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Research Framework for Ecosystem Vulnerability: Measurement, Prediction, and Risk Assessment

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Abstract: The fragility of ecosystem health has become a key factor hindering the sustainable development of the ecological environment. Through a review of published research from domestic and foreign scholars, starting from the endogenous logic of studies in the field of ecosystem vulnerability (EV), this paper sorts out the literature on the aspects of measurement models, prediction methods and risk assessment, comprehensively defines the research category and scientific framework of EV, and analyzes the research ideas and development trends. We arrived at the following conclusions: 1) The connotation of ecosystem vulnerability not only embodies the change in the vulnerability of the natural environment, but it also reflects the irreversible damage to the ecosystem caused by excessive development and industrial production activities. 2) The setting of ecosystem vulnerability indices should aim to fully reflect the essential features of that vulnerability, which should include the index systems of natural, social, economic and other related factors. 3) There are many types of ecosystem vulnerability measurement methods, prediction models and risk evaluation models, which have different focuses and advantages. The most appropriate method should be adopted for conducting comprehensive and systematic evaluation, prediction and estimation according to the different representation and evolution mechanisms of the chosen research object and regional ecosystem vulnerability. 4) Based on the regional system characteristics, corresponding risk management measures should be proposed, and pertinent policy suggestions should be put forward to improve the ecological safety and sustainable development of an ecologically vulnerable area.

Key words: ecosystem vulnerability measurement; prediction; risk assessment; research framework; prospects

1 Introduction

Due to the changes in the global climate and the restriction of human production or life styles, the behavior, processes and service functions of ecosystems are being destroyed, and the public resources with ecological value are affected to different degrees, such as the internal imbalance of the system, the poor stability of the whole system, and the deterioration of the external environment. The fragility of ecosystem health has become a key factor hindering the sustainable development of the ecological environment. Currently, domestic and foreign scholars have conducted relevant research spanning a wide range of topics, but mainly focusing on "the vulnerability assessment of Ecosystems" or "fragile zones". The research subjects cover various fields, from pure natural disasters to artificial and agricultural ecosystems, including the three major branches of the natural, social and economic ecosystems. From the perspective of endogenous logic in this research field, abundant research results and extensive research bases have been accumulated. However, it is unfortunate that a unified theoretical evaluation paradigm has not been established yet. This paper will integrate the research literature by scholars both at home and abroad, starting from the aspects of inherent logic, measurement model, prediction method and risk evaluation in the literature review. We aim to achieve a comprehensive grasp of the theory of the ecosystem vulnerability (EV) research cate-

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gory and scientific framework, and analyze the research idea and development trends.

2 Measurement models and prediction methods of EV

2.1 Connotation, representation and evolution mechanism of EV

The ecosystem refers to a unified in a stable dynamic equilibrium state achieved through the interactions and restrictions between organisms and the environment in a specific natural space. As a complex open system, it has the inherent attribute of vulnerability, which is reflected by the vulnerabilities of the subsystems and their interactions. Timmerman (1981) believed that vulnerability is the degree of damage caused by external interference to the system. Yang et al. (2017) proposed that the EV is a characteristic of the relationship between humans and nature, which reflects the degree of sensitivity of the natural environment. When it is difficult to repair the damage to natural resources, the ecological service function is reflected through an appropriate adjustment, thus realizing the harmonious development of society, ecology and economy. Cutter (1996) and Tran et al. (2010) defined the EV connotation from different angles, and reached a basic consensus on the properties of EV recognition: namely, after the ecosystem enters the "locked" state, a chain reaction occurs in the process of ecological evolution, resulting in "path dependence" between humans and the earth, which leads to the attenuation and deterioration of their relationship.

