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Original Research

Evaluation and Prediction of Coastal Zone Ecosystem Health at the County Scale

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Abstract

The coastal zone is a major area for human settlement and exploitation of marine resources. The assessment and prediction of ecosystem health in coastal zones is important for its environmental management and the formulation of sustainable development policy. In this study, based on the Pressure-State-Response model and Markov model, the health of the coastal zone ecosystem was assessed and predicted at the county scale. Landsat remote sensing images of the Ningde coastal zone in China captured in 2000, 2009, and 2014 were used. Previous studies have primarily evaluated ecosystem health at macroscopic scales; however, in this study, the research scale was reduced to the county scale to examine and predict coastal ecosystem health. The results of this study showed that the size of the composite indicators for the county ecosystems in the Ningde coastal zone was in the descending order of Fu'an > Jiaocheng > Xiapu > Fuding. The composite indicators of the Fu'an and Xiapu ecosystems were good, whereas those of the Fuding and Xiapu ecosystems were poor and moderate, respectively. In 2024, the stress indicators of the Fuding, Xiapu, Fu'an, and Jiaocheng ecosystems will continue to increase, whereas the state indicators will decline significantly. Increasing the area of forest and grassland will reduce the pressure on the Fuding and Xiapu ecosystems and improve their ecosystem status and service capacity. In contrast, the pressure, state and response indicators of the Fu'an and Jiaocheng ecosystems were unaffected by changes to forest and grassland areas.

Keywords: county, coastal zone, ecosystem evaluation, prediction

Introduction

The coastal zone is a unique ecosystem in which the ocean, land and atmosphere interact. Thus, this zone offers clear benefits in terms of (marine) resources, environment, geographic location, population, and economy. The coastal zone is characterized by excellent ports and is rich in biological resources, submarine mineral resources, coastal tourism resources, oil and gas, oceanic thermal energy, and marine power (e.g., wind, tides, waves, and currents) [1-3]. In terms of population and economy, two-thirds of the cities around the world with a population exceeding 2.5 million are located near the estuarine coastal zone; urban populations

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in coastal zones are also increasing [4]. The coastal areas in China account for only 15% of the total land area, while hosting more than 40% of its population [5-7]. The coastal zone has a complex and diverse environment and natural geographic conditions of high value. The advantages of rich resources, convenient transportation and broad markets make the coastal zone a key area for a country to implement the integration of marine and land-based economies and build maritime power; it presents an opportunity for the development of coastal zones.

Although the socio-economic development of the coastal areas in China has been supported, these regions are under tremendous pressure in terms of four aspects. First, the marine ecosystem is severely degraded and remains mostly in a unhealthy state. It is estimated that China has lost more than 50% of its coastal wetlands, 73% of its mangroves, and 80% of its coral reefs present in the 1950s [8-9]. Second, coastal zones experience severe pollution from land-based sources; more than 88% of the water from water bodies adjacent to outfalls cannot meet the environmental protection and quality requirements of the marine functional areas in which they are located. Wastewater discharge in coastal areas, urban construction, and rapid development of aquaculture cause eutrophication in which red tide disasters occur frequently [10-11]. Third, the overexploitation of offshore resources poses considerable challenges to coastal zones as it triggers an imbalance in the natural ecosystem. Fourth, sea level rise threatens the survival of coastal areas and social development. According to a survey, the rate of sea level rise along China's coastline since 1980 is higher than the global average for the same period (3.0 mm/y) [12-13]. This sea level rise has aggravated storm surge disasters, waves, coastal erosion and soil salinization in this region. If effective measures are not implemented, conflicts will occur between marine resources and environment and human socio-economic development in coastal areas. This will generate an imbalance between supply and demand and eventually exceed the maximum carrying capacity of coastal zones. Therefore, the evaluation and prediction of coastal zone ecosystem health is of theoretical and practical significance for the sustainable development of coastal zones. In this study, methods to protect the health of the Ningde coastal zone are explored. The outcomes from this study will improve the theory of coastal zone ecosystem health by providing an understanding of the mechanisms of pressure and ecosystem action in the Ningde coastal zone. This study will enrich the practical investigation of coastal zone ecosystem health through the construction of an evaluation method to assess the health of the Ningde coastal zone. The quantitative prediction of coastal zone ecosystem health is also realized by constructing a predictive system to forecast the health of the Ningde coastal zone.

Overview of the Study Area

Although the extent of the coastal zone boundary is uncertain, assessing the health of the coastal zone ecosystem requires the delineation of a coastal zone area. In this study, the administrative boundary was used as the criterion to divide the coastal zone; this was based on the feasibility of data acquisition between the social and economic subsystems of the coastal zone involved. Note that only the mainland components of the administrative boundary were studied and the islands were excluded. Four administrative units in Ningde City near the ocean were selected as the study area: the Xiapu, Fu'an, Jiaocheng and Fuding county ecosystems (Fig. 1). The area is located in the eastern

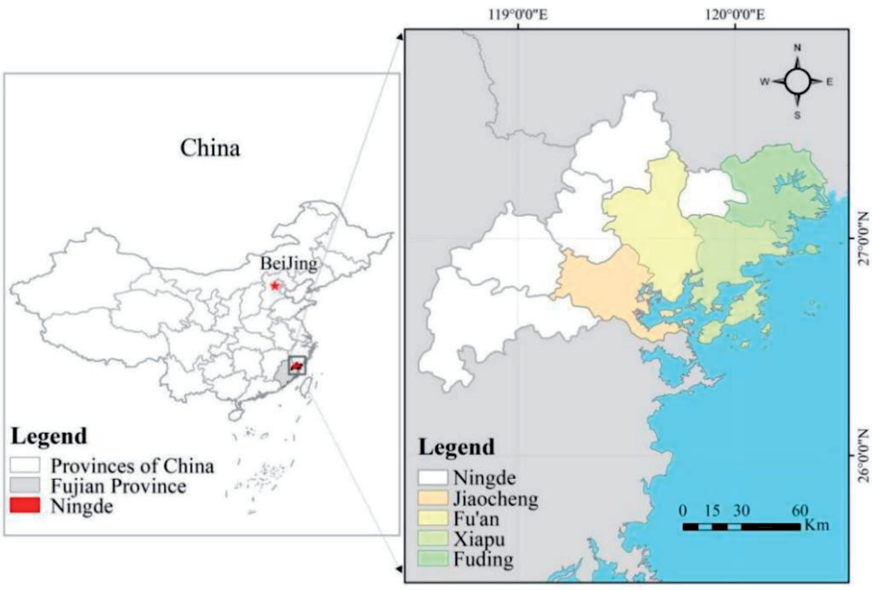

Fig. 1. Schematic diagram of the study area.

coastal region of China and experiences a mid-subtropical maritime monsoon climate with an annual average temperature of 16.0-20.7ºC and an annual rainfall of 1275-2085 mm. The coastline of Ningde is 943.2 km long, accounting for 28.35% of the total length of the coastline in the Fujian Province. The area of sea for Xiapu, Fuding, Jiaocheng and Fu'an is 29592.6 km^2, 14959.7 km^2, 280 km^2, and 83.76 km^2, respectively [14-16]. This area is also known as "the hometown of seaweed, fish, and rice in China." In 2018, Fuding was recognized as an advantageous area for unique Chinese agricultural products. Jiaocheng is the core of the northeastern center of the economic zone on the west side of the Strait with the largest rhubarb fish breeding base in China, and it is recognized as the "hometown of Chinese rhubarb fish" and "hometown of Chinese late-ripening longan." Jiaocheng is also famous in China and abroad for its world-famous natural deep-water port: the Sandu Gulf. In 2020, Fu'an was assigned as the pilot city for the "Internet+" project of purchasing agricultural products from the countryside into the city by the Chinese Ministry of Agriculture and Rural Development. The cities of the Ningde Coastal Zone are undergoing rapid economic development; by the end of 2019, Xiapu, Fuding, Jiaocheng and Fu'an had a regional gross domestic product of 25.46 billion, 41.80 billion, 67.94 billion, and 56.90 billion yuan, respectively [16].

