Acta Ecologica Sinica 35 (2015) 111–121

Contents lists available at ScienceDirect

Acta Ecologica Sinica

journal homepage: www.elsevier.com/locate/chnaes

Ecological security research progress in China

Dan Liu, Qing Chang *

Department of Ornamental Horticulture and Landscape Architecture, China Agricultural University, Beijing 100193, China

ARTICLE INFO

Article history:
Received 3 August 2013
Received in revised form 23 May 2014
Accepted 18 July 2014

Keywords:
Ecological security
Research progress
Bibliometric method
Research stage
Research hotspot

ABSTRACT

In the last two decades, China has experienced extensive economic development and urbanization. The consequential loss and degradation of natural resources and resulting environment pollution may adversely affect human health. As global changes ensue, ecological security becomes one hotspot of researches and practices all over the world. Based on the literature analysis from 1985 to 2012 and bibliometric methods, this paper examines the current research stage, contents and emerging topics of ecological security in China. Ecological security researches in China go through two stages: the conceptual and theoretical framework exploratory stage (1985–1999) and the theory formation and practical development stage (2000–2012). In the exploratory stage, researchers mainly focused upon ecological problems at the global and national level, rather than the local or regional level. Research hotspots involved national security strategy, ecological risk assessment, landscape ecology and ecological balance, all of which were not correlated tightly. During this period, researches concerning ecological security were still exploring the concept of ecological security and tried to form its theoretical framework and technical methods. In the practical stage, researchers examined concepts, spatial patterns, assessments and management systems of ecological security, especially the ecological security assessment index system. During this period, the research methods shifted from conceptual and exploratory qualitative analysis to quantitative analysis, including mathematical models, and digital terrain models, etc.; the research content developed from a theoretical exploration to a case study approach. We also reviewed the historical research of ecological security in China and suggest a research framework involving different research scales, different research objectives, and different research methods. Our statistical findings show that ecological security research on global and regional scales is one topic of increased research activity. From the perspective of research goals, the current focus is biodiversity conservation. Next, from the view of the research subject, environmental science is most frequently studied among domestic researchers on ecological security. The number of published articles concerning ecological security accounts for 40.73% of the total. Finally, in terms of sustentation funds, the fund of the ecological security research is mainly from Natural Science Foundation of China (NSFC), accounting for 38.01% of the total funds support. A total of 1178 papers were awarded sustentation funds, accounting for 23.83%. Our study summarized the research progress of ecological security assessment, ecological security warning, ecological security maintenance and ecological security patterns. Thus based on these statistic data and analysis, ecological security research in China may be emphasized from the following aspects: (1) to form the theoretical system of ecological security and to integrate the technical methods; (2) to improve ecological security warning mechanisms and environmental monitoring; and (3) to improve ecological security maintenance and management system. In conclusion, we believe ecological security warning and ecological security patterns will be given more attention in the future research. The correlation research will develop from the previously exploratory qualitative research and status analysis to the quantitative research and dynamic warning. At the same time, by using '3S' space technology and combining with the disciplines/professions of geography, environmental science, ecology, landscape ecology, restoration ecology and economics, there may be a stronger establishment of grounded ecological security knowledge. Therefore, the ecological security evaluation index system and grading standards of the evaluation results will be gradually integrated and improved plus the dynamic evaluation, simulation and warning research will be strengthened.

In recent decades, as the global confliction between people and land has been increasingly intensified, in general ecological environment presents a trend of deterioration [1], such as ecological damage caused by the unduly development and utilization of natural resources, the 'three wastes' pollution and other environmental aspects caused by urbanization, industrial and agricultural overexploitation, specifically erosion, desertification, decline of forest and grassland resources and decline of biodiversity. It has become the world focus topic to restore the degraded natural ecosystem and its sustainable ecosystem services

* Corresponding author.
E-mail address: changqing@cau.edu.cn (Q. Chang).

http://dx.doi.org/10.1016/j.chnaes.2015.07.001
1872-2032/

[2]. The report to the Eighteenth National Congress of China has promoted ecological civilization into the overall plan of the cause of socialism, and improved its strategic position, which indicates that ecological security has become a hotspot in the field of sustainable development strategies.

Currently, researches on ecological security in western counties began in the 1980s, which range from the field of forest management, timber harvesting and other agricultural issues to land use change, habitat suitability and river water quality problems [3]. The optimal allocation of land use and the landscape ecology planning have been put more focus by European and American scholars. However, domestic researches on ecological security began in the 1990s, and plentiful academic studies have been published on basic concepts and contents of ecological security [4], the design principles and methods [5], evaluation methods and indicators system [6]. The theoretical system and research methods are still under exploration. Conceptual, initiative or exploratory qualitative analysis are more than quantitative analysis, and the researches of opinion, principles and criteria are more than case study [7]. Therefore, it is of great importance to put the theoretical research results into practices, based on which the system of ecological security involving theory and methodology are established. Through the bibliometric method and content analysis, this paper tries to review the existing literatures in Web of Science (WOS) and China National Knowledge Infrastructure (CNKI) between 1985 and 2012, to summarize the ecological security research progress in China and to present a systematic framework for ecological security researches with the support of the software (Endnote X6 and CiteSpaceII). It is hoped to provide a reference to systematize the ecological security study, to help solving regional environmental problems and to promote ecological civilization and ecological security pattern construction.

1. Stage of ecological security research

Ecological security is a hot research topic in China. The issue about ecological security had been proposed in the early 1990s, but the study of ecological security began in 1998. In 1998 continuous flood for a few months on the Yangtze River region caused enormous social and economic losses, thus the negative impacts that environmental degradation had on the socio-economic aroused extensive attention, which drove and promoted the ecological security research. Xiao had studied the relationship between ecological security and ecological risk in 2002. He pointed out that the ecological security research is derived from the ecological risk analysis [8]. Therefore, this paper included the topic word—'ecological risk' into search scope when searching ecological security related papers.

In this paper, data are collected from Web of Science, in which database selections are SCI-EXPANDED, SSCI, CPCI-S, CPCI-SSH, IC and CCR-EXPANDED, literature type is ARTICLE. Taking 'ecological security or ecological safety or ecological risk' as the topic word to search for papers, up to 2012, there are 11,928 papers, of which 826 come from China, accounting for 6.92% of the total and ranking fourth among all countries. In CNKI, there are 9976 relevant papers by using the same topic words. According to the analysis of annual trend of published papers, it can be seen that the number of ecological security paper is gradually increasing (Fig.1). According to changes of the published literatures and national policies, this paper proposed two stages of ecological security development in China: (a) conceptual and theoretical framework exploratory stage (1985–1999) and (b) theory formation and practical development stage (2000–2012).

1.1. Conceptual and theoretical framework exploratory stage (1985–1999)

Research on ecological security began in the 1990s. Domestic scholars conducted a preliminary theoretical exploration of ecological security. During this period, there is a small quantity of papers. In CNKI, there are 158 journal articles. In WOS, the number is 1723, 7

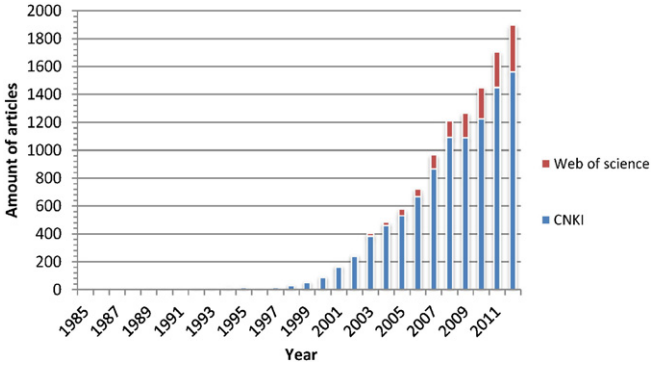

Fig. 1. Articles on ecological security between the years 1985–2012.

papers per year, but only 16 are from China. And the amount of 25-year-paper accounted for only 1.61% of the total. Based on content analysis and word frequency analysis, the top five keywords are respectively 'ecological risk assessment', 'ecological security', 'ecological risk', 'national security' and 'landscape ecology' (Fig. 2). Further analysis shows that during this period, the ecological security research focused on regional ecological risk assessment and national ecological security. The main focus of many scholars was ecological problems at global and national level, ranging from national security strategy and ecological risk assessment to landscape ecology and ecological balance. However, there also were a few scholars to explore regional ecological security. The most representative theory was presented by Yu [9,10]. He proposed a landscape ecological security pattern and introduced the concept of ecological security into the landscape pattern of biological protection. Moreover, he proposed using ecological security pattern to achieve the environmental and economic sustainable development.