At present, no uniform representation of the connotation of EV has been formed in the academic world, but it is generally believed that under the interference of external factors, EV is reflected by the sensitivity, resilience and anti-interference capacity in certain spatial and temporal scales. The representation of EV is conducted through the two aspects of natural factors and human factors. First of all, based on the natural conditions, many areas have sparse vegetation, a dry climate, frequent geological disasters and severe desertification of land due to the influences and constraints of geographical conditions, which has resulted in poor stability of the ecosystem. Secondly, because of interference by various human factors, such as the expansion of the scope of human activity and overly high population density, the environment has been damaged wantonly during the development and utilization of natural resources, which has caused severe pollution and overcutting of forests. Economic development has exceeded the carrying capacity of the ecosystem, and the deterioration of the ecological environment has continuously deepened. These two specific representation factors fundamentally reflect the EV. Because the ecosystem has the potential, dynamic, renewable and relative characteristics, economic development or deterioration will further weaken the resilience ability of ecosystem. Under the interference of both internal and external factors, the ecosystem balance will be broken, the capacity of the ecological environment will decline, and recovery of the ecosystem to its original ecological functions will be difficult (Bennett et al., 2003; Polsky et al., 2007; Richard et al., 2009).

In the research on the evolution mechanism of EV, Jabbar and Zhou (2011) analyzed the mechanism of EV in Southern Iraq using 3S technology, and found that the main factors contributing to land degradation are wind erosion and the climatic environment. Liu (2009) believed that karst EV is driven by internal hydrogeological conditions, including climate, terrain, soil and vegetation, which lead to the instability of the ecological system, and it is also affected by external driving factors, such as population pressure, the over exploitation of resources and poverty. Turner et al. (2003) put forward that the external cultural and environmental factors have more significant influences on the ecosystem, which make the system connected with the outside environment. The evolutionary mechanism of EV is reflected in the ecosystem's resistance to external interference, stability and sensitivity. This study concluded that the ecosystem has a strong sensitivity response and recovery ability due to the existence of disturbance factors in a specific space-time domain. When the influence of human activities is driven by external forces, the probability of EV is increased. When the disturbance caused by human activities to the ecosystem exceeds the threshold value of internal regulation, the self-regulatory function of the system will be lost, and the whole ecosystem will collapse, increasing the natural vulnerability of the ecosystem. Both natural factors and human activities are necessary conditions for the output and acceleration of EV (Boumans et al., 2015; Francesca et al., 2016; Gordon et al., 2018). Under the influence of these driving factors and the interactions between them, the degree of interaction among the subsystems within the EV becomes increasingly more intense, which will promote the long-term evolution within the vulnerability.

2.2 Index selection of EV measurement and prediction

With the deepening of studies on EV, the research direction has gradually expanded from qualitative research to quantitative measurement and prediction. The research scale and fields have been continuously broadened, involving different areas of study such as oceans, wetlands, rocky desertification and mining areas. In terms of indicator selection, different scholars have combined the dominant factors in the vulnerability characterization of the research object during the selection of related indicators (Grasso, 1998; Smit et al., 1999; De Groot et al., 2012). Natural factors, such as climate, soil, topography and geology, are taken as intrinsic vulnerability factors; while human factors, such as population density, economic index and spatial pattern, are regarded as extrinsic vulnerability factors with which to quantitatively evaluate or predict the degree of ecological vulnerability of the studied objects (Zhu et al., 2004; Costanza et al., 2014).

The published EV studies have mainly focused on theo-

Table 1 Literature review of EV measurement and prediction indicators

Target layer	Index layer	Research object	Literature sources
Exposure, sensitivity, adaptability	Population pressure, environmental degradation, industrial pollution, income difference, natural background, economic strength, infrastructure, fiscal expenditure, social security	Loess plateau area	Ma et al., 2019
Ecological environment, natural resources, social economy, sustainability	Vegetation index, soil organic matter, rainfall, water resources, engel coefficient, gross domestic product(GDP) index, natural population growth rate, contribution rate of tertiary industry	Hilly mining area	Liu et al., 2018
Pressure, sensitivity, stability	Population pressure, social pressure, environmental pressure, economic pressure, desertification sensitivity, salinity sensitivity, function, vitality, elasticity, structural limitations	Turpan area	Pei et al., 2015
Natural quality, anthropogenic pressure	Precipitation rate, drought index, soil depth, soil parent material, vegetation coverage, population growth rate, population density	Italy	Salvati et al., 2013
Causes and results	Land use type, annual average precipitation, temperature, humidity, population density, per capita income, cultivated land area	Qinghai-Tibet region	Zhou et al., 2011
Ecological pressure, ecological sensitivity, ecological resilience	Inverse fractal dimension, disturbance index, terrain index, soil sensitivity index, dominance, fragmentation	Wugong mountain	Zhang et al., 2018