Method

Data Sources and Processing

The data used in this study include socio-economic data and spatial data, among which the former were obtained from the Ningde Statistical Yearbook and Ningde Population Census. The spatial data for the Ningde area included the Landsat 5 Thematic Mapper (TM) images captured in 2000 and 2009 and the Landsat 8 Operational Land Imager images captured in 2014; both sets of images have a resolution of 30 m. These data were obtained from the Geospatial Data Cloud of the Computer Network Information Center of the Chinese Academy of Sciences (http: //www.gscloud.cn). The remote sensing data were pre-processed by applying geometric correction, atmospheric correction, cropping, and stitching. The land use classification of remote sensing images was performed using the object-oriented classification method based on different hue and texture characteristics with the support of ENVI 5.1 software. The land use types were classified into nine categories: forest and grassland, rivers, lakes, construction land, reservoirs, aquaculture, dry land, paddy fields, and other. The accuracy evaluation results show that the classification accuracy of land use types in each period exceeded 80%, meeting the accuracy requirements of this study. Following the vectorization of the land use classification map, the spatial statistics and spatial overlay analysis tools were used to obtain the total area of each land type in different time periods and the related transfer matrix using ArcGIS 10.1 software. The raster images after land use classification were imported into Fragstats to obtain the required landscape index data.

Ecosystem Health Evaluation Methods

Pressure-State-Response (PSR) Model

The PSR model was originally proposed by Canadian statisticians, Tony Friend and David Rapport. It was then modified and applied to environmental reporting by the Organization for Economic Cooperation and Development in the 1970s. The PSR model is considered a more advanced resource and environmental management system that has been used to describe interactions between humans and the environment. It focuses on the conservation and management of water, soil, agriculture, biology and marine resources [17-19]. The PSR model has a clear cause-and-effect logic relationship; human activities exert certain pressures on the environment, changing the state of the environment. Then, human society reacts to this environmental change to restore environmental quality and prevent further environmental degradation.

The PSR model consists of three indicators: pressure (P), state (S), and response indicators (R) (Fig. 2). Pressure indicators represent the human exploitation of natural resources and the various pressures on the ecosystem, such as soil erosion and industrial pollution. State indicators refer to the instinctive state or trend of the ecosystem under various pressures, such as vegetation cover and arable land area per capita. Response indicators refer to measures and countermeasures implemented by humans to cope with pressure and re-direct the state of the ecosystem towards a healthier condition. This is a process that introduces subjective initiatives such as investments into environmental protection, publicity on environmental protection and education.

Ecosystem Health Evaluation Indicator System

An evaluation system based on the analytic hierarchy process (AHP) was designed using the PSR framework model. This AHP design was also assisted by referencing previous research results [20-23] and extensive consultation with experts in safety management, environmental protection and agriculture, government officials and business executives. The AHP was designed to reflect the coordinated development of the Ningde coastal zone in terms of society, economy, resources and environment. This was realized through a survey of ecosystems in each region of the Ningde coastal zone and the current context of this coastal zone in terms of resources, environment and socio-economics. The principle of hierarchical analysis

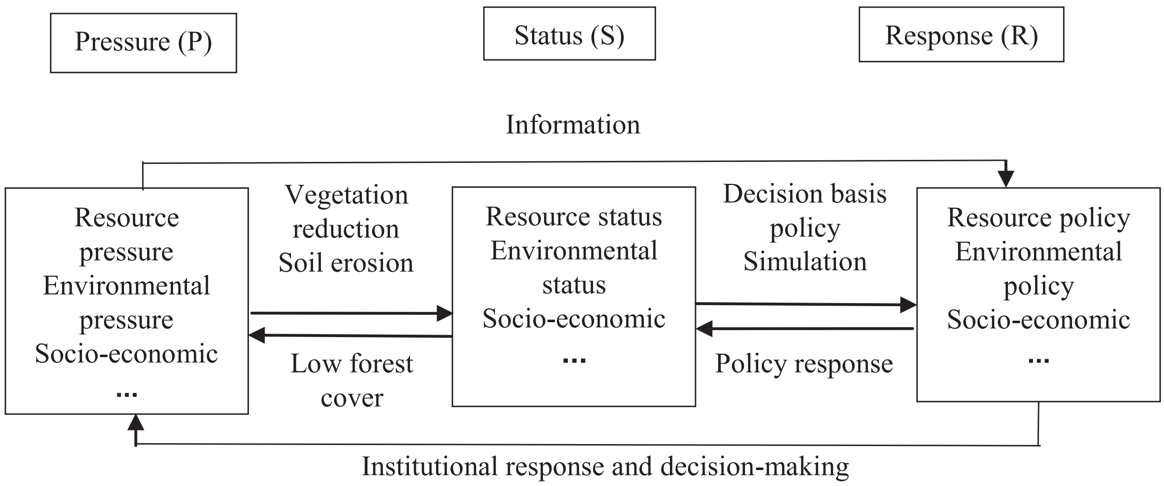

Fig. 2. Diagram of PSR model framework.

was applied to design indicators that could reflect the coordinated development of the Ningde coastal zone in terms of society, economy, resources and environment. An evaluation system was built with nine indicators at three levels: target, criterion and indicator. The target layer is a composite indicator reflecting the overall county ecosystem health in the Ningde coastal zone. The criterion layer is a decomposition of the target layer, consisting of three composite indicators of pressure, state and response. The indicator layer is a specific operational layer, which is a response to the criterion layer and consists of nine specific indicators. The indicator system to evaluate the health of the Ningde coastal zone ecosystem based on the PSR model is detailed in Table 1.

The description of each indicator is as follows.

Population density (I_1) is the number of people per unit of land area. It is an important indicator of the population distribution within a country or region. The larger the population density, the greater the population pressure on the ecosystem. The population number of each city in the Ningde coastal zone can be obtained from the Ningde Statistical Yearbook; the land area of each city was obtained from remote sensing images.

Human disturbance (I_2) refers to the proportion of construction land area to the total land area. A higher value indicates higher human pressures on the ecosystem. The construction land and total land areas were obtained from remote sensing images.

