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REVIEW ARTICLE

Navigating ecological security research over the last 30 years: a scoping review

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Abstract
Intensification of human activities is pushing our use of ecosystems beyond thresholds of resiliency. Given the accelerating global crisis of ecological sustainability, there has been enormous growth in research related to ecological security. However, differences in opinions on ecological security have hindered understanding and effective applications of this concept. To understand the development of research on ecological security, we reviewed its achievements and limitations over the past 30 years from three dimensions: definition, evaluation method, and approach to identify measures to improve the ecological security level. We used the Web of Science search engine to retrieve peer-reviewed journal articles published from 1990 to 2021 containing the keywords "ecological security" or "ecological safety". There are three main ethical perspectives among the definitions of ecological security: nature-centric, human-centric, and eclectic; the human-centric view, which focuses on human well-being, is predominant in the field. Most studies employed the following three evaluation methods: quantitative comparison, composite indicators, and spatial analysis. However, the results of ecological security analyses were difficult to compare. Three main approaches (causality, correlation, and landscape) were used to identify the drivers of ecological security and propose measures for ensuring or improving ecological security. Owing to the complexity and heterogeneity of ecosystems, universally effective measures to ensure ecological security rarely exist. For the definition and evaluation of ecological security, a broader, non-anthropocentric perspective that incorporates the intrinsic value of non-humans in the context of cost–benefit, security–efficiency evaluations is essential. When proposing evaluation methods, the comparability of evaluation results should be given priority. To improve ecological security level, identifying the key drivers and/or potential optimal patterns of ecological security may be a promising solution.

Keywords Ecological security · Ecological evaluation · Ecological indicator · Landscape pattern · Ecosystem modeling

Introduction

Humans are intricately dependent on ecosystem services for every function and requirement of socio-economic systems (Marten 2001; Millennium Ecosystem Assessment 2005). The Industrial Revolution resulted in exponential increases in population, economic productivity and resource exploitation, which have had immense impacts on natural ecosystems (Rockström et al. 2009; Steffen et al. 2015a). Rapid industrialization, population explosion, and urbanization have cumulatively contributed to the over-exploitation of natural resources through complex feedback mechanisms in coupled socio-ecological systems (Cumming et al. 2014), thereby undermining the safe operating conditions for human societies (Steffen et al. 2015b).

Several terms have been proposed to describe the state of an ecosystem or to indicate the interaction between humans and nature. For example, "environmental security" was defined as "the state of human–environment dynamics that includes restoration of the environment damaged by human activities that could lead to social disorder and conflict" (Millennium Ecosystem Assessment 2005). Additionally, another commonly used term, "ecosystem health" was

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defined as "a concept that integrates environmental conditions with the impacts of anthropogenic activities to provide information for the sustainable use and management of natural resources" (Burkhard et al. 2008). "Ecological integrity" refers to whether an ecosystem has the capacity equivalent to a natural habitat to support the survival of organisms within it (Parrish et al. 2003).

In recent years, "ecological security" has received widespread attention and has produced a rapidly expanding body of literature (e.g., Hodson and Marvin 2009; Su et al. 2016; McDonald 2017). However, a widely accepted definition of ecological security does not exist currently. For example, some researchers have defined ecological security as "the secure state of an ecosystem that should ensure nearly every aspect in good condition, such as structure, function, and process" (e.g., Hu et al. 2019), while others believe that ecological security can be guaranteed by maintaining a threshold, e.g., a minimum level of ecological stock required to provide the supporting services (Millennium Ecosystem Assessment 2003). These definitions provide different connotations of and requirements for ecological security. Moreover, ecological security has also been widely defined from the perspective of supply and demand in economics. For example, Xu et al. (2014) proposed that ecological security is the degree to which the production of ecological resources meets human consumption demand. This definition implies that ecological security can be simply referred to as the relationship between the supply and demand of ecological resources. Further, only humans are considered on the demand side. This not only affects our understanding of the concept, but the differences in its definition can profoundly affect the evaluation method and possible measures to ensure ecological security.

