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Urban Ecosystem Health Assessment based on Landscape Pattern and VOR Model

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Abstract

The rapid development of urban brings a series of urban ecological problems. It is the key issue to quantify the urban ecosystem by monitoring and simulating the dynamic change of ecosystem health objectively and accurately in urban, and it is the effective means to solve the urban ecological problems. Remote sensing images of 2005, 2009 and 2013 in Panji District, Huainan city were used as the data source, and the theory of ecosystem health were introduced, to characterize the urban ecosystem health. Besides, the landscape pattern analysis and Vigor-Organization-Resilience (VOR) model were applied to set up an evaluation index system of ecosystem health. Results showed high spatial heterogeneity in the landscape pattern during different time periods. With respect to the regional ecosystem health index, it experienced a rapid decline after a slight increase, and displayed an ordinary level at the end. Through this study, we can enrich the theoretical methods and practice of urban ecological quantitative research, deepen the understanding of evolution mechanism and spatial variation of urban ecosystem, and provide scientific methods and practice for the urban construction and the sustainable development strategy of city.

Keywords: Urban ecosystem health; Landscape pattern; VOR model

Introduction

Recent years, ecosystem health was commonly used to assess the quality of urbans [1], and it played increasingly important role in environmental management [2-4]. Healthy ecosystem can ensure the sustainability of human development [5], thus ecosystem health is regarded as the core content of integrated ecosystem assessment [6]. Health ecosystem has therefore become a major ecological concern. Though considerable evidence of the threat to health ecosystem has been released, seldomly studies have quantitatively characterized the change of health ecosystem under rapid urbanization, especially for developing countries.

The classical EHA models are always consist of three parts: the vigor index, the organization index, and the resilience index of ecosystem [7]. Among them, vigor represents the primary productivity of ecosystem, organization refers to the interrelationship between all creatures in an ecosystem, and resilience indicates the stability of an ecosystem under stress. In the last decades, many studies have been conducted for EHA using the VOR model [4,8]. In the 1990s, an expanded framework named Pressure-State-Response (PSR) model has been put forward by OECD [9]. Compared to previous studies, this model taken the human activities into account, which emphasized the integration of natural entities and human attributes remarkably in the EHA. In addition, the Millennium Ecosystem Assessment (MEA), which is a process designed to improve the management of ecosystems, also marked a new stage of ecosystem health research [10]. However, a large number of these studies were based on the annual statistics of research area instead of utilizing remote sensing images [11], therefore the broad scope of observation and assessment in real time cannot be implemented. Furthermore, nearly all of the discussions were analyzed at a systematical scale rather than regional scale. In this case, the human needs and the spatial adjacency impacts of landscape patterns on ecosystem health are ignored [6].

The change of landscape pattern will affect the regional ecosystem, and there have been many studies on landscape pattern change at different scales [12,13]. However, the relationship between landscape pattern and ecosystem health was seldom discussed, especially in the mining area. The mining activities of human being and natural factors drive landscape pattern changes, and the analysis of landscape pattern change is one of the most important methods to understand ecological processes. Landscape pattern change is usually quantified by landscape indices in previous studies [14,16], and this is a new attempt to analyze the EHA through the landscape indices in the mining

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Table 1: Description of landscape indices.

Type	Index	Formula	Significance
Connectivity	COHESION	$COHESION = \left[1 - \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} P_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{n} P_{ij} \bullet \sqrt{a_{ij}}}\right] \bullet \left[1 - \frac{1}{\sqrt{A}}\right]^{-1} \bullet 100$	Reflect the physical connectivity of landscape types on the landscape level.
Contagion	CONTAG	$CONTAG = \left[1 + \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} P_{(i,j)} \ln P_{(ij)}}{2\ln(m)}\right] \bullet 100$	Reflect the degree of agglomeration or extension of different block types in the landscape.
	SHDI	$SHDI = -\sum_{i-1}^{m}\left[P_i \ln(P_i)\right]$	Based on the information theory of measurement index, reflecting the landscape heterogeneity.
Diversity	SHEI	$SHEI = \frac{-\sum_{i-1}^{m}\left[P_i \ln(P_i)\right]}{\ln m}$	Measures the extent to which the landscape is dominated by a few or many land cover types.

Table 2: Resilience coefficient and resistance coefficient of different landscape types.