The land reclamation rate (I_3) represents the ratio of cultivated land area to the total land area within a certain region. The larger the value, the more natural resources are occupied by humans, and the more pressure is placed on the ecosystem. The data on cultivated land areas were extracted from remote sensing images.

The normalized difference vegetation index (NDVI; I_4) is the sum of the difference between the reflectance value in the near-infrared band and the reflectance value in the red band in remote sensing images. Studies have shown that the NDVI is significantly and positively correlated with vegetation cover. Therefore, this index was used as a state indicator to evaluate ecosystem health. The value of this index ranges from -1 to 1, where a negative NDVI indicates that the ground

Table 1. Indicator system to evaluate the health of the Ningde coastal zone ecosystem based on the PSR model.

Target layer	Criterion layer A	Indicator layer I
Composite indicators of the health of the Ningde coastal zone ecosystem	Pressure indicator, A_1	Population density I_1
		Human disturbance I_2
		Land reclamation rate I_3
	State indicator, A_2	Normalized Difference Vegetation Index I_4
		Shannon Diversity Index I_5
		Evenness index I_6
		Average patch area I_7
		Resilience I_8
	Response indicator, A_3	Ecosystem Services Value I_9

surface is covered by highly reflective objects (e.g., water and snow), and a positive NDVI indicates that the ground surface is covered by vegetation. This value increases with vegetation cover on the ground surface; when the value is zero, the ground surface is covered by rocks or bare soil. This value was directly obtained from remote sensing images.

The Shannon diversity index (SHDI; I_5) is equal to the negative value of the sum of the area ratio of each patch type multiplied by the natural logarithm of its value at the landscape level. Its formula is as follows:

$$SHDI = -\sum_{i=1}^{m} \left[P_i \ln P_i\right] \tag{1}$$

where P_i is the existence probability of patch type i in a landscape, and m is the total number of patch types. A value of zero indicates that the entire landscape consists of only one patch. The SHDI increases with the number of patch types in the landscape or when each patch type has a balanced distribution in the landscape. This indicator reflects landscape heterogeneity and is particularly sensitive to the unbalanced distribution of each patch type in the landscape. This means, the SHDI emphasizes the contribution of rare patch types. For example, in a landscape system, the richer the land use type, the higher the fragmentation of that landscape and the higher the calculated SHDI.

The evenness index (I_6) is a quantitative index that describes the distribution of the total number of patches in a landscape. This indicator reflects the uniformity of patch distribution in the landscape and is negatively correlated with dominance.

The average patch area (I_7) is the average area of all patches or a particular type of patch in the landscape. The smaller the value, the higher the fragmentation of the landscape. The values of I_5, I_6, and I_7 can be obtained by importing remote sensing images into the Fragstats software.

Resilience (I_8) refers to the ability of an ecosystem to return to its original state after being damaged by external disturbing factors. This indicator can be calculated as

$$F = \sum_i \frac{A_i \times F_i}{A} \tag{2}$$

where F is ecosystem resilience; A_i is the area of the i-th land use type; F_i is the resilience coefficient of the i-th land use type and A is the total study area. Based on previous studies [24-25], the assigned resilience coefficients were 1, 0.8, 0.6, 0.5, 0.3, and 0.1 for watersheds, forest and grassland, aquaculture, cropland, construction land and other, respectively.

The ecosystem services value (ESV; I_9) is the valuation of the services and natural capital of an ecosystem using economic laws. When an ecosystem is subjected to external disturbances, it affects its ability to provide services to human society. Therefore, the value of ecosystem services is the most direct representation of ecosystem response when it is subjected to external pressure. The ecosystem service value was selected as a response indicator for ecosystem health evaluation and can be calculated as

$$V = \sum_i A_i \times V_i \tag{3}$$

where V is the ESV; A_i is the area of the i-th land use type; and V_i is the ecosystem services value per unit area of the i-th land use type. The ESV per unit area of each land use type in the Ningde coastal zone and nearby areas was calculated [26-27], (Table 2). These datasets were directly used to calculate the ESV of each land use type in the Ningde coastal zone.

Weighting Ecosystem Health Evaluation Indicators

The importance of evaluation indicators relative to a certain ecosystem health evaluation objective varies for each indicator. The magnitude of relative importance among evaluation indicators can be expressed by weighting each coefficient. When the evaluated object and evaluation indicators were determined, ascertaining a reasonable weighting for each coefficients is related to the credibility of the comprehensive evaluation results. Therefore, determining the weighting of coefficients for the evaluation indicators should be approached with caution. In this study, the AHP was used to determine the weighting of the evaluation indicators. This hierarchical analysis is a multi-level weight analysis decision-making method proposed by an American operations researcher, T. L. Satty, in the mid-1970s [28]. It systematically combines qualitative analysis with quantitative analysis and decomposes complex problems into several levels and

Table 2. Ecosystem service values per unit area of each land use type in the Ningde coastal zone.

Land use type	Unit area value (10^6 yuan·km^{-2}·a^{-1})
Other	0.0723
Construction land	-0.65
Dry land	4.5977
Forest and grassland	10.83
Aquaculture	38.89
Reservoirs	1.63
Paddy fields	4.5977
Rivers	1.63
Lakes	1.63

Table 3. Weightings assigned to indicators used to evaluate the health of the Ningde coastal zone ecosystem.

Criterion layer	Weights	Indicator layer	Weights
Pressure	0.340	Population density	0.161
		Human disturbance	0.108
		Land reclamation rate	0.071
State	0.472	Normalized difference vegetation index	0.060
		Shannon diversity index	0.098
		Evenness index	0.065
		Average patch area	0.134
		Resilience	0.114
Response	0.188	Ecosystem services value	0.188

factors from different perspectives. This method is widely used in practical applications. Based on the PSR framework and the principles of AHP, the hierarchical analysis software YAAHP version 5.3 was used to establish the hierarchical model and calculate the weights of each evaluation indicator (Table 3).

Composite Indicator Method

The composite indicator method can comprehensively reflect the health status of an ecosystem; this can be easily used as a reference in decision-making. The calculation of the composite indicator for ecosystem health evaluation is as follows:

$$DI = \sum_{i=1}^{n} L_i W_i \tag{4}$$

The smaller the *DI*, the poorer is the health of the ecosystem. Table 4 presents the grading criteria and descriptions.

Prediction of Ecosystem Health Status

Different Scenarios

Forests and grasslands provide a large amount of timber and other forestry by-products for humans. They also play an important role in maintaining the stability of the biosphere and improving the ecological environment by regulating climate, cleaning water, maintaining soil and water, preventing wind and fixing sand. It was found that the ESV of forests and grasslands in the Ningde coastal zone is much higher than other land use types. Therefore, increasing the area of forest and grassland may enhance

Table 4. Grading and description of each indicator used for ecosystem health evaluation.