Those data and keywords show that research on the ecological safety during this period was still in the conceptual and theoretical exploration stage, lacking mature theoretical support, technical methods and research system. Scholars mainly focused on the problems at global or national level rather than that at local or regional level. Furthermore, the attention attached to the special relationship between environmental pressures and some local or regional security was insufficient [11].

1.2. Theory formation and practical development stage (2000–2012)

After 2000, the amount of ecological security research paper increases rapidly year by year. The number of research paper in 2000 is as 1.68 times as that in 1999. On December 29, 2000, the State Council promulgated the 'Outline of National Ecological Environment Protection', which for the first time clearly stated the goal of 'maintain national ecological environment security'. Then ecological security was rapidly becoming a hot issue of academic research and public discussion [12, 13]. In addition, China's ecological security research developed into the theory formation and practical development stage.

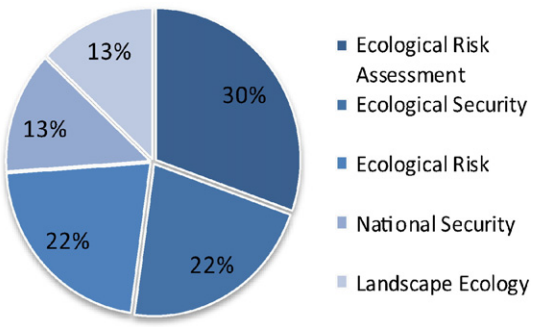

Fig. 2. Keywords of exploratory stage.

In WOS, there are 810 relevant papers from China, whereas in CNKI, there are 9869 relevant papers. The average annual amount of papers is 821, the aggregate number of 13 years accounts for 98.86%, indicating that this period research on ecological security is very active and at the stage of rapid development and has fruitful scientific research achievements.

Use word frequency analysis method to extract the key words arranged in the top ten (Fig. 3). As a result, 'heavy metal', 'sediments', 'ecological risk assessment,' 'assessment' and 'indicator system' belong to ecological security assessment content, and 'measures', 'environment' are a part of ecological security management. Scholars have exerted great effort to explore the concept of ecological security, spatial pattern, assessment, management and security system, especially the index system of ecological security assessment. As for theoretical research, Xiao [8] proposed that main contents of ecological security study include ecosystem health diagnosis, regional ecological risk analysis, landscape security pattern, ecological security monitoring and early warning, ecological security management and other aspects; when it comes to spatial pattern, Ma [4] and Yu [14], respectively, did some research on ecological security pattern at regional scale and national scale; in practice research, Wang [15], Jia [16], Fu [17], Xu [18] carried out ecological risk, ecological security analysis and assessment in the Three Gorges Reservoir Region, Gansu pastoral, Liaohe River, the Yellow River, etc.

In sum, in this period, the ecological security research has transformed from macro global, national and other large scale to smaller scale like regional and urban scale; research methods have developed from conceptual, exploratory qualitative analysis to quantitative analysis, such as mathematical model, digital terrain model, etc.; scholars pay more attention to case study rather than merely theoretical exploration.

2. Contents of ecological security research

2.1. Concept and research framework

1980s, the World Commission on Environment and Development proposed the concept—'sustainable development' for a range of social, economic and environmental problems, and for the first time used the term 'environmental security'. It clearly stated that the definition of security must be extended beyond national sovereignty political and military threats, but includes environmental degradation and destruction. At the same time, the development of human civilization, characterized by urbanization and industrialization, and the global environmental change began to gain attention. The discussion about environment security gradually increased, ranging from taking environmental stress as a major threat to national security to taking the environment change as a common topic of global security. The changes in the concept of environmental security and environmental management triggered the rapid development of ecological risk research and in the 1990s put forward the concept of ecological security (Fig. 4).

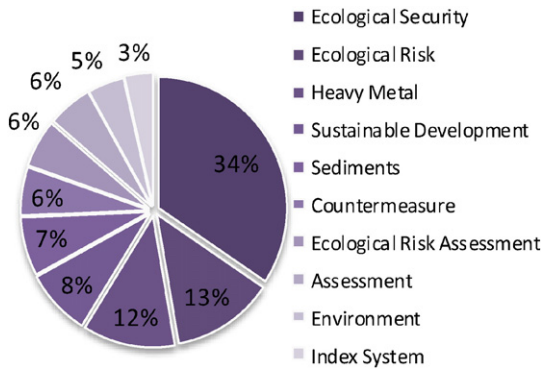

Fig. 3. Keywords of practical stage.

Ecological risk is defined as 'a process or event caused by one or more external factors that have or may have adversely effect on ecosystem structure, function or dynamic development, thereby affecting the survival and development of human and other organisms' [19–21]. Ecological security is an inverse function of ecological risk. Scholars discuss and summarize the ecological security concept, content and essence from different angles but still there are many claims, no generally accepted definition. Currently widespread ecological security has both broad and narrow interpretations.

The broad definition is presented by the International Institute for Applied Systems Analysis (IIASA) [13]. This definition is mainly from the perspective of the human society, including the three 'security': (1) security of human production and life; (2) security of human adaptation and development; and (3) security of environmental resources. Domestic scholar Peng Shaolin [22] claimed that the definition of ecological security boils down to three areas: environmental and resource security, biological and ecological systems security, nature and social security. And Yang [23], Zhang [24], Zheng [25], et al. elaborated the definition from the human ecological sense. Some scholars [12] tend to equal ecological security to the environmental security, namely ecological environment and resource that human depend on. The narrow definition is defined as natural or semi-natural ecosystems security that reflects the overall level of ecological integrity and health system [13]. This ecological security includes biosecurity and ecological system security. Some scholars believe that the most important part of the ecological security is biosecurity that can be affected by factors such as biological invasions, genetic drift resulting from biotechnology issues and so on. Ecosystems security includes whether ecosystem structure and function is compromised.

In the context of global environmental change, facing enormous challenges of global, national and regional demands of sustainable development, domestic researchers in different fields have been carried out ecological security research work at different scales (Fig. 4).

In CNKI, this paper searched for 'ecological security or ecological safety or ecological risk' relevant papers from different scales, different research objectives (Fig. 5). The results can be seen from the statistics show that ecological security research at the national and regional scales [26] is the focus of the current study, respectively accounting for 36.55% and 35.13%. From the perspective of research goals, papers concerning biodiversity conservation account for 45.51%, followed by soil and water conservation, whose paper proportion reaches 31.18%. The number of both accounts for 76.69% of the total, showing the current research focus is biodiversity conservation.

In CNKI, this paper searched papers from different subjects, different funds (Fig. 6). From the view of the research subject, environmental science is most frequently studied among domestic researchers on ecological security. The number of published articles concerning ecological security accounts for 40.73% of the total, followed by agricultural science, including forestry and other disciplines. Papers mainly distribute in three areas: environmental science, agricultural science and economy, accounting for 87.11% of the total. In terms of sustentation funds, the fund of the ecological security research is mainly from Natural Science Foundation of China (NSFC), accounting for 38.01% of the total funds support. A total of 1178 papers were awarded sustentation funds, accounting for 23.83%, in which 809 papers were awarded national funds, accounting for 68.68%. The above data show the ecological security research is provided with high-level funding, but the overall funds papers rate is still low.