retical and policy research from the late 1980s until 2000; after 2000, a large number of empirical studies on EV began to emerge. They were mainly for specific areas, and selected the suitable index systems and measurement models to quantitatively measure the objects of study and the present status of EV. The determination of indicators is a key step in the scientific and objective evaluation and prediction of EV. During EV evaluation and forecasting, from the perspective of the characteristics and mechanisms of the EV, scholars have tried to achieve better understanding of the essence of regional EV based on the principles of integrity and dominance. According to the research status of domestic and foreign scholars, this paper establishes an operable and general EV index system, including three primary indicators, eight secondary indicators and 21 tertiary indicators, as shown in Table 2.

Table 2 The EV index system

Primary index	Secondary index	Tertiary index
Indicators of Natural factor	Terrain, climate, soil, vegetation, geology, water resources	Vegetation coverage rate, terrain distribution, precipitation, soil type, soil erosion rate, total water resources
Indicators of social factors	Social development index	Population density, natural population growth rate, per capita arable land area, urbanization level, poverty rate, unemployment rate, school enrollment rate
Indicators of economic factors	Economic development index	Per capita GDP, proportion of primary industry, proportion of secondary industry, per capita net income of farmers, consumer price index, industrial wastewater discharge, energy consumption

2.3 Measurement model and evaluation

There are many measurement models and methods for EV. In the process of quantitative evaluation of EV, choosing the appropriate measurement models and methods is very important, and adopting the appropriate methods to evaluate and predict the vulnerability of research objects comprehensively or systematically according to their different characteristics and evolutionary mechanisms is necessary (Shipley, 2000; Brian et al., 2004; Christoph et al., 2009; De Groot et al., 2010). In this paper, based on the content organization and analysis of EV measurement models, we conduct an objective evaluation of the methods adopted by the models, summarize their scopes of application and organize them by utilizing the practicality of each model.

As for the measurement method, some researchers use the PSR, VSD, and Cause-result evaluation methods, and they treat EV as the vulnerability features caused by external pressures (including natural factors and human factors), which has exposure and sensitivity. They also discuss how to respond to and recover from the pressure represented by vulnerability. These models are based on the presentation and status quo of vulnerability. However, the shortcoming is that the measurement method is too simple, and while it can be used to roughly evaluate the vulnerability of simple ecosystems, it cannot comprehensively measure complicated ecosystems. Some scholars use the Grey relational degree, Analytic hierarchy process (AHP), and Principal component method. Based on the causes and influencing factors of the vulnerability of the research object, they consider which factors are associated with the status quo of vulnerability, and use these factors as the indices for the setting and quantitative analysis of the weights. The shortcomings here are that these analyses are too subjective, manual setting is the main method, and the measurement cannot be conducted based on objective data. Some scholars focus their research on the mathematical and computer technology processing after the selection of indices. They choose the Fuzzy evaluation method, BP neural network method, Set pair analysis, Matter-element extension model, etc., so that the processed indices are closer to the real vul-