Status	Pressure indicator	State indicator	Response metrics	Composite indicator	Description
Good (less pressure)	<1.4	>3	0.6-1	>1.8	The ecosystem has a stable structure and function; the system is highly restorative and regenerative and is under less stress. The socio-economic development is coordinated and may be considered the ideal state of sustainable development.
Fair (low pressure)	1.4–1.6	2–3	0.4-0.6	1.6-1.8	Ecosystems are relatively well-functioning and can generally recover from disturbances with low stress. Ecological disasters can essentially be prevented and controlled.
Moderate (high pressure)	1.6-1.8	1-2	0.2-0.4	1.4-1.6	Although the ecosystem is damaged to a certain extent, it can still maintain its basic functions; however, it is prone to deterioration following disturbance. Socio-economic development is at the preliminary stage.
Poor (higher pressure)	>1.8	<1	0-0.2	<1.4	Ecosystem structure and function have almost collapsed and the ecosystem has been severely damaged. There are large ecological and environmental problems, which often become ecological disasters. Socio-economic development has regressed.

the health of the Ningde coastal zone. Based on this, three different scenarios were established to predict the health of the Ningde coastal zone ecosystem. Based on the study in this paper, it was found that the main land use types that could be shifted to forest and grassland were dry land, paddy fields and rivers. Using the land use transfer probability matrix data on the Ningde coastal zone from 2009 to 2014, the transfer values from dry land, paddy fields and rivers to forest and grassland increased by 0% (scenario 1), 30% (scenario 2), or 50% (scenario 3), respectively.

Markov Model

The Markov model is currently the most widely used method for modeling land use change in studies on land use simulation, land use and cover change simulation and urban landscape pattern change prediction [29-32]; this is because of its clear advantages in long-term prediction. The Markov process is a discrete stochastic motion based on Markov chains in state and time. This means it is a process in which the state in the future is only related to the currently known state and not to the previous state. The principle of Markov chain analysis is examining transitions between various states through different initial states of a moving system. Then, it determines the transfer probabilities of various states and predicts future state change trends. In Markov chains, the transfer of system states can be described by a probability matrix that is expressed as

$$P = P_{ij} = \begin{bmatrix} P_{11} & P_{12} & . & P_{1n} \\ P_{21} & P_{22} & . & P_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ P_{m1} & P_{m2} & \cdots & P_{mn} \end{bmatrix} 0 \le P_{ij} \le 1, the \sum_{j=1}^{n} P_{ij} = 1 \tag{5}$$

where m and n are the number of land use types, and P_{ij} is the transfer probability of land use type i changing to land type j.

After one transfer from any state, one of all states of the system will appear and the process can be expressed as

$$R(t+1) = R(t)\, P \tag{6}$$

where $R(t)$ is the initial state; R(t+1) is the subsequent state; and P is the transfer probability of a land use type from the initial state to the subsequent state. Thus, the one-time Markov model can be inferred from the known state at time *t to* the state at time t+1.

In this study, the area of each land use type in each unit of the Ningde coastal zone in 2024 was initially predicted using the Markov model. Following this, the predicted area of each land use type in different scenarios was introduced into the PSR model for calculation. Then, the pressure, state, response and composite indicators for each unit under different scenarios were obtained.

Results and Analysis

Evaluation of the Health of the Ningde Coastal Zone Ecosystem at the County Scale

Pressure Indicator

Fig. 3 and Table 4 show that the pressure indicator of Fuding in 2000 was 1.845, representing a higher level of pressure. In 2009, this pressure indicator decreased to 1.168, a lower level of pressure, whereas in 2014, it increased to 1.822, representing a return to a higher level of pressure. In contrast, the pressure indicators for Xiapu in 2000, 2009, and 2014 were 0.853, 0.975, and 0.761, respectively. These values did not exceed 1.4, indicating that the pressure on the Xiapu ecosystem was low and this ecosystem was less disturbed by human society.

The pressure indicators for Fu'an in 2000 reached 2.405; thus, the pressure on this ecosystem was high in 2000. This indicator then rapidly decreased to 1.319 (less pressure) in 2009 and 1.474 (low pressure) in 2014. The pressure indicators for the Jiaocheng ecosystem in 2000 and 2019 were lower at 1.377 and 0.622, respectively. The latter value was the lowest pressure

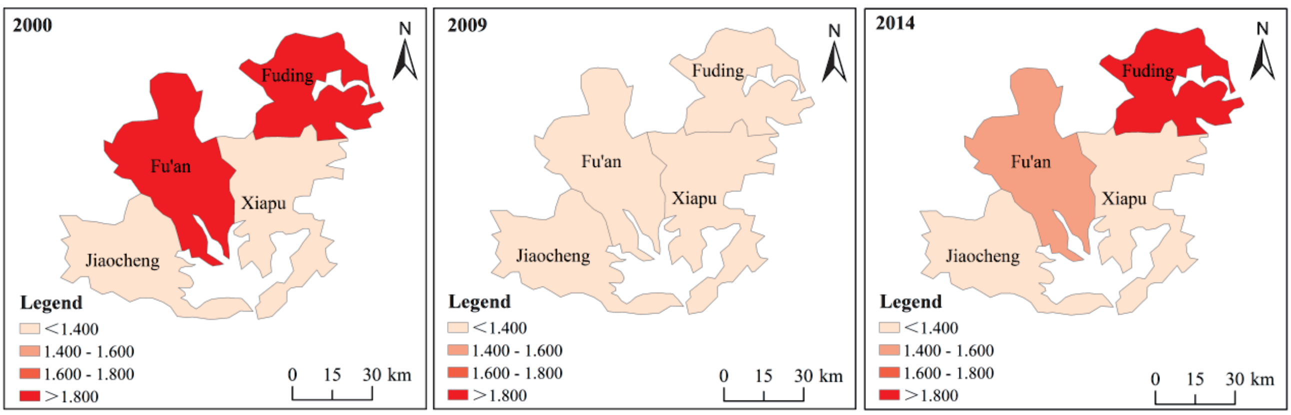

Fig. 3. Pressure indicators to evaluate the health of county ecosystems in the Ningde coastal zone.

indicator for all regions throughout the study period. In 2014, the pressure indicator of Jiaocheng increased to 1.280, although it remained at a low level. The pressure on the Jiaocheng ecosystem has remained low throughout the study period. In summary, the Xiapu ecosystem experienced the least stress throughout the study period, with a three year average of 0.863. The Fu'an ecosystem experienced the greatest stress from human disturbance, with a three year average of 1.733.

State Indicator

Fig. 4 and Table 4 show that the state indicators for Fuding in 2000, 2009, and 2014 were 0.477, 1.769, and 1.873, respectively. These values indicate that the state of the Fuding ecosystem has significantly improved and stabilized throughout the study period. However, the average of the Fuding state indicator for these three years was only 1.373. This means that although the state of the Fuding ecosystem has improved, its state was at a moderate level. The state indicator for Xiapu in 2000 was 1.778, signifying a moderate level. The state indicator for this ecosytsem in 2009 and 2014 were 2.028 and 2.056, indicating that it was in a fair state for these years.