Types of landscape	Farmland	Construction land	Water	Forestland
resilient coefficient	0.4	0.2	0.7	0.5
resistant coefficient	0.5	0.3	0.8	1

area. This study focuses on analyzing the ecosystem health in the mining area response to landscape pattern, using the VOR model. Specifically, our objectives are to (1) apply landscape indices to identify the local variations in landscape pattern as well as their changes; (2) employ VOR model to analyze the ecosystem health change in the study area during 2005-2013; and (3) explore the influence of mining activities on the regional landscape pattern and ecosystem health in mining cities.

Study Area and Data Source

Study area

As an important mining area in China, Panji District locates in the north of Huainan city, Anhui Province (Figure 1), covering an area of 600 km^2. The study region has a mostly warm temperate monsoon climate with average annual precipitation of 937mm, and the annual mean temperature of 14.3–16°C. Due to the influence of the monsoon climate, rainfall and high temperatures in the study area all appeared in the same season.

Data sources

Landscape classification maps and the Normalized Difference Vegetation Index (NDVI) were generated from Landsat TM/Landsat 8 OLI images, in summer of 2005, 2009 and 2013. These images were downloaded from the websites of the Geospatial Data Cloud (China) (http://www.gscloud.cn/). After image geometry correction, visual correction methods and maximum likelihood classifier were used to obtain landscape classification maps in different periods through ENVI 5.1 and ArcGIS 10.1 (ESRI Inc). Four land use types were classified: forestland, water bodies, farmland and construction land (Figure 2). Google Earth was used to check the accuracy of image interpretation [6], and 240 sample points were selected in the study area for verification. The results showed that the overall classification accuracy of landscape classification map was 95.69%, 88.06% and 91.24%, and the Kappa coefficients were 0.93, 0.82 and 0.86 in 2005, 2009 and 2013.

Methods

Landscape pattern analysis

Landscape pattern refers to the spatial distribution and arrangement of landscape patches [17]. Landscape indices are effective in studying landscape pattern [12,18]. This study employed regional landscape pattern to analyze the ecological process changes, and evaluate the regional ecosystem health quantitatively. Panji District is a typical mining area, and the distribution of natural resources is extremely uneven. Four landscape indices were used: landscape connectivity (COHESION), landscape contagion (CONTAG), and landscape diversity (SHDI, SHEI). The ecological meaning and calculation formula of each landscape index are shown in Table 1.

Modeling ecosystem health

The ecosystem health is a comprehensive characteristic of an ecosystem [19], thus we introduced a generally recognized EHA model-the Vigor-Organization-Resilience model (VOR). As a complicated system, the ecosystem of mining cities is affected by some special industries like coal mining. To avoid migration caused by mining production, multi-temporal remote sensing images and annual statistics are commonly applied in this study. In addition, normalized difference vegetation index (NDVI) and landscape pattern characteristic in research area are also used to select appropriate evaluation indicators [20,21]. In accordance with the definition of the ecosystem health index, and in order to preclude a calculation that magnified the index when they are multiplied, this study modified the MEHI to the cube root of three indicators:

$$MEHI = \sqrt[3]{V * O * R} \qquad (1)$$

where *MEHI* is the ecosystem health index, *V* is regional ecosystem vigor, *O* is regional ecosystem organization, and R refers to the resilience of spatial entities.

Specifically, ecosystem vigor is generally weighed by ecosystem's primary productivity. NDVI has been certified to be effective in evaluating the metabolism of an ecosystem. It is calculated with various bands of Landsat Thematic Mapper images and Landsat 8 OLI images:

$$NDVI = (NIR - R)/(NIR + R) \qquad (2)$$

where *NIR* and *R* refer to near infrared band, and infrared band, respectively.

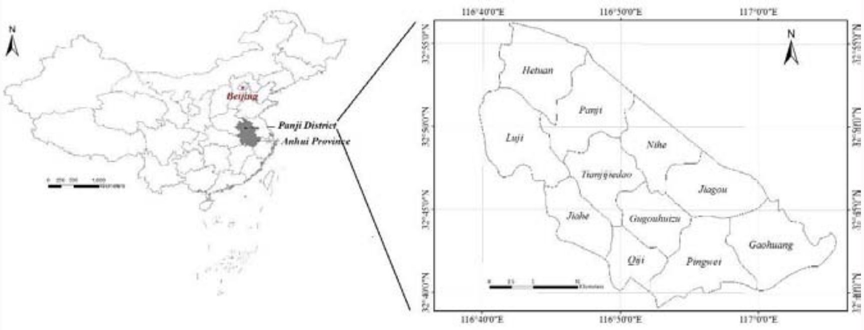

Figure 1: Location of study area.

