl River Delta region, the Northern Guangdong region has a lower level of economic development and a slower process of industrialization and urbanization, which results in higher pressure and greater potential for ecological protection. The factors causing ecological sensitivity in the Northern Guangdong region are complex and diverse, resulting from the combined effects of nature, climate, topography, human activities, and so forth. On the basis of fully considering the ecological background of the region and referring to the findings of related studies, we selected 13 indicators from four dimensions (topographic, climate, human activity, and natural resource sensitivities) to construct the ecological sensitivity assessment system of the Northern Guangdong region. These indicators include elevation, slope, aspect, temperature, vegetation coverage, species diversity, and human activity intensity.

To be specific, the indicators selected in the two dimensions of topography and climate were similar to those used in other studies. The natural resources dimension not only considered traditional indicators such as vegetation coverage, water system distribution, and soil erosion, but also incorporated species diversity and reserve distribution. These are indicators that can reflect the ecological background characteristics of the Northern Guangdong region. In the dimension of human activities, we not only considered the impact of roads on ecosystems but also introduced the nighttime light index to directly reflect the intensity and density of human activities, thereby improving the accuracy of the assessment of the ecological impact of human activities. In terms of weight assignment, this study differed from other studies in that it did not rely on the traditional expert scoring method to determine the weights of indicators. This is because the expert scoring method depends on the experience and preferences of experts and is easily affected by personal subjective judgment, which can compromise the accuracy of the assessment. Instead, in this study, we adopted the CRITIC objective weighting method, which measures the linear relationship between indicators by constructing a correlation matrix. By determining the weights of indicators entirely on the basis of data analysis, this method avoids the effect of human subjective factors. In addition, it features a transparent calculation process and high verifiability. The weight results calculated by this method not only reflect the ecological background characteristics of the Northern Guangdong region but also capture the impact of human activities on ecosystems in this region.

When analyzing the spatial distribution characteristics of ecological sensitivity in the Northern Guangdong region, many studies have selected the grid scale as the basic unit of analysis. This approach, while capable of precisely displaying the spatial distribution characteristics of different sensitivity levels, makes it difficult for administrative units at all levels to formulate accurate and effective ecological protection policies. Building on grid analysis, we calculated the proportions of different types of ecological sensitivity zones in each district/county and identified the ecological sensitivity protection needs of different areas, making it possible to formulate more targeted ecological protection strategies. Note that administrative units serve as the execution units of policy implementation, and that assessment results based on administrative units can better align with the management functions of local governments, thereby facilitating the implementation of policies. According to the assessment results, local governments can formulate specific ecological protection plans, clarify the division of responsibilities, and ensure the effective implementation of ecological protection measures. At the same time, spatial aggregation analysis can also provide a scientific basis for cross-regional cooperation in ecological protection and management across different cities.

5. Conclusions

In this study, we systematically assessed the ecological sensitivity of the Northern Guangdong Ecological Development Area based on RS images and multisource geographic information data. The assessment results revealed the following:

(1) Ecological sensitivity in the Northern Guangdong region showed significant spatial differentiation characteristics. Specifically, extreme-sensitivity and severe-sensitivity zones were mainly concentrated in the east and northwest, whereas insensitive and mild-sensitivity zones were mainly distributed in the southwest.

(2) The overall ecological stability of the Northern Guangdong region is good. However, in future development, we should be cautious about the disturbances of human activities to ecosystems and pay close attention to the protection of extreme-sensitivity zones to avoid irreversible ecological damage.

(3) The results of spatial aggregation analysis showed that areas with a high proportion of extreme-sensitivity zones were mainly concentrated in cities in the east of the Northern Guangdong region, while insensitive zones were mainly distributed in cities in the southwest. Cross-regional cooperation should be strengthened in ecological protection and management.

Although a series of innovations have been made in this study, there are still some shortcomings. In terms of indicator selection, we have added characteristic indicators such as species and reserve distributions, but the Northern Guangdong region is rich in ecological resources and has complex ecological background characteristics. Therefore, more indicators need to be considered in the future to further improve the accuracy of the assessment. In terms of weight assignment, although the CRITIC method is objective and scientific, it cannot account for the nonlinear relationships between indicators. In addition, it overlooks the relative importance of indicators and is sensitive to data quality. In the future, we will introduce deep learning and other advanced techniques into weight assignment to enhance the accuracy of the assessment. In addition, the economic development of the Northern Guangdong region, as an ecological functional area, is constrained by ecological protection to some extent. In this context, how to achieve the coordinated development of ecology and the economy through ecological compensation mechanisms will be another focus of future research.

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