The state indicators for Fu'an in 2000 was 2.387, indicating that this ecosystem was in a fair state. However, in 2009 and 2014 the state indicator was 4.170 and 3.613, respectively, signifying that the state of the Fu'an ecosystem improved to a good state. The state indicators for Jiaocheng in 2000 and 2014 were 2.687 and 2.922, respectively. This indicates that this ecosystem was in a fair state in these years. In 2009, the state indicator for the Jiaocheng ecosystem was 3.567, signifying a good state.

In summary, the mean of the three phase state indicators throughout the study period for the Fu'an and Jiaocheng ecosystems (located on the west side of the study area), were 3.390 and 3.059, respectively. This means that the states of the Fu'an and Jiaocheng ecosystems were at a good level. In contrast, the mean of the three phase state indicators for the Fuding and Xiapu ecosystems (located on the east side of the study area), were 1.373 and 1.954, respectively; this signifies that the ecosystem states were at a moderate level.

Response Indicator

Fig. 5 and Table 4 show that the response indicator for Fuding in 2000 was 0, indicating that this ecosystem was unable to provide services to humans. In 2009, the response indicator for Fuding increased to 0.623, indicating an increased capacity to provide services; this value is considered a good capacity. In 2014, the response indicator for this ecosystem decreased to 0.395, which represents a moderate capacity to provide services.

The response indicator for the Xiapu ecosystem in 2000 was low at 0.190, representing a poor capacity to provide services to humans. This value then increased to 0.682 and 0.964, in 2009 and 2014, respectively. This increase across these three years indicates an improved capacity of the Xiapu ecosystem to provide services, from poor to good.

The response indicator for the Fu'an ecosystem in 2000 was 0.333, indicating that this ecosystem had a moderate capacity to provide services to human. In 2009 and 2014, the response indicator of this ecosystem was 0.666 and 1.000, respectively; this is indicative of a good capacity to provide services. The three year average (0.666) for the Fu'an ecosystem was the highest compared with the other units.

In 2000, the response indicator for the Jiaocheng ecosystem was only 0.066, which signifies a poor capacity provide services to humans. Although there was an improved capacity in 2009, in which the response indicator was 0.605; in 2014, this value decreased to a moderate capacity at 0.222. Thus, the capacity of the Jiaocheng ecosystem to provide services was the poorest among all regions throughout the study period, with the lowest three year average response indicator of 0.339.

Overall, the response indicators of all four units in the Ningde coastal zone were low in 2000, where

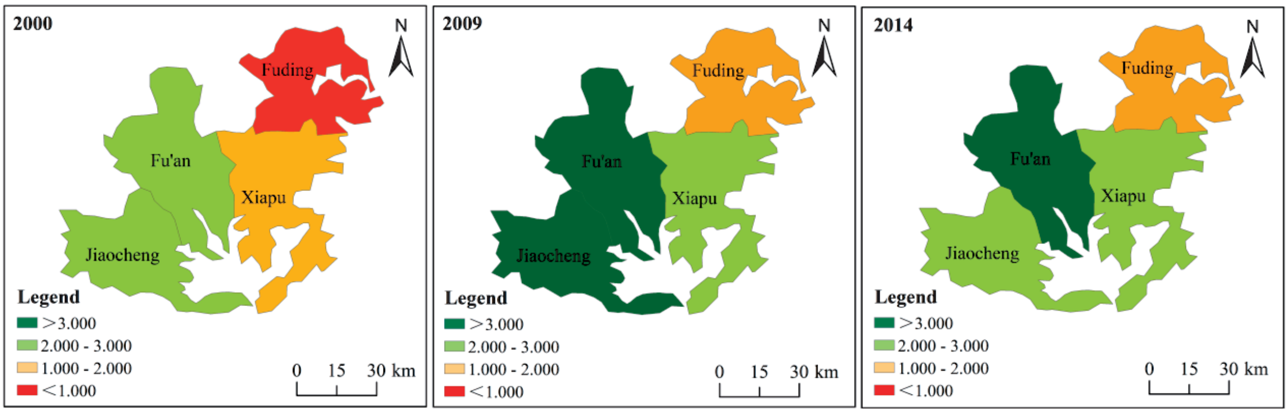

Fig. 4. State indicators to evaluate the health of the Ningde coastal zone ecosystem.

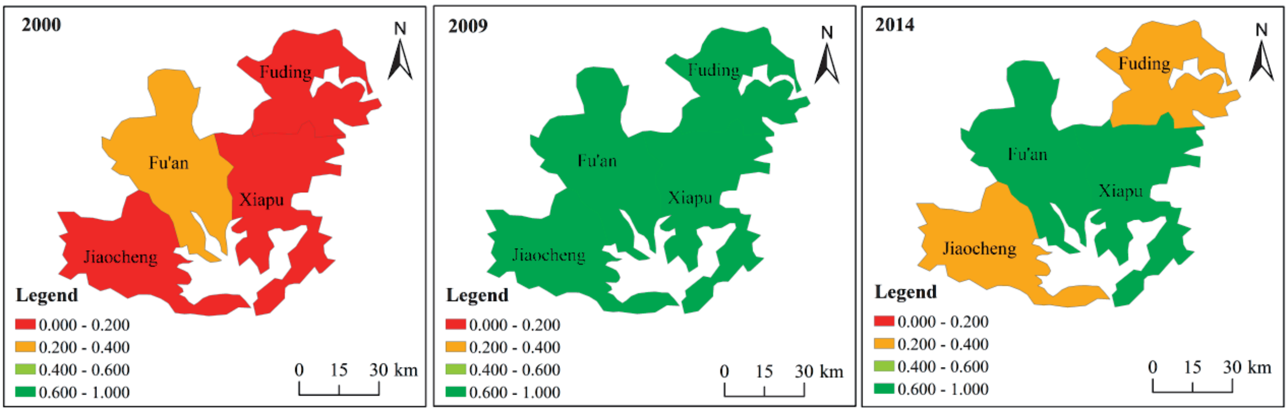

Fig. 5. Response indicators to evaluate ecosystem health in the Ningde coastal zone.

the average was only 0.147; this signifies a poor capacity to provide ecosystem services. The average of the response indicators from the four units were 0.644 and 0.645 in 2009 and 2014, respectively, reaching a good capacity. Thus, the capacity of the Ningde coastal zone ecosystem to provide services to humans has improved rapidly since 2000 and has stabilized in the following years.

Composite Indicator

Fig. 6 and Table 4 show that the composite indicator for the Fuding ecosystem was 0.853 in 2000, indicating this ecosystem experienced poor health at this point in time. This indicator rose to 1.349 in 2009, indicating continued poor health despite improvements to the composite indicator. In 2014, this value increased to 1.578, indicating an improvement to a moderate level.

The composite indicator for Xiapu in 2000 was 1.165, indicating that the health of this ecosystem was also poor. In 2009 and 2014, this value was 1.416 and 1.410, respectively. Although the composite indicator for Xiapu increased from 2000 to 2009, the health of this ecosystem in 2009 and 2014 was still at a moderate level.

By contrast, the ecosystem health of Fu'an and Jiaocheng depicts a very different situation from that of the Fuding and Xiapu ecosystems. The mean three year composite indicator values for the Fu'an and Jiaocheng ecosystems were 2.314 and 1.871, respectively. This is indicative of good ecosystem health throughout the study period. Despite fluctuations in health for the Fu'an and Jiaocheng ecosystems, overall ecosystem health remained at a good level.