2.2. Research hotspots

According to the 9976 papers concerning ecological security in CNKI (Table 1), current domestic ecological security research can be summarized as four hot fields, 12 research areas, quantitatively constituting a significant pyramid. Ecological assessment and analysis accounts for 52.33%, specifically including four main research areas: ecological

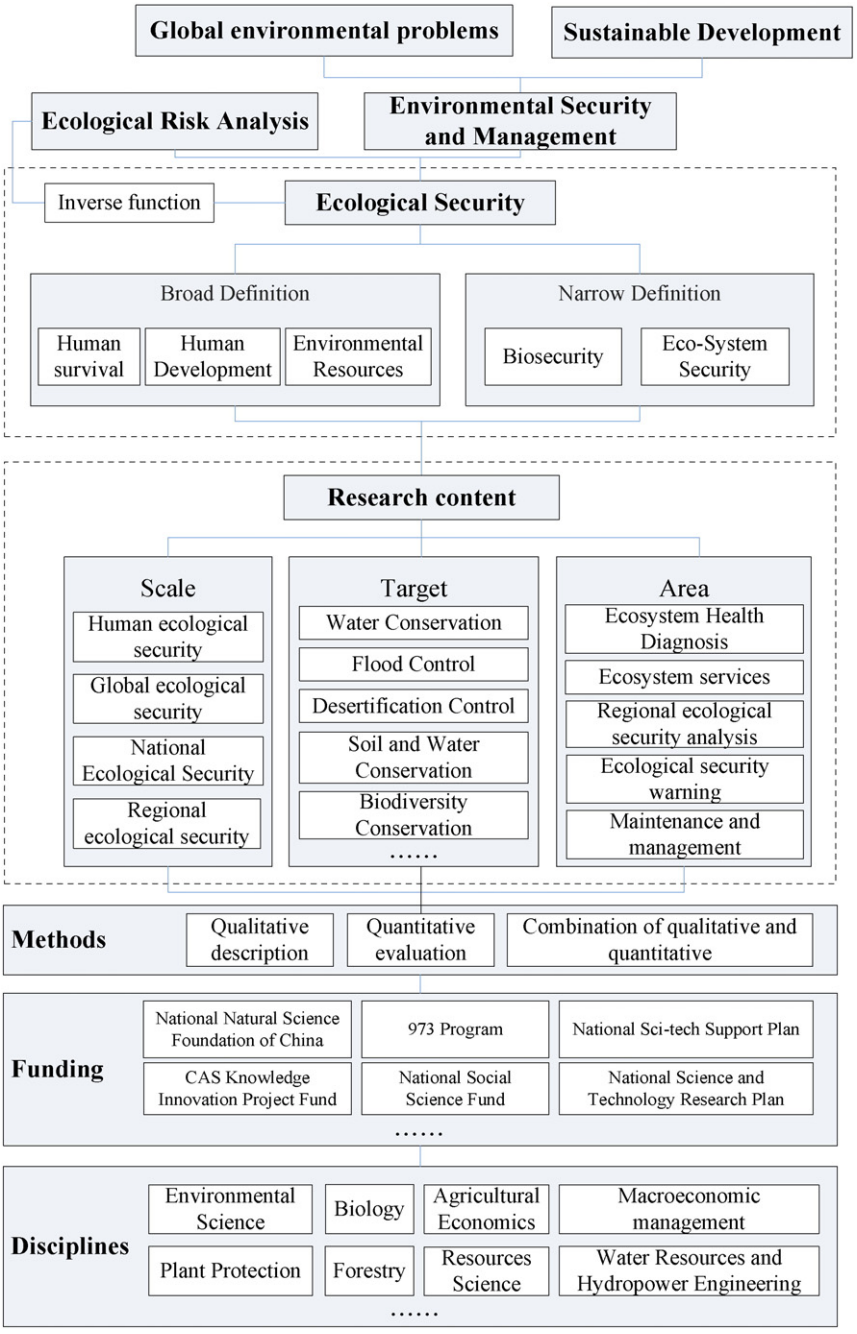

Fig. 4. Theoretical framework of the ecological security.

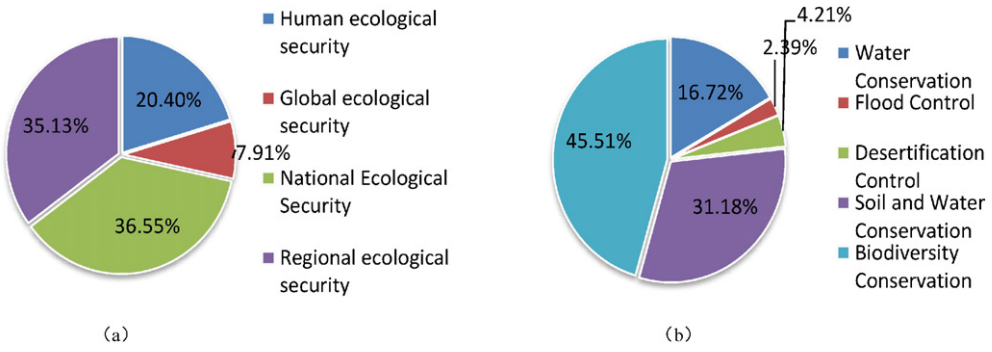

Fig. 5. Articles on ecological security research: (a) different scales; (b) different research objectives.

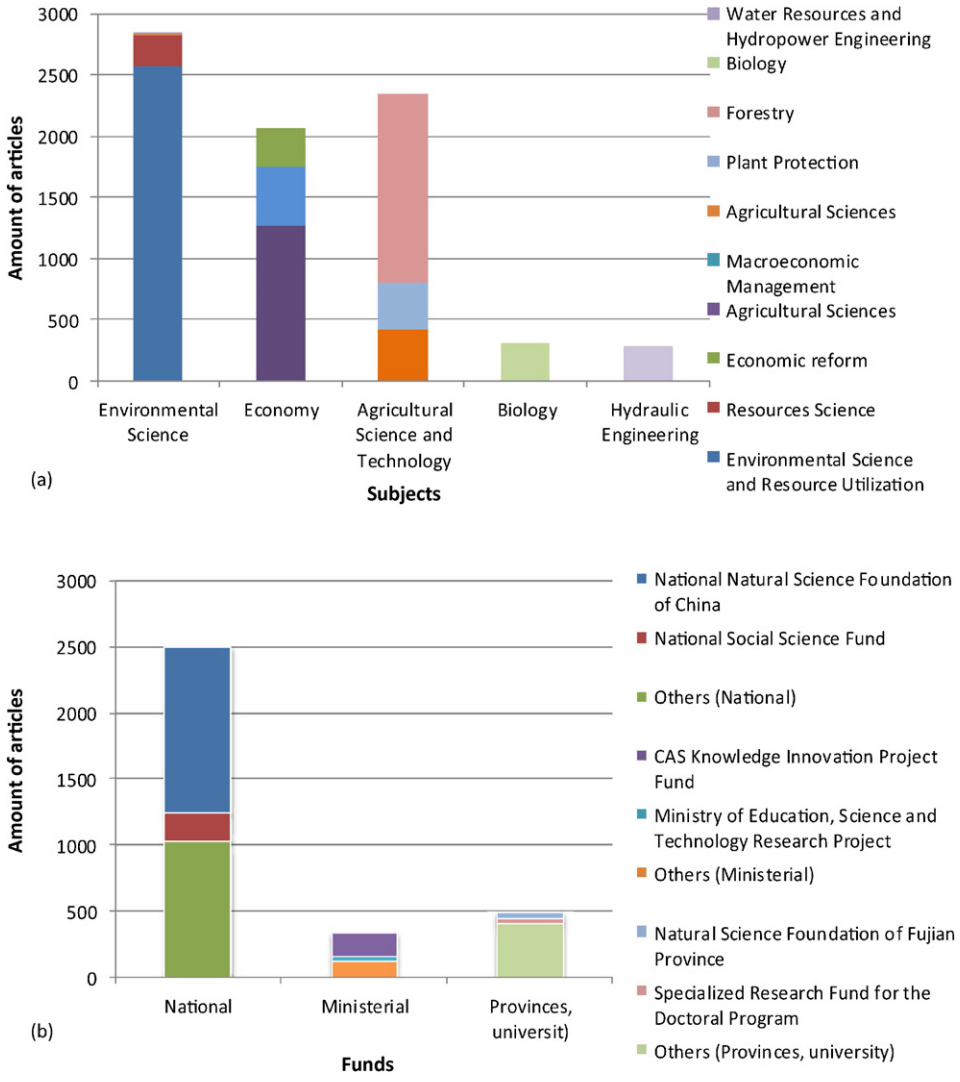

Fig. 6. Distribution of ecological security research: (a) subjects; (b) funds.