Table 3 Brief evaluation of EV measurement models

Measurement model	Model content	Model evaluation	Scope of application
PSR (pressure-state-response) model	Pressure indicators based on the effects of human economic and social activities on the environment, the status quo of ecosystem and natural environment represented by the status indicators, and the response indicators are established to prevent the negative impacts of human activities on the environment	Three basic questions "what happened, why did it happen and how to do it" are answered, which fully explain the situation of the evaluation object compared with the reference standard	Applicable to regional environment, soil and water resources and agricultural protection
VSD (exposure-sensitive-adaptation) model	Vulnerability is studied from three dimensions: exposure degree, sensitivity and adaptive potential. Each indicator is refined with circle-level data, and evaluated effectively and clearly by "aspect layer—index layer—parameter layer"	It fails to clarify which reflects the natural factors, and which reflects the human factors	Suitable for the basic data of comprehensive regional EV measurement
Pressure sensitivity resilience model	The intensity of ecological pressure includes area-weighted average fractal dimension reciprocal and disturbance indexes. The ecological sensitivity includes soil erosion sensitivity index, terrain index and landscape fragmentation index. The ecological resilience refers to the self-resilience of an ecosystem and when it is disturbed, it is related to the stability of its internal organizational structure	The emphasis is put on the natural factors, and the proportion of human factors in the index is not high	The vulnerability of ecologically fragile areas are measured and compared
Fuzzy evaluation method	Establish the index system and weight, calculate factors for the membership of each evaluation index vector, evaluate regional vulnerability degree	Fuzzy trigonometric functions can reduce the shortcomings of subjective effects, which has certain objectivity, but the index of significance is not obvious, and is a heavy workload	Suitable for a specific areas or multiple regions
Analytic hierarchy process (AHP)	Establish the evaluation index, score and weight the index, multiplied by the score value and weight, which are added up to obtain the total score to determine the degree of ecological vulnerability	It provides a clearer idea and logic for selection of related indices. The index selection is subjective	Suitable for the analysis of regional and internal evaluation units
Principal component method	Data standardization, set up the correlation coefficient matrix, calculate eigenvalues and eigenvectors and cumulative contribution rates, and obtain the main ingredients of vulnerability analysis	Variable selection of dimensions is not restricted, but it particularly focuses on the main ingredients, which causes some information to be missed, and fails to fully reflect the index of all information	Suitable for regional analysis of the internal evaluation unit
BP neural network method	Set the objective function of the calculated index, and the weight between the input and output layers of the index can be adjusted and modified with the gradient descent method	Intervention processing, compatibility	Deals with the measurement of regional ecological vulnerability with some complex states
Cause-result evaluation method	Establish the corresponding index system according to the characteristics and causes of EV, and the entropy weight method is usually used to assign the weight to each index	Relatively simple, and difficult to deal with complex state	Used for the comparison of vulnerability degrees between regions for a rough analysis
Set pair analysis	Establish coefficient of difference degree and correlation degree, weights set, scheme set and evaluation set, the standard deviation classification method is used to measure and classify the EV	The calculation is complicated, and the analysis result has some intuitiveness	Can be used to measure and analyze the EV of regional units
Landscape ecology model	Computer simulation data is used to characterize the dynamic characteristics of EV, which is combined with GIS, remote sensing data and other system analysis data	This model focuses on local spatial analysis and ignores the influence of human factors	Analysis of EV from the perspectives of regional space and spatial heterogeneity
Grey relational degree	The reference sequence of ecological vulnerability characterization and the comparative sequence of influencing system behavior are determined, the data are processed dimensionless, the grey correlation coefficients of the reference sequence and the comparative sequence are calculated, and the correlation degree is sorted	The degree of correlation between vulnerability factors is emphasized	Used for comparative analysis between regions
Matter-element extension model	The classical domain, node domain and object element to be evaluated are determined, the index weight is set, the correlation degree is calculated, and finally the vulnerability degree of the member to be evaluated is obtained	This method is suitable for multi-factor analysis, which uses formal language to deal with the characteristics of ecological vulnerability	Used for delicate analysis of fragility between regions

nerability state of the research object, and they use related data for the prediction of the vulnerability state. Although these methods conduct accurate measurements by utilizing the objective principle of data, they have the limitation that the operation process is too complicated. Furthermore, from disciplinary perspectives such as geography and ecology, some scholars use the Landscape ecology model, 3S and other proper technologies, and combine regional space, GIS and remote sensing data technology for a dynamic description of the EV of research object. The main limitation of these methods is that they focus on depicting the natural state of EV, while lacking the necessary consideration of human factors (Smithers and Smit, 1997; Simmie and Martin, 2010).