Prediction of Ecosystem Condition in the Ningde Coastal Zone

Pressure Indicator

Fig. 7 and Table 4 show that the Fudin stress indicator for scenario 1 was 2.149, whereas it was 1.822 in 2014. This means that pressures on the Fudin ecosystem will continue to increase in 2024 according to scenario 1. By contrast, the values of the Fudin stress indicator under scenarios 2 and 3 were 1.421 and 1.346, respectively. This suggests that the stress on this ecosystem will reduce if there is an increased probability of transferring dry land, paddy fields and rivers to forest and grassland.

The stress indicator for Xiapu in scenario 1 was 1.050, whereas it was 0.761 in 2014. This indicates that the stress on the Xiapu ecosystem will continue

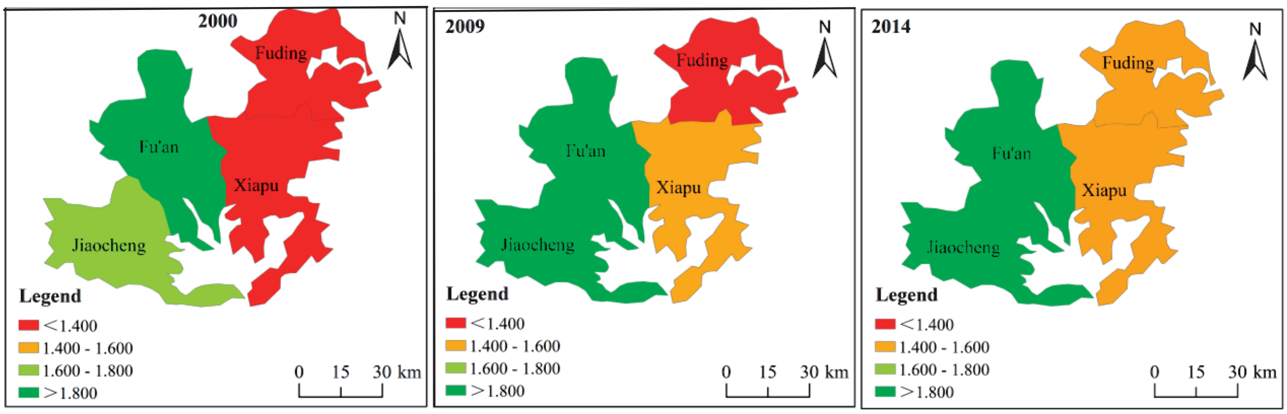

Fig. 6. Composite indicators to evaluate the health of ecosystems in the Ningde coastal zone.

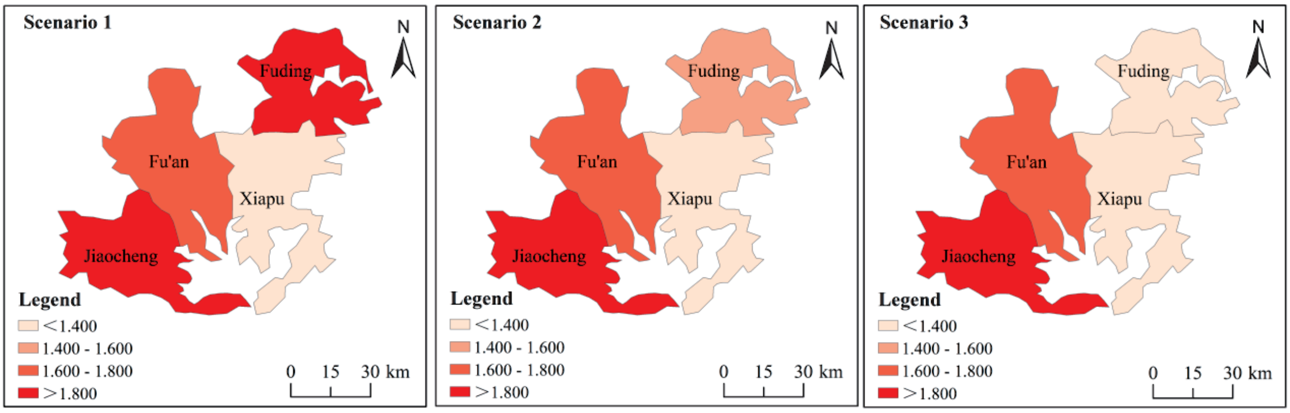

Fig. 7. Prediction of the county ecosystem pressure indicators in the Ningde coastal zone.

to increase in 2024 based on the model development of scenario 1. However, this increase is insignificant and the stress indicators for scenarios 2 and 3 were only 0.413 and 0.339, respectively. This means the increase in the probability of transfer from dry land, paddy fields and rivers to forest and grassland will reduce the pressure on the Xiapu ecosystem.

The stress indicator for Fu'an under scenario 1 was 1.717, which is higher than the value in 2014. This means that stress on the Fu'an ecosystem will increase in 2024 based on the development of scenario 1. The indicator was 1.717 in scenarios 2 and 3 for the Fu'an ecosystem; this suggests that increasing the probability of transferring dry land, paddy fields and rivers to forest and grassland will not affect the stressed condition of this ecosystem.

The stress indicator for the Jiaocheng ecosystem in 2014 (1.280) was lower than the value in the scenario 1 model (1.957). This means the stress on this ecosystem will increase in 2024 under the modeled scenario 1. The stress indicator for Jiaocheng under scenarios 2 and 3 was 1.957; this indicates that the stress condition of this ecosystem is unrelated to the transfer probability of dry land, paddy fields and rivers to forest and grassland.

State Indicator

Fig. 8 and Table 4 show the state indicator for the Fuding ecosystem under scenario 1 was 1.399. Although it is lower than the value in 2014, the state of the Fuding ecosystem is still at a moderate level under scenario 1 conditions. The state indicator for scenarios 2 and 3 was 2.156 and 2.302, respectively; this represents a fair state under these scenario conditions. Therefore, the Fuding ecosystem is in a better condition under scenarios 2 and 3, in which the latter scenario is better than the former.

The state indicator in scenario 1 for the Xiapu ecosystem was 1.462, indicating that this ecosystem is in a moderate state under this scenario. This value increased to 2.440 and 2.607 for scenarios 2 and 3, respectively, indicating an improvement to a fair state under these scenarios. This ecosystem is also in a better state under the latter scenario compared to the former.