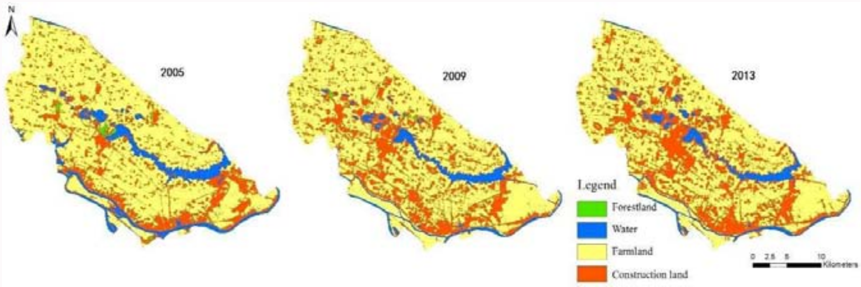

Figure 2: Land cover images in Panji District (2005, 2009, and 2013).

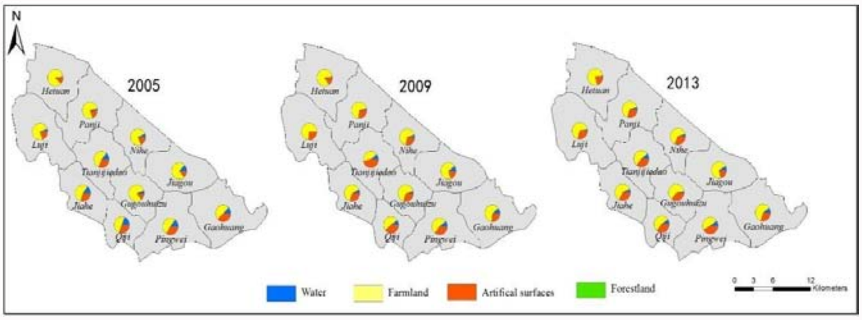

Figure 3: Spatial variation of landscape types in each town in Panji District.

Ecosystem organization represents the structural stability of an ecosystem [22]. It can be quantitively assessed from several landscape pattern indices: landscape heterogeneity, landscape connectivity, the connectivity of patches and so on. In our research, four indices have been chosen as the ecosystem organization factors: landscape cohesion index (COHESION), landscape contagion index (CONTAG), Shannon's diversity index (SHDI), and Shannon's evenness index (SHEI). These indices mentioned above are positive and the normalization method was used to avoid extreme values using the following formula:

$$x_i' = x_i / \max(x_i) \qquad (3)$$

x is the initial value of the index, x' is the normalized value within the range of (0,1]. If there were multiple indices in the criterion layer, the mean of theme was calculated to be the layer's value.

The ecosystem organization index was defined as follows:

$$O = \frac{\sum x_i'}{n} \qquad (4)$$

where O refers to the ecosystem organization index, and n means the numbers of indices involved.

Ecosystems are continually interfered by the external environment, either naturally or artificially. The stress-resilience capacity of the ecosystem was termed as resilience [23]. In detail, it indicates the ability of an ecosystem to maintain its structure, function, and service after some interferences. Ecosystem was observed to recover to original status when the external stress is within its ability of self-adjustment, and it was related to the resistance coefficient and resilience coefficient of regional landscape types. To establish our ecosystem elasticity score of each type of ecosystem in Table 2, we referenced the study of Peng et al., [21], and the formula of resilience is defined as follows:

$$R = 0.3 \times \sum P_i * Resil_i + 0.7 \times \sum P_i * Resist_i \qquad (5)$$

where P_i is the area ratio of each landscape type in the research area, Resili and Resisti is the resilient coefficient and resistant coefficient corresponding to each landscape type, respectively.