2.4 Prediction methods and evaluation

The prediction of EV is based on the measurement. The prediction is conducted by identifying the fragility and sustainability of the ecosystem, and quantitatively investigating the results of the interactions of natural or human interference factors and the future development trend. Therefore, the vulnerability prediction of a specific region is often associated with the measurement. Xu and Li (2015) argued that the regional ecosystem status is not set in stone, but is constantly changing as time goes by, and understanding the regional ecological state of the system not only depends on accurate evaluation, but also requires scientific prediction for the future. For the ecological vulnerability in "targeted" governance, the thought of "nipping it in the bud" should be followed. This paper categorizes and briefly evaluates the prediction methods, as shown in Table 4.

Table 4 Prediction methods and evaluation of EV

Qualitative prediction		Quantitative prediction	
Method	Evaluation	Method	Evaluation
Deduction method	Based on the past and current data, the future trends of EV can be deduced. At the macro level, the prediction has good applicability in the case of low precision and missing data	Life zone model	Select a specific model according to the vulnerability data, input parameters and constraints, and simulate the evolutionary trend of the ecological vulnerability. It has the limitation of a high requirement of data quality, which requires strict discrimination, otherwise significant errors may exist in trend judgment
		Scenario analysis model	It can be used for scenario prediction of greenhouse gas emission and concentrations, and prediction of the change trend of climate vulnerability. It has the limitation that it can only conduct simulations and predictions based on the natural ecosystem, and rarely involves the social and economic ecosystems
		Logistic regression method	According to the law of succession, the trend characteristics of data are used for prediction. It has the shortcoming of excessive dependency on the subjective evaluation of the principles, which does not have a high requirement for the quality and prediction of data
		Neural network model	With certain accuracy, it can efficiently process noisy and incomplete data and non-linear complex systems. However, this model does not have strong interpretability for simple ecosystems

As for the prediction of EV, due to a lack of relevant theoretical support and research basis, there are few studies on the prediction of EV using qualitative methods in academic circles, and most of them are based on quantitative predictions. By using specific models to simulate the evolution of ecological vulnerability, the literature mainly focuses on the prediction of the vulnerability of natural ecosystems, such as climate, water and land use. In the study of quantitative prediction, more attention is paid to the transformation trends of data, but no consideration is given to the stability and responsiveness of the predictions. The prediction method with good stability will eliminate more factors of random interference, while the prediction method with a good response degree can adapt to the actual changes. If a single prediction model can be reasonably and scientifically combined to achieve these two goals, then the reliability and validity of the prediction will be much more accurate.

The EV measurement model and evaluation of the technology are already quite mature. Various researchers employ different measurement methods to reveal the regional EV degree based on the explanation of the model, the research methods are constantly being improved, the object of study has been expanded from a single region to various fields, and there is more in-depth research content. The overall research idea here basically follows such internal logic: research object→status characteristics→indicator selection→weight setting→quantitative evaluation→analysis results→numerical simulation→trend prediction→policy suggestions. However, there are very few studies of the internal formation mechanism and prediction of EV, so these need to be further explored by more scholars.

3 Risk assessment and prevention of EV

With the continuous progress achieved in the measurement and prediction of EV, the academic community has gradually realized that they should not only evaluate the level of EV, but also the regulation of EV and probability, which are realized through the development of EV risk assessments that can partly explain the problem of ecological environment deterioration and its internal mechanisms. As a relatively new research direction at present, the risk assessment of EV aims to evaluate the level of the region's ecological vulnerability quantitatively by studying the possibility and magnitude of the states of several uncertain factors. Specifically, it requires further evaluating the risk of vulnerability beyond measuring the degree of EV, and studying the degree of potential impacts of vulnerability risks and the probability of their occurrence. Table 5 presents an intro-