The state indicators for Fu'an and Jiaocheng ecosystems were the same in scenarios 1, 2 and 3. This implies that simply changing the transfer probability of dry land, paddy fields and rivers to forest and grassland does not change the state of these ecosystems. In addition, the state indicator values

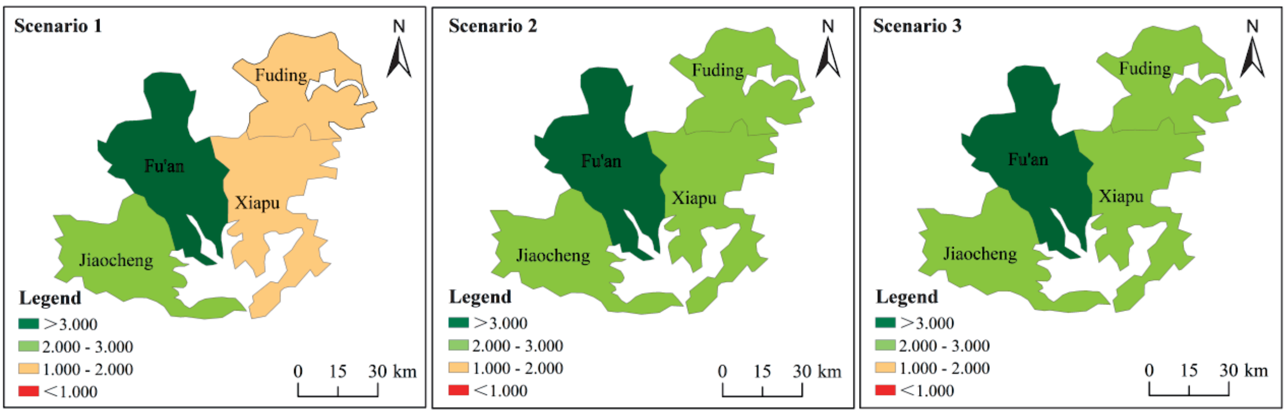

Fig. 8. Prediction of the county ecosystem state indicators in the Ningde coastal zone.

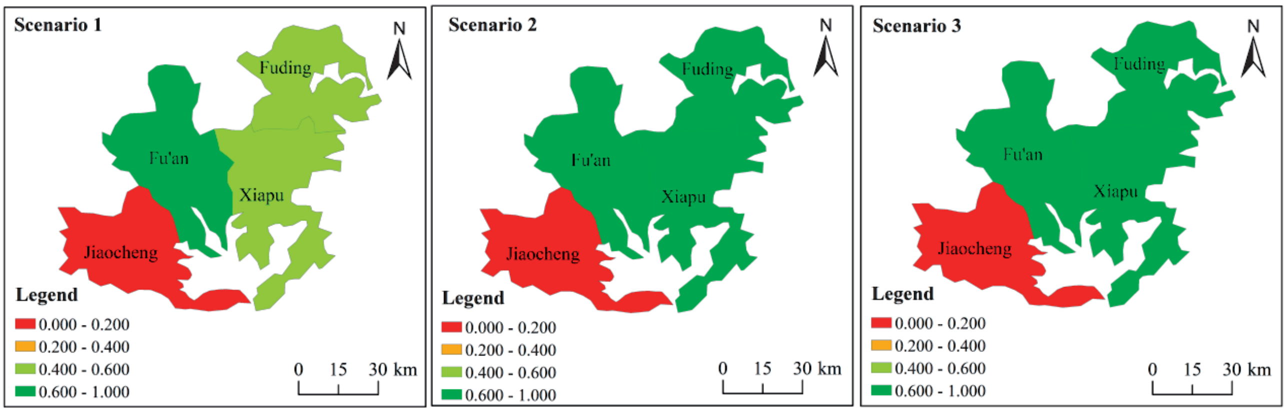

Fig. 9. Prediction of the county ecosystem response indicators in the Ningde coastal zone.

for the Fu'an and Jiaocheng ecosystems in 2024 were 3.297 and 2.565, respectively; this means that these ecosystems are predicted to be in good and fair states in 2024, respectively.

Response Indicator

Fig. 9 and Table 4 show that the response indicators for the Fuding and Xiapu ecosystems under scenario 1 were 0.423 and 0.479, respectively. This means that these ecosystems had a fair capacity to provide services to humans in 2024. The response indicators for the Fuding and Xiapu ecosystems under scenarios 2 and 3 exceed 0.8, indicating a good capacity to provide services. Moreover, the response indicator for scenario 3 in both ecosystems was greater than that for scenario 2. This means the greater the transferrance probability, the higher the capacity of the Fuding and Xiapu ecosystems to provide services to human society.

The response indicators for the Fu'an ecosystem in scenarios 1, 2, and 3 were all 0.706. This means that this ecosystem is predicted to have a good capacity to provide services. As the response indicators across all modeled scenarios were the same, the transfer probability is unrelated to the response indicators of the Fu'an ecosystem.

The response indicators from scenarios 1, 2, and 3 for the Jiaocheng ecosystem were all 0.011; this is at a poor level. This indicates that the transfer probability of dry land, paddy fields and rivers to forest and grassland is adjusted in 2024 and cannot change the fate of these in the Jiaocheng ecosystem. In summary, the response indicators for the Fu'an and Jiaocheng ecosystems are unrelated to the transfer probability. By contrast, the response indicators for the Fuding and Xiapu ecosystems were positively related to the transfer probability of dry land, paddy fields and rivers to forest and grassland.

Composite Indicator

Fig. 10 and Table 4 show that the composite indicators for the Fuding ecosystem in scenarios 1, 2 and 3 were 1.471, 1.658, and 1.709, respectively. This means that the ecosystem health of Fuding increased from moderate to fair. This indicates that the ecosystem health of Fuding is still at a moderate level under scenario 1. However, when increasing the probability of transfer from dry land, paddy fields and rivers to forest and grassland, the health of the Fuding ecosystem also improved to fair.

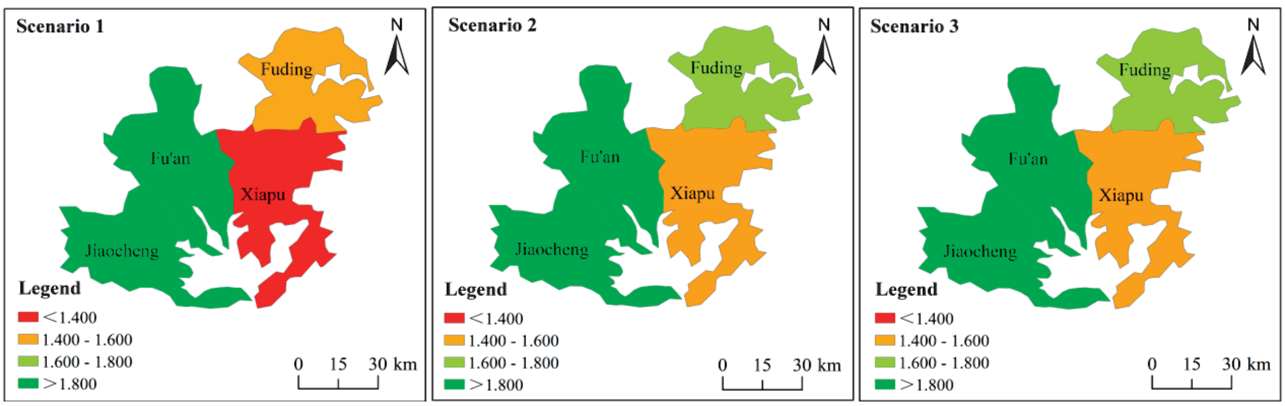

Fig. 10. Prediction of composite indicators for the county ecosystems in the Ningde coastal zone.