Results and Discussion

Change of landscape pattern

The farmland is the landscape matrix in the study area, while the construction land, water bodies and forestland are embedded in

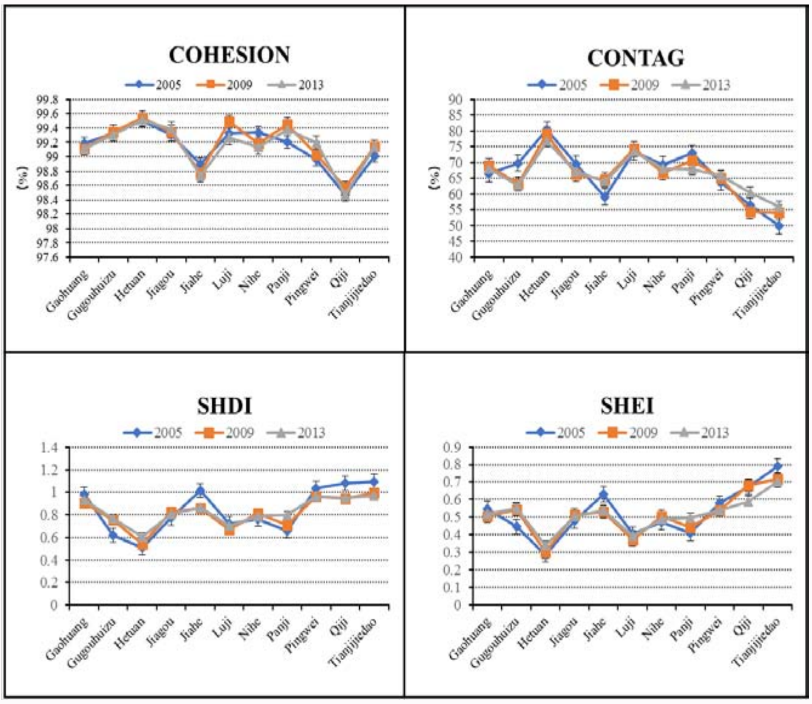

Figure 4: Change of landscape pattern index for each town in Panji District from 2005 to 2013.

the form of plaque or corridor (Figure 2). As shown in Figure 3, the landscape types of the towns have very high spatial heterogeneity. From the perspective of space, the largest proportion of farmland appeared in Hetuan town, which is located in the northwest of Panji District. Tianjijiedao Town, as the administrative center of the study area, have the highest proportion of construction land, besides, water bodies concentration in the east and the southwest in the study area, this study also showed that the proportion of forestland area in the study area is very small.

Figure 4 shows that the landscape connectivity of the towns in different years changed little in the study area, but a greater spatial difference. Qiji Town and Jiahe Town, which located in the southwest of Panji District, had lower COHESION index than other towns, indicating poor physical connectivity with landscape types in these regions. The landscape contagion of the towns changed without regularity, and the CONTAG index in some areas was declining as time goes on, e.g., Hetuan Town, Panji Town, while others were just on the opposite, e.g., Qiji Town and Tianjijiedao Town. It is suggested that the agglomeration or extension in the landscape trends vary in different study areas. Based on the spatiotemporal analysis of the regional landscape pattern, it can be found that the landscape pattern of the towns in study areas changed less at time scale, but present a higher spatial heterogeneity.

Change of ecosystem health indicators

Classified with the natural breaks method, the change of ecosystem vigor level was most obvious (Figure 5), the overall trend of it was increasing first and dropping afterwards during the study period. In 2005, the ecosystem vigor level in northwest of the study area was higher, while the southeast was lower, the highest vigor was in Hetuan Town, and the lowest was in Pingwi Town in Panji District. In 2009, the ecosystem vigor level in the region was at good level as a whole, while the vigor of Pingwei Town remained at the minimum with substantial decline, which was chiefly due to that, it is the town with the largest construction land area among all the towns in the study area, and natural vegetation area was replaced by construction land continually. The results also showed that Gaohuang Town transformed from a relatively low level in 2005 to a higher level in 2009, and the local government attached great importance to the ecological environmental and protected the vegetation area. But in 2013, the ecosystem vigor level in the region was drastically deteriorate, due to the intense mining production and the enhancement of human activities. The majority of towns showed significantly lower vigor, and the largest decline occurred in Panji Town.

The ecosystem organization level was relatively stable, with little change of the study area within the study period. The southern regional ecosystem organization level was superior to the northern region as there was higher landscape diversity in south than that in north. During 2005–2013, the ecosystem organization showed an increase in Jiagou Town, and kept steady in the other towns. It showed that the structure and function of ecosystem remained stable within the study period.