Table 5 Risk assessment methods and evaluation of EV

Method	Content and evaluation
Risk assessment index method	Based on the subjective evaluation method, the severity and possibility of EV are determined according to the evaluation purpose, and an expert questionnaire is compiled for scoring, so as to determine the possibility and risk level of adverse effects. It has certain subjectivity, which is applicable to fragile ecosystems affected by both human and natural factors. The model has the limitation that the subjective factor is too strong, so it cannot be evaluated in an objective and effective way
Risk synthesis index method	The relationship between the landscape structure and the regional EV risk is established, and the vulnerability risk index is determined by the area proportions of landscape components and landscape loss index. It is mainly used to analyze complex ecosystems that are more strongly influenced by natural factors than by human factors. The shortcoming is that it can only analyze simple ecosystems under the influence of natural factors, while it does not work for complicated ecosystems with less interference of human factors
Risk causal chain model	Three-dimensional models are established by identifying the risk receptors, exposure - response processes and ecological endpoints. Risk = risk probability ×vulnerability ×degree of loss. It includes the explicit characterization of the system exposure response process, the sensitivity of loss as a loss correction factor, and a more comprehensive reflection of the vulnerability pattern of the ecosystem. The main limitation is that it is too objective, and so it lacks a certain subjective judgment
"Probability-loss" two-dimensional model	Determines the probability and consequences of ecological vulnerability events. Risk = probability of risk × outcome. The method is simple, but it does not consider whether the ecosystem is affected by the risk source or its sensitivity

duction and evaluation of the main content of EV risk evaluation methods.

The assessment of vulnerability risk is mainly conducted based on two aspects: the probability of risk and the consequences of risk. Most researchers adopt the two-dimensional model of "probability-loss" because this method is relatively simple and feasible. To expand on the "two-dimensional" model, some scholars put forward a "three-dimensional model" with the causal chain of risks, including vulnerability factors in the model, to allow evaluation of the vulnerability risk of the ecosystem in a more comprehensive way. In risk assessment, the risk synthesis index law is employed to conduct quantitative evaluation from the perspective of vulnerability measurement. The difference between these two is that the former is more subjective, while the latter is applicable to research on natural ecosystems. The risk prevention and control of EV are based on the risk assessment of vulnerability, and the targeted risk prevention and control suggestions are put forward. According to the level of vulnerability risk and the main influencing factors, Du et al. (2016) conducted a zoning study on ecological risk prevention related to geological disasters from the perspectives of single factors and multiple factors, based on the risk level of EV in Dali prefecture basin. They concluded that prevention zoning is conducive to the investigation of the internal mechanism of ecological vulnerability risk, and that specific prevention and control measures can be put forward according to the results. The studies on the prevention and control of the risk of EV are mainly based on the assessment of the risk of vulnerability, and risk partition is carried out. Corresponding risk management countermeasures are then proposed for different zones, and policy suggestions are put forward to promote the ecological security and sustainable development of ecologically fragile regions.

4 Theoretical framework and development direction of EV research

At present, although domestic researchers have not reached a consensus on the basic concepts of vulnerability or ecological vulnerability, significant advancement has still been achieved in the research in this field. EV itself involves a wide range of different realms, including ecology, economics, geography and other interdisciplinary systems, with a strong comprehensive nature. The research domain of EV has been expanded from the pure natural ecosystems to the complex social and economic ecosystems (Smit and Cai, 1996; Parris and Kates, 2003). The research framework has been constantly improved and gradually extended in the comprehensive and systematic direction. In the published studies, scholars have qualitatively and quantitatively analyzed the connotation, characterization, measurement and prediction of EV of the research objects from different perspectives using different research methods, and they have proposed related suggestions and countermeasures for the sustainable utilization and development of ecological resources (Harris et al., 2006; Costanza et al., 2012). With the deepening of the research field, these aspects constitute the basic framework of the theoretical research system on EV, and this framework should be the path that is pursued for the research to become fully mature, as shown in Fig. 1.