security assessment, ecological risk assessment, ecological vulnerability assessment and ecosystem services assessment. The research focus is still to establish evaluation index system and select evaluation model. Ecological security protection and management account for 27.52% of the total, including ecological security management, ecological protection and restoration. In CNKI, using 'ecological security management' as the topic word to search for papers, there are only 40 relevant papers, which indicates that ecological security management system in our

Table 1
Contents of ecology security research achievements.

Research hotspots	Keywords	Amount (proportion)	Research areas
Ecological security analysis and assessment	Ecological security, ecosystem health, evaluation model/index, country/region/city, GIS	2537 (52.33%)	Ecological security assessment
	Ecological risk, regional ecological risk, index system, evaluation model, heavy metals, sediments		Ecological risk assessment
	Ecological risk, ecosystem sensitivity/vulnerability assessment model/index, country/region/city, GIS		Ecological vulnerability assessment
	Ecological environment, environmental security, biodiversity, ecosystem services		Ecosystem services assessment
Ecological security prevention and warning	Ecological risk prevention system, risk sources, risk receptors	452 (9.32%)	Ecological risk prevention
	Ecological risk prevention system, warning mechanisms/systems		Ecological security warning
	Dynamic, monitoring, natural disasters, geological disasters		Ecological security monitoring
Ecological security pattern optimization	Ecological functions, connectivity, nodes, corridors	525 (10.83%)	Ecological network Planning
	Sustainable, land use, urban space, green/ecological infrastructure, planning/optimization		Urban spatial planning/optimization
	Optimization/planning, biodiversity, GIS, ecosystem structure		Ecological security pattern
Ecological security protection and management	Natural ecosystem management, social environmental management, environmental issues	1334 (27.52%)	Ecological security management
	Sustainable development, ecological restoration, species diversity		Ecological protection and restoration

country is not consummate and mature, lack of a complete study of regional ecological security system maintenance and management, especially research on warning mechanisms and prevention mechanisms of risk management, therefore, it is of great importance to develop further study. While search for papers concerning 'ecological protection and restoration', 1294 papers are found, which indicates that China begin to focus on a win–win development model that environment and economy are mutually beneficial, and also pay attention to symbiosis between man and nature. Furthermore, it also shows that our research system and management mechanism of disaster management and ecological restoration are comparatively mature. Ecological security pattern accounts for 10.83%, including three main research areas: ecological network planning, urban spatial planning and ecological security pattern. The study involved areas include nature reserves, scenic spots, ecologically fragile areas, rapid economic development region and major projects, where rapid economic development region is the focus of the study [26]. In contrast, ecological security and warning merely accounts for 9.32%, including ecological risk prevention, ecological security warning and ecological security monitoring. In CNKI, respectively taking 'ecological risk prevention', 'ecological security warning' and 'ecological security monitoring' as topic words to search, obtain relevant papers 132, 262 and 58, a total of 452. It can be seen from the data of four research areas above that currently ecological security assessment is the research hotspot, while ecological security warning and ecological security management system still lags behind, in the future it needs to be given more attention and research efforts .

In addition to topic words, keyword indexing is a highly generalization of a paper that can reflect the quality of academic papers and degree of standardization. Keywords with higher frequency often are positively correlated with the hot issues or focus issues in academic development [28]. Import the above papers into analysis software Endnote X6 and extract keywords. The top ten keywords are 'ecological security', 'ecological risk', 'heavy metal', 'sustainable development', 'sediment', 'ecological risk assessment', 'countermeasures', 'evaluation', 'environment' and 'index system'. The 'heavy metal', 'deposits', 'ecological risk assessment,' 'evaluation' and 'index system' belong to the contents of ecological risk assessment. It also proves that ecological risk assessment is the research hotspot.

3. Progress of four ecological security research hotspots

3.1. Ecological risk assessment and ecological security

Ecological risk and ecological security are mutually inverse functions [8]. Ecological risk assessment is to analyze and evaluate the stress degree of ecological environment or regional ecosystem, or the uncertainty of events. Moreover, it identifies risk-averse approaches and maintains the stability of ecological environment. Ecological security assessment is to evaluate the reliability of ecological environment to maintain the security status and the development trends, and to prevent the occurrence of uncertain events, protect and improve the environmental security [29].

Ecological risk assessment includes two aspects: ecological environment security analysis and ecological security assessment [30]. Ecological environment security analysis mainly focuses on natural environment analysis and social environment analysis. Environmental analysis can be launched from natural ecosystems, ecological landscape and ecological risk, while social environment analysis involves the political and national interests, diplomatic, economic globalization, laws and other aspects. Among them, the ecological risk assessment is the primary means of ecological security analysis, originated in human health assessment, which was conducted to protect human from the threat of chemical exposure and the environmental health assessment, aimed to analyze harmful effects of pollutants on ecosystems or some component [19–21]. Nevertheless, ecological security assessment has yet to form a comprehensive, systematic evaluation system. Commonly used index system includes single factor evaluation index and multi-factor comprehensive evaluation index. Most single factor index, which aim at the risk assessment for environmental pollution and toxicological hazards and the evaluation of micro-ecosystem quality and healthy, are key biological factors or environmental factors that are set up to characterize the level of system security [6,31]. Multi-factor comprehensive evaluation index system includes indexes of biological and environmental resources and life support systems that have effects on the socio-economic and human health. Commonly used indicator systems include PSR model (pressure–state–response), the extended and revised models of PSR model, etc. With the further study of ecological security, evaluation method has also been considerably developed, from conceptual, exploratory qualitative description to quantitative evaluation. Evaluation methods currently used are shown in Table 2.

3.2. Ecological security warning

Ecological security warning means to make predictions for reverse evolution, degradation and deterioration of environmental quality and ecosystem, then carry out ecological security warning, namely issue ecological security crisis alert or warning in advance [39,40], including the ecological risk warning. Ecological risk warning refers to predictions, analysis and evaluation of external influences on the ecosystem caused by engineering construction, resources development, territorial management and other human activities or natural disasters [35]. Zhou and Meng [36] proposed the establishment of a long-term dynamic monitoring mechanism for the risk prevention before the arrival of the risk. At the same time obtain different levels of risk areas according to the results of ecological risk analysis and evaluation; therefore, establish a grading warning mechanism. Zang [35] based on the ecological risk assessment and prediction, conducted warning analysis of ecological environment in Daqing City. Wang Jun [37] and Wang Bo [38], respectively, tested the soil heavy metals in Shanghai Chongming Island and Dayanghan urban wetland park, evaluated the soil quality, and carried out ecological risk of warning assessment aimed at heavy metals in soil.

Ecological security warning is a complex statistical prediction process, requires a combination of warning theory and ecological security assessment system to establish warning assessment index system, rationally design the structure of warning system, and form multi-level parallel warning subsystem [39]. As early as the 1990s Fu [41] proposed that regional ecological environment warning is the evaluation, prediction and warning of the ecological consequences of regional resource development and utilization, the changes in regional ecological environmental quality and the coordinated development of environment and socio-economy. Xu [34], applying ecological ecotone theory to analyze the ecological environmental condition of the Yellow River Delta, proposed calculating formula of environmental potential index. Also he conducted the status evaluation and warning research of the ecological environment in Yellow River Delta.