The ecosystem resilience level showed a downward trend during the study period, and changed inconsistent in the different parts of the study area. In 2005, the resilience of ecosystem was at the same level in Panji District. In 2009, the lowest resilience was in Panji Town, while remained at the minimum with substantial decline in 2013. As shown in Table 2, the resilience and resistance coefficient of construction land was far lower than the others, in the towns with the lower ecosystem resilience, the intensity of human activities was high. For Panji Town, the large national coal production base: Pan-3 mines and Pan-North mine, is located in the area. Impact of the mining industry, regional landscape pattern was extremely complex and resilience level was lower. Compared with each index, the ecosystem vigor index changed most obviously in determining the regional distinction in all indices, while the organization and resilience index have lower differences. Mining activities in the region has enormous

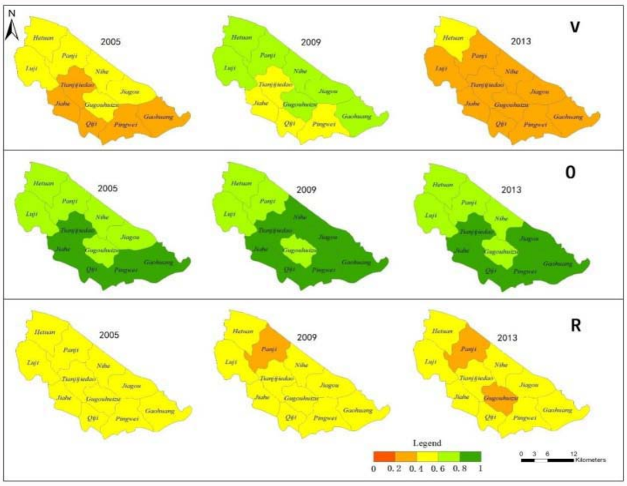

Figure 5: Change of ecosystem health indicators for each town in Panji District from 2005 to 2013.

influence on the vegetation area, during and after mining, regional landscape pattern changes frequently, affected the regional ecosystem health.

Ecosystem health change

"Health" is usually a relative concept in the field of ecology [21], the evaluation of the degree of regional ecosystem health generally adopts quantitative and qualitative methods. Based on the calculation results of the ecosystem health indicators of each town in Panji District, this study combined with the above calculation method of mining city ecosystem health index, and refer to previous study [6], dividing the ecosystem health into five levels with fixed thresholds to detect the change trend at a macroscopic view: weak level (0–0.4), relatively weak level (0.4–0.5), ordinary level (0.5–0.6), relatively well level (0.6–0.7), and well level (0.7–1).

As shown in Figure 6, the change of ecosystem health was more obvious in the east part than in the west part of the study area. In2005, the highest town of the ecosystem health level was Hetuan of Panji District, other towns were all at ordinary level, and northern was superior to the south on the whole. In 2009, the ecosystem health level in northeast of the study area was higher, and the lowest was in the Tianjijiedao town, during 2005-2009, the ecosystem health of towns in the study area showed mainly a rising trend, but Tianjijiedao town descending slightly. In 2013, the ecosystem health in the region was at worse level as a whole. Among them, the largest decline occurred in Nihe Town, from relatively good level in 2009 to relatively weak level in the 2013, and the first weak level appeared in Tianjijiedao town. During the study period, it was found that there were three major trends of ecosystem health level in the entire study area, one was a distinct deterioration in ecosystem health, mainly concentrated in the southwest of Panji District, the other was increased first and then decreased, such as Nihe Town, Jiagou Town, and Gaohuang Town, located in the northeast of the study area, and the last was essentially unchanged in the ecosystem health level, as the Panji Town always in the ordinary level during 2005-2013. Besides, it was evident that as the regional administrative center, the Tianjijiedao town ecosystem health descended rapidly during the study period, turning to the worst level in the area.