Although great progress has been made in the study of EV, there are still some problems and deficiencies that need to be addressed in the theory and in practical applications. This is also the future direction of theoretical and application research, which is mainly reflected in the following four aspects:

First, the research contents need to be further expanded and improved. The academic literature mainly focuses on the connotation and manifestation of EV. The research contents generally include the characterization and evaluation of EV in specific regions, and there is less discussion of the evolutionary mechanism and influencing factors of EV (Endfield et al., 2012; Camino et al., 2013; De Araujo et al., 2015). The content can be expanded by combining the fields of human and land systems, ecological protection, service value, etc. Alternatively, the coupling effects between vulnerability subsystems can be investigated to continuously enrich the categories of theoretical and practical research.

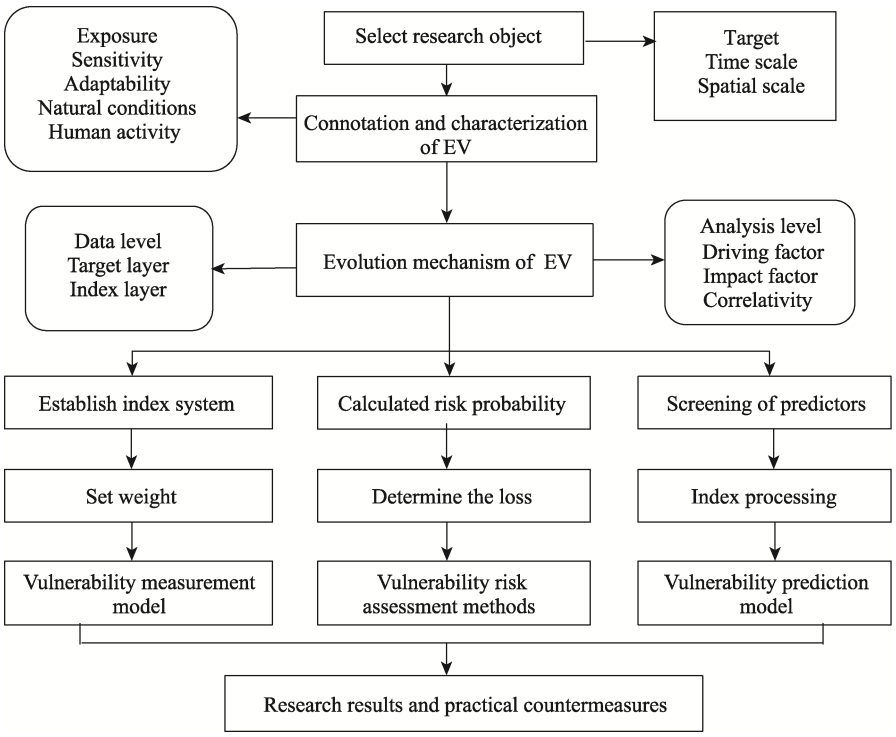

Fig. 1 Logical framework of EV research system

Second, the measurement and prediction evaluation systems need to be comprehensive and standardized. In recent years, most of the research studies are based on the differences of academic backgrounds, research objects and perspectives, which lead to subjectivity in the selection of measurement indicators. They are limited to setting corresponding parameters based on the cause-result relation, and lacking in objective and scientific demonstration. At the prediction level, the potential impacts of natural ecological subsystems can be simulated and predicted, but the effect of prediction on the uncertainty and complexity of social and economic ecological subsystems is not ideal. The rapid development of modern economic and geographic information technologies, such as measurement evaluation and prediction models, provides great technical potential for revealing, evaluating, forecasting and identifying the vulnerability of ecosystem. The internal mechanism and prediction of spatial patterns of regional EV will also become the focus of future research. In the specific studies, we should make all efforts to highlight the actual situation of the research object and combine its vulnerability characteristics. Starting from the formation mechanism of the vulnerability of the research object, we should carefully select the index system and evaluation method to obtain more reasonable and objective evaluation results, and enhance the application and guidance of the measurement and prediction results in practice.