With the emphasis on ecological security, domestic scholars have exerted great effort to research 'ecological security warning'. Construction of ecological security warning index system is the basis for the establishment of a warning mechanism. He Yan [42] took Shanghai as example, employed 'state–pressure–response' index system to discriminate the ecological security risk degree, risk sources in water environment from the perspective of time and space distribution, established warning system and came up with countermeasures to response the possible water resource exhaustion and environmental crisis. Hao [43] analyzed the meaning, classification and characteristics of ecological security warning in the ecological security system, and built basic principles, index system and content elements for ecological security warning system in Hebei Province. Wang [44] proposed warning index calculation method; Guan and Xie [45] from the perspective of regional integrated warning, created a desertification hazards warning model including ecological vulnerability in desertification areas and

Table 2
Methods of ecology security assessment.

Models	Methods	Feature	Case
Mathematical model	Comprehensive Index	Obtaining ecological security index by the mathematical model, this method is comprehensive, holistic and hierarchical	Quantitative evaluation of ecological security status and trends: a case study of Guangdong Province, China
	Analytic hierarchy process (AHP)	Using less quantitative information to make the decision-making process mathematical, but it is arbitrary and is difficult to accurately reflect the actual situation	Study on assessment of the regional eco-security based on PSR—as an example of Yubei District in Chongqing
	Gray correlation method	According to various factors' sample data, use gray correlation to describe the strength, size and order of the relationship among factors	The ecological security evaluation of small watershed based on entropy weight and Gray correlation analysis
	Fuzzy comprehensive analysis	By constructing the hierarchical fuzzy subset to quantify the fuzzy indicators, which reflect the evaluated things, and then use the fuzzy transformation to synthesize the indicators	Application of entropy weight and fuzzy synthetic evaluation in urban ecological security assessment
	Matter element analysis	Mainly used to solve complex, incompatible problems, suitable for multi-factor evaluation	Evaluation of land eco-security based on matter element analysis
	Principal component analysis	Use the idea of dimension reduction, turn the multi-index into a few comprehensive index, and reduce variable	Ecological safety evaluation of land use in Jian City based on the principal component analysis
Ecological model	Ecological footprint	Computing is simple and practical, and by the method it is easier to compare human demand for ecological space with the Earth's limited supply of space	EFAA (Ecological Footprint Analysis Approach) based on city ecological security
	Landscape analysis	From a quantitative description of the spatial structure of the landscape to establish the landscape structure function model and relevant evaluation index	Spatial neighboring characteristics among patch types in oasis and its ecological security
	Ecological carrying capacity	Determine whether the ecological load condition exceeds the system carrying capacity	Eco-security capacity in Yunyang County
	Ecological security pattern	Some potential landscape spatial pattern	Security patterns and surface model in landscape ecological planning [27]
Digital terrain model		Combining RS with GIS and using raster data structure, it is easily superimposed and has simple logic operations	Comprehensive assessment and mapping of the regional ecological safety—a case study of Zhongxian County, Chongqing City
Simulation model		Usually there are spatial model and non-spatial model that describes the behavior characteristics of the environment system or system elements, or the effect human activities have on ecosystems	Land use change simulation on the edge of metropolis—a case study of Changping District in Beijing
Ecological risk	Health risk assessment	Apply toxicology to environment research, and use ecotoxicology in the laboratory or in the field to study the response relationship between toxic substances and ecological environment	Health risk assessment on heavy metals in soil based on GIS—a case study in Cixi City of Zejiang Province
	EIA index	Combine ecosystems and ecology to identify the type of risks, then build ecological risk assessment index system	A risk assessment system for alien plant bio-invasion in Xiamen, China [32]
	Spatial statistical or geo-statistical method	Used to study the distribution, class structure, change characteristics of spatial risk	Regional eco risk analysis of based on landscape structure and spatial statistics
	Relative risk model (RRM)	Mainly used in regional ecological risk assessment	A regional multiple stressor risk assessment of the Codoms Creek watershed applying the relative risk model [33]

hazards evaluation when desertification occurs. In the theory formation and practical development stage, many scholars carry out practice-based warning research on ecological environment. However, compared with the ecological security assessment, ecological security warning remains to be further and detailed studied in the future.

3.3. Ecological security protection and restoration

Ecological security protection and restoration specifically includes two parts: ecological protection and ecological restoration. Currently domestic research on ecological protection are mostly conceptual and exploratory, specific protection measures, method system and ecological protection compensation mechanism need to be further explored. In the view of theory, domestic scholars have active researches on necessity and practical significance of ecological protection, and on regional ecological compensation theory and methods. As for practice aspect, researchers carry out the correlation study on how to coordinate the development of ecological protection and hydropower development, resource utilization, tourism management, land use change and other aspects, including the study of forest resources, water resources, grassland resources, wetlands and biodiversity. In Hu Yi's paper [46], a method is proposed to build ecological protection compensation mechanism of inter-regional watershed, and he thinks that the calculation of compensation funds and sharing mechanism are the key points of ecological compensation. Chu [47], taking Tianmu Mountain Nature Reserve for example, proposes the establishment of reasonable compensation mechanism and the implementation of different land policies in different functional areas. Furthermore, regard the eco-tourism as a breakthrough to resolve land use conflicts and to coordinate the conflict between land use and ecological protection.

Ecological restoration refers to the management and operation that restore the damaged ecosystem to or close to the natural conditions before interference [48]. Study areas involve mining wasteland, industrial wasteland, landfills, rivers, lakes, wetlands and a series of areas that are ecological damaged and its ecosystem is seriously degraded. Apart from the ecosystem self-maintenance and the strength of resistance that responsible for the degradation of ecosystem, the more direct reason is the external driving force, namely interference [49]. Therefore, human activities, no matter in the degradation process of an ecosystem or under restoration, are factors that cannot be ignored. At present, domestic research on ecological restoration has fruitful achievements, ranging from wasteland landscape regeneration to vegetation restoration. Zhang [50] carried out the research to discuss the methods and reconstructive measure for river ecosystem restoration, from the aspects of

river flood control, river water environment improvement, shoreline morphology restoration, ecology embankment design, and river buffer zone design. From the perspective of ecological economy, Shen [51] conducted wetland restoration, proposed to restoration planning strategy, such as adjust the wetland ecosystem structure and strengthen wetland protection and management, to restore the wetland biodiversity.

3.4. Ecological security pattern

Ecological security pattern is able to maintain the integrity of the ecosystem structure, function and processes. At the same time it can achieve effective control and continuous improvement of the ecological environment problems. Rational optimization of ecological security pattern helps prevent and avoid ecological risk, reduce the negative impact that environmental degradation have. In terms of ecological of security pattern, domestic scholars have made relevant discussion from both basic theoretical and practical perspective [52,53] (Table 3). Yu [26] claimed that the construction of ecological security pattern is an important approach and basic protection to achieve the regional and urban ecological security. Based on the application of landscape security pattern theory and methods, he also discussed the construction approach of regional and urban ecological security. In addition he proposed the land use pattern and implementation strategies that can assure the long-term ecological security of Beijing. Chen [54] analyzed the type and characteristic of engineering construction, and its impact on regional ecological environment. Then on this basis, he proposed basic principles and methods of the restoration and construction of ecological security pattern in major projects.

4. Discussion

4.1. Research frontier of ecological security in western countries

Import all the 11928 papers searched in Web of Science and CNKI into analysis software CiteSpace II to analyze the research frontier and hotspot. According to the result, current ecological security research abroad focus on ecological security management, ecological risk assessment, biodiversity protection and landscape security pattern. Therefore, it shows that the ecological security research abroad has covered the evaluation, management, pattern, etc. multiple levels with a wide research field. Besides, management has formed a mature system. However, only import papers from China into CiteSpace II, the result shows that domestic ecological security research hotspots include pollution or contamination, heavy metal, sediments and ecological risk assessment, which means that in China ecological security is still mainly focused on ecological risk and ecological security assessment.