As mentioned above, ecosystem health was quantified using three dimensions: ecosystem vigor, organization, and resilience. From Figure 5, the vigor of the ecosystem was increased first and then decreased during 2005-2013, which was represented by NDVI, and all the remote sensing images were acquired in the same month. The difference between vegetation growing seasons could not be regarded as the main reason for the change in the NDVI, therefore, the trend of the ecosystem vigor was considered to be a result of human activities. Local government decisions played a key role in the distribution of landscape types, especially in construction land and farmland, this resulted in a significant influence on the ecosystem vigor. The organization of the ecosystem performed at a nearly stable value during 2005-2013, with little change of ecosystem type and pattern during the study period. It was shown that there were no significant changes in the landscape connectivity, contagion, and diversity in Panji District throughout this period. Ecosystem resilience showed a downward trend during the study period, effect of mining industry on ecosystem resilience was slowly exposed, with the expansion of mining production and urbanization, the area of construction land sharply increased, and the resilience of the ecosystem in the study area was declining. The results indicated that the ecosystem health is primarily expressed by the ecosystem vigor index.

In this study, the mining city ecosystem health was assessed from the perspective of landscape pattern, for the landscape pattern change is very important for land use and planning. As the land use has generally been considered as a local environmental issue [24], and land use change can effectively integrate natural ecological processes with the development of economic and society [25], it has become a force of global importance. In mining cities, the mining activities of human being have exerted great influence on the regional landscape pattern which reflect on the change of ecosystem health [26].

As a result of underground coal seam, land subsidence has become an inevitable problem in the development of the study area. With the continuous development of mining industry, the coal mining subsidence area has brought about the destruction of the farmland, construction land, and water bodies, which caused the

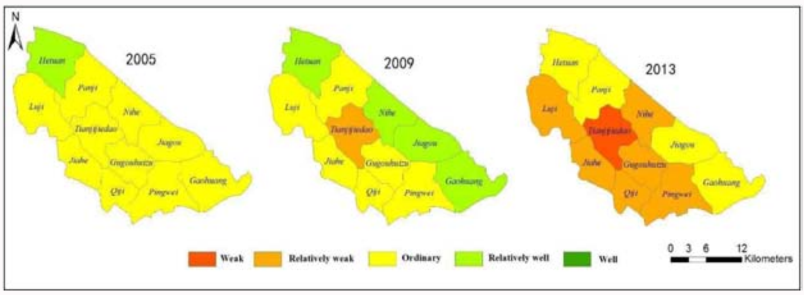

Figure 6: Change of ecosystem health for each town in Panji District from 2005 to 2013.

change of the regional landscape pattern. This paper involved the Panji District of Huainan city as the typical area of mining industry, within the jurisdiction of it there were seven coal plants and 3.7 billion tons reserves of raw coal, facing mining coal subsidence and the worsening ecological environment problems in the long term It is suggested that the Panji District is complicated in the process of subsidence and reclamation, which made the evolution of regional landscape pattern more complicated. The water bodies in the study area except normal flows through the river, and it also contained water in the coal mining subsidence area, e.g., A1, A2, A3, located in towns and villages surrounding the mining area, resulting in a large number of population migration and loss of farmland. In recent years, with the attention of the local government, the coal mine subsidence land reclamation work was promoted continually, making the area of mined areas get some governances, and the landscape pattern of the mining area has subtle changes. Through the above series of these processes, it is obvious that the land use of mining area is very complex and not necessarily changes rule, leading to the regional landscape pattern change irregular, and the evaluation of ecosystem health in mining area more difficult. Thus, there is still a considerable need for EHA research in mining area, and multi-subject integration of natural sciences and social sciences may become a trend of model building in the EHA research.

Conclusion

Our study analyzed ecosystem health response to landscape pattern in the Panji District of Huainan city during 2005-2013, while the ecosystem health dimensions associated with the indicators of ecosystem vigor, organization, and resilience. It was found that landscape diversity in the study area decreased with time, while the landscape connectivity and contagion changed little in different years. It concluded that as the regional administrative center, the ecosystem health in Tianjijiedao town descending rapidly during the study period, turning into the worst level in the area. While for the Hetuan Town, which located in the northwestern outskirts of Panji District, stayed in relatively good level, and was superior to other towns. Besides, the landscape pattern had distinct influence on the EHA, and the ecosystem health is primarily expressed by the ecosystem vigor index.

Our work suggests that the mining activities of human being had great influence on the regional landscape pattern which reflected on the change of ecosystem health in mining cities. Land subsidence had become an inevitable problem in the development of the study area, leading to the regional landscape pattern change irregular, and the evaluation of ecosystem health in mining area more difficult. For further research, we will focus on ecosystem services, integration with natural sciences and social sciences for the EHA research.

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