Third, the risk assessment and prevention issues need to be further studied. Most scholars intend to put forward corresponding policy suggestions for avoiding vulnerability risks from different perspectives based on the development status of the research objects. However, very few scholars study how to establish an early-warning prevention and control mechanism against the vulnerability risk crisis. The selection of risk assessment models needs to be further explored based on related mathematical and computer knowledge of loss degree and probability. In addition, efforts should also be made to strengthen the research on early warning and prevention mechanisms. The objective of the theoretical research on EV is to measure the degree of ecological security of the research object and to obtain insight into the internal problems, so that effective measures can be taken to reduce the degree of vulnerability and promote the healthy and stable development of ecologically fragile areas (Salvati et al., 2013; Fetzel et al., 2016).

Fourth, the research results and countermeasures need to emphasize practicality. Effective ecological control is the ultimate goal of EV research, so it should be the key direction of future research and development in order to measure the vulnerability and risk of the investigated ecosystem and to carry out the measurement and risk partition. According to the results of the measurement and risk assessment, (i) the research objects should be divided into reasonable zones; (ii) different ecological management countermeasures should be taken for different zones; (iii) comprehensive

management and effective control of the research objects should be put into practice; (iv) the pattern of ecological space development should be promoted in order to provide a scientifically theoretical basis and practical decision-making basis to the relevant departments.

5 Conclusions

By considering related research studies of both Chinese and foreign scholars, starting from the endogenous logic of studies in the field of ecosystem vulnerability (EV), this paper defines the connotation and representation of EV, and conducts a literature review and evaluation on the aspects of the selection of index system, measurement model, prediction method and risk assessment to comprehensively understand the framework and scope for the theoretic research on EV. From this, we draw the following conclusions:

(1) The connotation of ecosystem vulnerability not only embodies the change of the vulnerability of the natural environment, but also reflects the irreversible damage to the ecosystem caused by excessive development and industrial production activities.

(2) The setting of ecosystem vulnerability indices should aim to fully reflect the essential features of its vulnerability, which should include the index systems of natural, social, economic and other related factors.

(3) There are many types of ecosystem vulnerability measurement methods, as well as prediction and risk evaluation models, which each have different focuses and advantages. A proper method should be adopted for conducting comprehensive and systematic evaluation, prediction and estimation according to different representation and evolution mechanisms of research objects and regional ecosystem vulnerability.

(4) Based on the regional system characteristics, corresponding risk management measures should be proposed, and pertinent policy suggestions should be put forward to improve the ecological safety and sustainable development of ecologically vulnerable areas. Future research needs to explore innovative research methods, expand the space and time of the study areas, and further develop the literature research system, which is also the development direction of EV theory and empirical research in the new era.

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生态系统脆弱性研究框架：测度、预测及风险评估

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摘　要：生态系统的健康状况所体现的脆弱性特征，已成为阻碍生态环境可持续发展的关键因素。通过综述国内外学者的相关研究，从生态系统脆弱性的内生逻辑领域出发，整理测量模型、预测方法和风险评估等方面的文献，全面掌握生态系统脆弱性的研究范畴和科学框架，并分析其研究思路及发展趋势。本文得出了以下结论:（1）生态系统脆弱性的内涵既体现自然环境脆弱性的变化，又反映出由于过度开发、工业化生产活动对生态系统造成不可逆的破坏。（2）生态系统脆弱性指标设立应以全面反映其脆弱度的本质特征为目标，包含自然、社会、经济等相关因子的指标体系。（3）生态系统脆弱性测度方法、预测及风险评估的模型种类较多，侧重点及优势各有千秋，应依据研究对象及区域生态系统脆弱性的不同表征及演化机理，采用适宜的方法进行综合、系统性地评价与预测。（4）针对区域系统特点，提出相应的风险管理对策，以及具有针对性的促进生态脆弱区域生态安全和可持续发展的政策建议。

关键词：生态系统脆弱性测度；预测；风险评估；研究框架；展望