Based on the long-term ecological security research, the United States, Britain, Germany, the European Union and the United Nations Environment Programme formed specialized regulations and guidelines to ensure the ecological security. In the United States, the U.S. Environmental Protection Agency (EPA) formed the outline of ecological risk assessment to improve the quality and consistency of ecological risk assessment in the late 1990s. Currently, EPA have developed a

Table 3
Ecology security pattern research.

Research content		Feature	Case
Theoretical basis	Optimal landscape pattern	Retain small natural plaques in the development areas and built-up areas	Land mosaics: the ecology of landscapes and regions [55]
	Landscape security pattern	Landscape process is a process that achieve landscape control and cover by overcoming the space resistance	On the basic concepts and contents of ecological security [8]
	Ecological security pattern	Some potential landscape spatial pattern	Security patterns and surface model in landscape ecological planning [27]
Methods	System dynamics	To reflect the interaction among complex system structure, function and dynamic behavior	Study on the system dynamics about the adjustment of the land use structure in the arid zones—a case study of Tulufan City, Xinjiang [56]
	Scenario	By analyzing the characteristics and driving force of the most uncertain and most influential factor that affect the future to understand the future	The function of ecological security patterns as an urban growth framework in Beijing [27]
	Interference analysis	Analyzing the interference caused by spatial growth to ecosystem will provide support to exclude the human interference or to optimize the ecological patterns and processes through useful human interference	A study on space method of urban pattern for ecological security [57]
	GAP analysis	Using GIS, satellite image and field survey data to determine biodiversity conservation gaps, omission region and the areas need protective action	A method for assessing regional ecological security pattern to conserve biodiversity—GAP analysis [58]
	Landscape dynamic analysis	Analyze landscape change based on plaques to get information of drive mechanism of landscape and its future development trend	The landscape pattern changes and simulation in Lushan Mountain national park [59]
	Minimal cumulative resistance (MCR) model	Reflect the potential movement and trend of species	Research on applying minimal cumulative resistance model in urban land ecological suitability assessment: as an example of Xiamen City [60]
Study areas	Nature reserves	Taking every level or node of biological systems as the protected object, connect the nodes into a whole protective network	On the methods of ecological security design for nature reserves [61]
	Scenic spots	Unique cultural landscape of human interaction with the natural landscape activities	Construction and organization of the landscape networks: discussion on the landscape ecological planning of the Beijing Shihua cave scenic area [62]
	Ecologically fragile areas	Anti-interference capability is weak and is sensitive to global climate change. Also its spatial and temporal fluctuations are strong and it has significant edge effects and high environmental heterogeneity	Changes of landscape pattern between 1986 and 2000 in Jiuquan oasis, Heihe River basin [63]
	Rapid economic development region	Through human initiative intervention to ensure the stability of the ecosystems structure and the continuity of function while meeting the needs of economic development	Establishing the ecological security pattern in rapidly developing regions—a case in the AYRAP [64]
	Major projects	The basic principles of ecological security construction: dual security, regional, multi-scale, interactive, targeted	Principles and methodology for ecological rehabilitation and security pattern design in key project construction [54]

corresponding evaluation methods, models and databases for air, water, climate change, ecosystem health, sustainable development, land and waste management and various other topics, while China has not yet developed specialized guides and research methods aimed at specific ecological problems. In addition, EPA have conducted studies of ecological security practice in the United States and throughout the Americas, and carried out a project called 'Environmental Monitoring and Assessment Program' (EMAP). EMAP was a research program that measured the current and changing conditions of the nation's ecological resources, aimed to establish the scientific basis for eco-environmental monitoring and ecological risk assessment. At the same time, it enhanced the awareness of ecosystem integrity and dynamic through large-scale regional projects and guided monitoring programs of countries, organizations as well as departments. In short, through the integration of ecological security research achievements, ecological security research and practice abroad formed regulations and guidelines concerning ecological security management, meanwhile emphasizing the dynamic monitoring, assessment and warning of the ecological environment, which has a certain reference significance for China's ecological security research in the future.

4.2. Suggestion for future ecological security researches in China

In China, ecological security researches began before the last two decades, so the theories, methods and case studies have a long way to go. According to the statistics and analysis of literatures concerning ecological security, it can be concluded that currently China's ecological security research focuses on ecological security assessment, in which the key points are the index selection and evaluation methods [65].

The report to the Eighteenth National Congress of China came up with the idea that 'the construction of ecological civilization is the long-term plan concerning people's welfare and the nation's future'. In addition, it included the construction of ecological civilization into the 'five in one' overall layout for the first time, which can have a positive effect on promoting the development of ecological security research. By contrast with the research frontier and trend of ecological security in west countries, it can be predicted that in the future China's ecological security research will be strengthened from the following aspects:

(1) To form the theoretical system of ecological security and to integrate the technical methods
In the future, ecological security research may establish and improve the index selection criteria and evaluation methods, particularly establish ecological security assessment specifications and standards that may lay the foundation for the establishment of ecological risk warning mechanism and the optimization of ecological security pattern. Some measures, such as dynamic monitoring and supervision of ecological environment, improvement of the methods of quantitative analysis, using mathematical models, digital terrain model and creating a composite evaluation model, can help strengthen the uncertainty analysis and treatment in ecological security research [66]. Also, it is necessary to combine landscape ecology, geography and other related

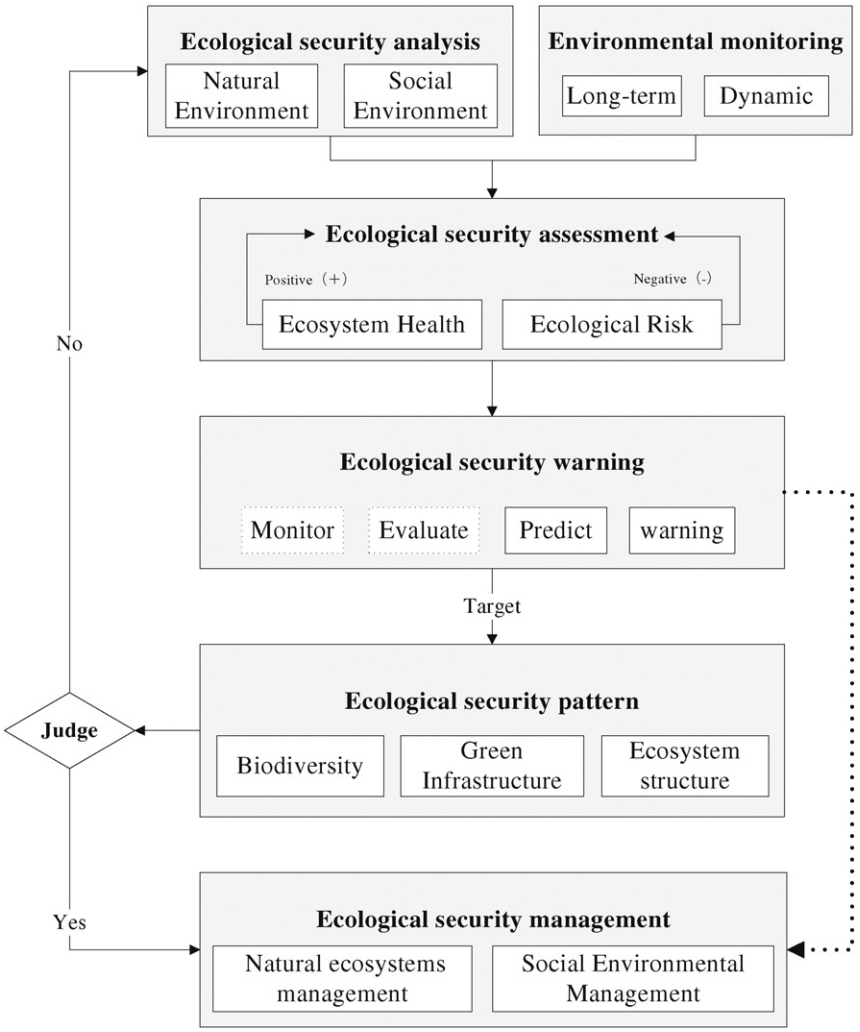

Fig. 7. Research system of the ecological security.

theories with ecological security research. Then, rationally apply it into the establishment of warning mechanism and the evaluation and design of ecological security pattern, which can lead to the formation of a theoretical system with multi-disciplinary support. Combined with the conceptual model, mathematical model and spatial model we can form a research system: analysis–assessment–warning–pattern optimization (Fig. 7).