The health of the Xiapu ecosystem follows the same pattern; its health status was also positively correlated with the transfer probability. The difference between the Xiapu and Fuding ecosystems is that the health status of the former under scenarios 1, 2, and 3 is poor and moderate, respectively. Therefore, the health of the Xiapu ecosystem is less influenced by the transfer probability, resulting in a weaker enhancement effect on the health of Xiapu.

The composite indicators for the Fu'an and Jiaocheng ecosystems under scenarios 1, 2 and 3 were the same. This means the health of these ecosystems are unaffected by the probability of transfer from dry land, paddy fields and rivers to forest and grassland. The composite indicators for the Fu'an and Jiaocheng ecosystems exceeded 1.8, indicating that the health these ecosystems in 2024 is predicted to be good.

Discussion

Ecosystem health assessment is gaining greater recognition as an effective tool for integrated ecosystem management as the frequency of human disturbance increases. However, it has been 20 years for these assessments to emerge and there are still many problems and defects in ecosystem health assessment; the key issues are as follows.

(1) A need to improve the evaluation system for coastal zone ecosystem health. Due to the complexity of coastal zone ecosystems, it is difficult to summarize ecosystem health into specific indicators that are easily measured. Additionally, evaluation methods require improvement, particularly in terms of the health of coastal zone ecosystems; very few researchers have been involved in this aspect.

(2) Lack of research on the prediction of coastal zone ecosystem health. Some researchers have used historical monitoring data or ecological software to predict the future trends in ecosystem health. However, there is a lack of comprehensive and systematic prediction studies on the natural, social and economic coastal zone composite ecosystems.

(3) Insufficient research on the management and control measures implemented coastal zone ecosystems that seek to improve ecosystem health. At present, research on ecosystem health is mainly focused on the construction of theories and indicator systems and existing research on coastal zone ecosystem management and control measures is insufficient. The research on ecosystem health and government-led integrated coastal zone management is incompatible. This creates challenges in integrating research on ecosystem health into the management system. Moreover, research findings are not suitable for providing valuable decision support for the government.

(4) Uncertainty in the health of coastal zone ecosystems. The definition of "ecosystem health" continues to be debated and although many criteria for ecosystem health have been proposed, there is uncertainty in these criteria. Ecosystems are dynamic systems that are born, grow, and die; thus, it is difficult to determine the symptoms of disturbance or unhealthiness, particularly in young or old ecosystems.

Conclusion

Throughout the study period, the pressure on the Fuding ecosystem changed dramatically; it was the highest in 2000, decreased to a lower level of pressure in 2009, and returned to a high level in 2014. The pressure on the Xiapu and Jiaocheng ecosystems was more stable and remained at a low level of pressure. The pressure on the Fu'an ecosystem showed a clear decrease, declining significantly from a high pressure level in 2000 to the less pressure level in 2009 and then increasing slightly to the low pressure level in 2014. The pressure indicators of the Ningde coastal zone ecosystem were ranked in descending order: Fu'an> Fuding>Jiaocheng Xiapu.

Between 2000 and 2014, the state of the Fuding ecosystem improved significantly, although it remained at a moderate level. The state of Xiapu ecosystem also improved significantly, from moderate to fair, and the state of Fu'an and Jiaocheng ecosystems remained at good, although their overall states were declining. Thus, between 2000 and 2014, the state indicators of the ecosystems in the Ningde coastal zone were ranked in descending order: Fu'an>Jiaocheng>Xiapu>Fuding.

Throughout the study period, the response indicators of the Fuding ecosystem showed an upward trend overall, remaining at the moderate level. The response indicators of the Xiapu ecosystem showed a clear upward trend, from poor in 2000 to good in 2014. Similarly, the response indicators of the Fu'an ecosystem also showed a clear upward trend, from moderate in 2000 to good in 2014. The response indicators of the Jiaocheng ecosystem increased from poor in 2000 to good in 2009; then, it decreased to moderate in 2014. Overall, the response indicators of the Fuding, Xiapu, and Fu'an ecosystems showed an increasing trend, whereas the response indicators of the Jiaocheng ecosystem showed a decreasing trend. Between 2000 and 2014, the response indicators of the Ningde coastal zone ecosystem were ranked in descending order: Fu'an>Xiapu>Fuding>Jiaocheng.

Although the composite indicators of the Fuding and Xiapu ecosystems showed a gradual upward trend between 2000 and 2014, their composite indicators were still at the poor and moderate levels, respectively. Although the composite indicators of the Fu'an and Jiaocheng ecosystems fluctuated throughout the study period, their composite indicators were at a good level.

The prediction of ecosystem health for the units in the Ningde coastal zone shows that the pressure on the Fuding and Xiapu ecosystems under scenario 1 will continue to increase compared to 2014. By contrast, the pressure on the Fuding and Xiapu ecosystems will decrease under scenarios 2 and 3. This indicates that increasing the area of forest and grassland will reduce the pressure on the Fuding and Xiapu ecosystems. Compared with 2014, the pressure on the Fu'an and Jiaocheng ecosystems will also increase under scenario 1. However, they will be under the same pressure in scenarios 2 and 3, indicating that increasing the area of forest and grassland will not benefit these ecosystems in terms of pressure reduction.

The state of the Fuding and Xiapu ecosystems in scenario 1 declined significantly compared with their state in 2014, with both ecosystems being at a moderate state. In scenarios 2 and 3, their state significantly improved to fair. This indicates that increasing the area of forest and grassland can improve the state of the Fuding and Xiapu ecosystems. The state of the Fu'an and Jiaocheng ecosystems was good and fair, in all three scenarios, respectively. When the ecosystem state indicator reaches a fair level, simply increasing the area of forest and grassland does not improve ecosystem state.

The response indicators for the Fuding ecosystem under scenario 1 were higher than those values in 2014, whereas the response indicators for the Xiapu ecosystem were lower than the values in 2014. In scenarios 2 and 3, the response indicators for the Fuding and Xiapu ecosystems were higher than their respective values in scenario 1. This implies that increasing the area of forest and grassland can effectively improve the response indicators for these ecosystems. The response indicators for the Fu'an and Jiaocheng ecosystems were good and poor in all three scenarios, respectively. This means that when the ecosystem response indicator is at the highest or lowest level, simply increasing the area of forest and grassland cannot improve the ecosystem response indicator.

In scenario 1, the composite indicators of Fuding and Xiapu ecosystems in 2024 showed a decreasing trend compared with 2014. However, compared with scenario 1, the composite indicators of the Fuding and Xiapu ecosystems in scenarios 2 and 3 were increasing. This means increasing the area of forest and grassland can improve the composite indicators of these ecosystems. In all three scenarios, the composite indicators for the Fu'an and Jiaocheng ecosystems were the same. This signifies that simply increasing the area of forest and grassland is unlikely to improve the composite indicators for these ecosystems.

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Conflict of Interest

No conflict of interest exists in the submission of this manuscript, and the manuscript is approved by all authors for publication.

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