(2) To improve ecological security warning mechanisms and environmental monitoring

Ecological security warning includes ecological security assessment and warning. It requires a combination of these two parts to set up warning index system, as well as the rational design of the warning system structure. Based on the specific condition of each region to carry out the warning analysis and to establish regional, watershed, provincial and national ecological security warning system, ecological security warning researches mostly are the evaluation of current condition, lacking warning prediction, whereas warning is a vital part of the ecological security research system. Thus, future research is supposed to pay more attention to the temporal dynamics of ecological security research [67]. Furthermore, future research will help to improve the prediction precision and accuracy of methods and models. In addition, it is of great importance to improve the management measures like laws, regulations, policies and public education, and to further promote the study of ecological risk prevention.

(3) To improve ecological security maintenance and management system

It has a great significance of maintenance and management of ecological security for a region, nation and even the whole world. It is the key to achieve sustainable development and long-term stability. Nevertheless the maintenance and management system of ecological security is not perfect. Therefore, under the theoretical system of multi-disciplinary support, future research may fully integrate the ecological security system from all perspectives of social, economic, natural and others and scientifically maintain and manage ecological security.

As a result, ecological security warning and ecological security patterns will be given more attention in the future researches. The correlation research will develop from the previously exploratory qualitative research and status analysis to the quantitative research and dynamic warning. At the same time, by using '3S' space technology and combining with the disciplines/professions of geography, environmental science, ecology, landscape ecology, restoration ecology and economics, there may be a stronger establishment of grounded ecological security knowledge. Therefore, the ecological security evaluation index system and grading standards of the evaluation results will be gradually integrated and improved plus the dynamic evaluation, simulation and warning research will be strengthened [6].

Acknowledgment

This research is supported by The National Natural Science Foundation of China (NO. 41001112).

References

[1] C.X. Zou, W.S. Shen, Advances in ecological security, Rural Eco-Environ. 19 (1) (2003) 56–59.
[2] D.N. Xiao, F.J. Xie, J.B. Wei, Regional ecological construction and mission of landscape ecology, Chin. J. Appl. Ecol. 15 (10) (2004) 1731–1736.
[3] Y. Liu, J.J. Meng, L.K. Zhu, Progress in the research on regional ecological security pattern, Acta Ecol. Sin. 30 (24) (2010) 6980–6989.
[4] K.M. Ma, B.J. Fu, X.Y. Li, W.B. Guan, The regional pattern for ecological security (RPES): the concept and theoretical basis, Acta Ecol. Sin. 24 (4) (2004) 761–768.
[5] X.Y. Li, K.M. Ma, B.J. Fu, S.K. Niu, The regional pattern for ecological security (RPES): designing principles and method, Acta Ecol. Sin. 24 (5) (2004) 1055–1062.
[6] C.L. He, H. Rao, X.Q. Zhao, Advances in ecological security assessment research in China, Yunnan Geog. Environ. Res. 22 (3) (2010) 104–110.
[7] S.B. Fang, D.N. Xiao, S.Q. An, Regional ecosecurity pattern in urban area based on land use analysis: a case study in Lanzhou, Chin. J. Appl. Ecol. 16 (12) (2005) 2284–2290.
[8] D.N. Xiao, W.B. Chen, F.L. Guo, On the basic concepts and contents of ecological security, Chin. J. Appl. Ecol. 13 (3) (2002) 354–358.
[9] K.J. Yu, Landscape ecological security patterns in biological conservation, Acta Ecol. Sin. 19 (1) (1999) 8–15.
[10] K.J. Yu, The effectiveness of approaches towards sustainable environment and development planning, J. Nat. Resour. 13 (1) (1998) 8–15.
[11] S.H. Cui, H.S. Hong, Y.F. Huang, X.Z. Xue, Progress of the ecological security research, Acta Ecol. Sin. 25 (4) (2005) 861–868.
[12] F.H. Guo, On the relationship between ecology-protection forestry and the national ecological security, J. Beijing For. Univ. 22 (1) (2000) 101–102.
[13] X.F. Jiang, Challenge of entering WTO to China's ecological security and strategic countermeasures, Environ. Prot. 10 (2000) 23–25.
[14] K.J. Yu, H.L. Li, D.H. Li, Q. Qiao, X.S. Xi, National scale ecological security pattern, Acta Ecol. Sin. 29 (10) (2009) 5163–5175.
[15] H.M. Wang, H.E. Wang, H.Y. Sun, X.L. Wang, X.Y. Liao, Z.J. Chen, X.W. Li, Assessment of the ecological security in the three gorges reservoir area by using the ecological footprint method, J. Mt. Sci. 9 (6) (2012) 891–900.
[16] Y.H. Jia, J. Zhao, Z.R. Nan, C.Y. Zhao, S.L. Wang, Ecological safety assessment of grassland based on entropy-right method: a case study of Gansu pastoral area, Chin. J. Ecol. 25 (8) (2006) 1003–1008.
[17] Z.Y. Fu, X.G. Xu, H.P. Lin, X.L. Wang, Regional ecological risk assessment of in the Liaohe River Delta wetlands, Acta Ecol. Sin. 21 (3) (2001) 365–373.
[18] X.G. Xu, H.P. Lin, Z.Y. Fu, R.C. Bu, Regional ecological risk assessment of wetland in the Huanghe River Delta, Acta Sci. Nat. Univ. Pekin. 37 (1) (2001) 121–127.
[19] G.Q. Li, S.Q. An, X.L. Chen, J.L. Zhang, J.H. Zhang, J.K. Tan, X.L. Zhu, A summary on ecological risk assessment, Chin. J. Ecol. 18 (4) (1999) 57–64.
[20] L. Dai, Z.J. Dai, Ecological risk assessment research, Environ.Sci. Trends 3 (2001) 7–10.
[21] H.F. Cao, Y.W. Shen, Brief review: ecological risk assessment research, Environ. Chem. 10 (3) (1991) 26–30.
[22] S.L. Peng, Y.R. Hao, H.F. Lu, B.S. Wang, The meaning and scales of ecological security, Acta Sci. Nat. Univ. Pekin. 43 (6) (2004) 27–31.
[23] J.P. Yang, J.B. Lu, Systematic Analysis of Ecological Security, Chemical Industry Press, Beijing, 2002.
[24] Q.Y. Zhang, X.J. He, F. Qing, Z.Y. Zhang, A.Y. Shen, Impacts of global warming of ecosecurity in China, Chin. J. Nat. 24 (4) (2002) 212–215.
[25] W.S. Zheng, J.F. Wang, G.F. Sun, Strategic countermeasure and globality of ecological security problem, J. Harbin Univ. 23 (7) (2002) 120–122.
[26] K.J. Yu, Security patterns and surface model in landscape ecological planning, Landsc. Urban Plan. 36 (1) (1996) 1–17.
[27] K.J. Yu, S.S. Wang, D.H. Li, C.B. Li, The function of ecological security patterns as an urban growth framework in Beijing, Acta Ecol. Sin. 29 (3) (2009) 1189–1204.
[28] N. Chen, F.M. Zhang, W.H. Xu, H.M. Wang, Statistical analysis of keywords in papers in 'Journal of Information' from 2001 to 2009, J. Libr. Inf. Sci. Agric. 23 (3) (2011) 83–86.
[29] Y.L. Lu, X.G. Xu, Advances in ecological risk assessment and eco-security assessment methods and prospects, J. Saf. Environ. 10 (1) (2010) 132–137.
[30] X. Chen, C.H. Zhou, Review of the studies on ecological security, Prog. Geogr. 24 (6) (2005) 8–20.
[31] H. Liu, H. Wang, K. Liu, A review of ecological security assessment and relevant methods in China, Environ. Prot. 8 (2005) 34–37.
[32] J. Ou, C.Y. Lu, D.K. O'toole, A risk assessment system for alien plant bio-invasion in Xiamen, China, J. Environ. Sci. 20 (8) (2008) 989–997.
[33] A.M. Obery, W.G. Landis, A regional multiple stressor risk assessment of the Codorus Creek Watershed applying the relative risk model, Hum. Ecol. Risk. Assess. 8 (2) (2002) 405–428.
[34] X.G. Xu, Study on evaluation and pre-warning of ecological environment in the Yellow River Delta, Acta Ecol. Sin. 16 (5) (1996) 461–468.
[35] S.Y. Zang, X. Liang, D.B. Han, Z.K. Feng, Ecological risk warning and management countermeasures based on 3S technology in Daqing City, northeastern China, J. Beijing For. Univ. 30 (S1) (2008) 152–156.
[36] P. Zhou, J.J. Meng, Progress of ecological risk management research: a review, Acta Ecol. Sin. 29 (4) (2009) 2097–2106.
[37] J. Wang, Z.L. Chen, C. Wang, M.W. Ye, J. Shen, Z.L. Nie, Heavy metal content and ecological risk warning assessment of vegetable soils in Chongming Island, Shanghai city, Chin. J. Environ. Sci. 28 (3) (2007) 647–653.
[38] B. Wang, C.W. Feng, X.Q. Liu, S.B. Zhou, W.H. Dai, Heavy metal pollution and the assessment of its ecological risk early warning in Dayanghan Metropolitan Wetland Park, Chin. J. Soil Sci. 44 (2) (2013) 484–489.
[39] W. Dong, X.H. Zhang, D. Su, J.X. Gao, Z.A. Jiang, Progress on forewarning of ecological security, Environ. Sci. Technol. 30 (12) (2007) 97–99.
[40] G.J. Chen, An approach on environmental warning, Chongqing Environ. Sci. 18 (5) (1996) 1–4.
[41] B.J. Fu, Early warning theory on regional eco-environmental issues and its application, Chin. J. Appl. Ecol. 4 (4) (1993) 436–439.
[42] Y. He, W.H. You, The ecological alarm assessment and analysis of the water environment in Shanghai, Safety Environ. Eng. 11 (4) (2004) 1–4.
[43] D.H. Hao, J.A. Xie, Constructing eco-security early-warning system in Hebei Province, Contemp. Econ. Manag. 27 (1) (2005) 59–62.
[44] G. Wang, W. Wu, Research on region ecological security early warning index: a case of Liaohe River watershed, Acta Ecol. Sin. 28 (8) (2008) 3535–3542.

[45] W.B. Guan, C.H. Xie, C.P. Li, M.S. Ye, B.P. Sun, G.D. Ding, Principles and assessing methods for early warning of desertification damages, J. Beijing For. Univ. 25 (3) (2003) 79–83.
[46] Y. Hu, Y.S. Li, The establishment of the Inter-catchment's ecological compensation system, J. Fujian Norm. Univ. 6 (2006) 53–58.
[47] S.J. Chu, G. Xu, Conflictive and coordinate mechanism in land use and ecosystem conservation in mountainous area of north Zhejiang—in Case of Tianmu Mountain Nature Reserve, Resour. Environ. Yangtze Basin 13 (1) (2004) 24–29.
[48] Z.P. Deng, Q.Q. Yu, W. Zu, Y.K. Zhang, Application of the ecological restoration theory in the construction of planting landscape design of Urban Wetland Park—a case in Xixi National Wetland Park, J. Northwest. For. Univ. 24 (6) (2009) 162–165 (176–176).
[49] W.K. Bao, Q.H. Chen, The degraded processes and features of ecosystem, Chin. J. Ecol. 18 (2) (1999) 36–42.
[50] W.D. Zhang, Y.X. Zhai, River landscape ecological design in North China, Planners 26 (S1) (2010) 44–48.
[51] S.Y. Shen, H.H. Zeng, W.W. Wang, The exploration of ecological restoration planning for the international key wetland—Honghu Wetland in Hubei Province, Chin. Landsc. Archit. 25 (2) (2009) 46–50.
[52] R. Li, T.H. He, Basic theory and practical significance of the construction of regional pattern for ecological security, J. Anhui Agric. Sci. 40 (10) (2012) 6113–6115.
[53] X.F. Ren, S.H. Ren, Study on planning principle and method of urban pattern for ecological security, Chin. Landsc. Archit. 25 (7) (2009) 73–77.
[54] L.D. Chen, Y.H. Lv, H.Y. Tian, Q. Shi, Principles and methodology for ecological rehabilitation and security pattern design in key project construction, Chin. J. Appl. Ecol. 18 (3) (2007) 674–680.
[55] R.T.T. Forman, Land Mosaics: The Ecology of Landscapes and Regions, Cambridge University Press, 1995.
[56] L.J. Wang, H.L. He, B.Z. Peng, H.S. Bao, Study on the system dynamics about the adjustment of the land use structure in the arid zones—a case study of Tulufan City, Xinjiang, Econ. Geogr. 17 (4) (1997) 43–48.
[57] H. Long, J.W. Wang, A study on space method of urban pattern for ecological security, Urban Plann. Forum 6 (2009) 99–104.
[58] B. Wang, W.B. Guang, J.A. Wu, K.M. Ma, G.H. Liu, X.L. Wang, A method for assessing regional ecological security pattern to conserve biodiversity—GAP analysis, Res. Soil Water Conserv. 13 (1) (2006) 192–196.
[59] H.S. Hu, M.C. Wei, J.G. Tang, F.Q. Zhang, Y.P. Zheng, The landscape pattern changes and simulation in Lushan Mountain national park, Acta Ecol. Sin. 27 (11) (2007) 4696–4706.
[60] X.F. Liu, J.M. Shu, L.B. Zhang, Research on applying minimal cumulative resistance model in urban land ecological suitability assessment: as an example of Xiamen City, Acta Ecol. Sin. 30 (2) (2010) 421–428.
[61] H.G. Xu, H.S. Bao, On the methods of ecological security design for nature reserves, Chin. J. Appl. Ecol. 15 (7) (2004) 1266–1270.
[62] K.J. Yu, G. Huang, D.H. Li, H.L. Liu, Construction and organization of the landscape networks: discussion on the landscape ecological planning of the Beijing Shihua cave scenic area, Urban Plann. Forum 3 (2005) 76–81.
[63] M. Guo, D.N. Xiao, X. Li, Changes of landscape pattern between 1986 and 2000 in Jiuquan oasis, Heihe River basin, Acta Ecol. Sin. 26 (2) (2006) 457–466.
[64] Z.Y. Li, G.S. Yang, Y.W. Dong, Establishing the ecological security pattern in rapidly developing regions—a case in the AYRAP, J. Nat. Resour. 22 (1) (2007) 106–113.
[65] S.L. Liu, B.S. Cui, M.X. Wen, S.K. Dong, Ecological effects and ecological security index system of major engineering project, Ecol. Environ. 16 (1) (2007) 234–238.
[66] F. Deng, Y.J. Yu, Z.J. Quan, Research progresses of regional ecological risk assessment, Environ. Sci. Technol. 34 (S1) (2011) 141–147.
[67] W.L. Li, Review of research on the ecological security in China, Safety Environ. Eng. 15 (3) (2008) 78–81 (86–86).