These differences in the definition of ecological security consequently influence the methodology for evaluating its status and trend. For example, in some studies, the ecological security level was determined by calculating the supply and demand of ecological resources and their ratio (e.g., Xu et al. 2014; Guo and Wang 2019). Additionally, many studies have comprehensively reported the ecological security degree by establishing indicator systems that reflect the state of the natural ecosystems and social systems (e.g., Xu et al. 2019; Liu et al. 2021b). Spatial analysis methods driven by advances in geographic information system (GIS) technology are also increasingly used to evaluate ecological security (e.g., Liu et al. 2021a; Rao et al. 2021). Despite the proliferation of evaluation methods on ecological security, the differences in the applied methodologies have hindered effective decision-making because the results of different evaluation schemes cannot be easily compared, thereby making it difficult to accurately compare the ecological security status measured in different studies. Moreover, different approaches employed to determine suitable measures to improve ecological security for specific areas are also emerging. Some studies focused on driving or correlation factors of ecological security (e.g., Zhang et al. 2019), while some have focused on areas that significantly influence ecological security, e.g., ecological sources and corridors (e.g., Li et al. 2019). Different approaches that can be used for specific areas or scales are also worth discussing.

Overall, these contrasting views on ecological security may hinder our understanding and application of ecological security. To date, a critical literature review on ecological security has not been conducted. This paper is the first of its kind to provide a reference for the development of the concept of ecological security. This study aimed to extract the significant achievements and limitations from the aforementioned three dimensions of definition, evaluation method, and approach by conducting an extensive literature review of relevant studies in recent years that can pave the way for future research.

Materials and methods

The scoping review method, which is defined as a preliminary assessment of the potential size and scope of available research literature (Grant and Booth 2009), was used in this study. Scoping review is generally recommended when extensive literature has not been thoroughly reviewed or exhibits a complex or heterogeneous nature that makes a precise systematic review impossible (Peters et al. 2022). Unlike other types of reviews, such as systematic reviews, scoping reviews are more topic based rather than question based. As extensive, but diverse studies exist on ecological security, we believed that scoping review is suitable for this research topic. Furthermore, scoping review is especially useful in clarifying concepts, exploiting knowledge gaps, or highlighting potential problems (Munn et al. 2018; Lockwood et al. 2019), which are the main goals of this study.

We used the Web of Science search engine to retrieve peer-reviewed journal articles published between 1990 and 2021 containing the keywords "ecological security" or "ecological safety" in the titles. To save time and effort, the search scope was the core dataset of the Web of Science. Another criterion for selecting articles was that the main body and abstract of the articles must be written in English. 518 related articles were initially obtained by screening the keywords and publication year. Moreover, papers were retained if they included content on the definition, evaluation methods, or measures to ensure or improve ecological security. After examining their titles and abstracts, 35 articles were excluded owing to low relevance. Consequently, our literature pool was composed of the remaining 483 studies. By reading the abstracts of all these papers, they were marked with specific aspects of definitions, evaluation methods, approaches to improve ecological security, etc. Further, papers with similar definitions, evaluation methods, or approaches for improving ecological security were grouped together. Depending on the size of the group, 5–10 articles are randomly selected from each group to read through the full text. Finally, a total of 60 papers in the literature pool was examined in detail.

Figure 1 shows the frequency of the authorship of the papers in the literature pool, which is highly concentrated among a few nations. For example, 81.6% of all papers in the pool have a first author from China. This is followed by Russia as origin of the lead author of 11.6% of the papers in the pool. No other nation has more than 2% of the total papers written by a first author. Most of the other nations represented in the pool with first authors are from former Soviet nations such as Ukraine (seven papers) and Poland (six papers). India (four papers), USA (three papers), UK (two papers), and Vietnam (two papers) are the only other nations with multiple lead authored papers in the pool.

The time series of frequency of papers in the pool (Fig. 2) shows exponential growth in the field's publications since approximately 2004 when the rate of Chinese first-authored papers increases greatly. Prior to 2004, the majority of papers in the pool were written by authors from Russia. From 2004 to 2014 Chinese first authors were highly dominant. Russian authored papers increased proportionally from 2015 to 2020, but the large majority of papers in this period were still authored by Chinese first authors.

It is important to emphasize and clarify the scope of the current study. As mentioned in the introduction, some concepts (e.g., ecosystem health, ecological integrity, and ecological resilience) with some conceptual similarity to ecological security are also well developed and widely applied. It is clearly important to compare these concepts to clarify their relationships, differences, perspectives, and

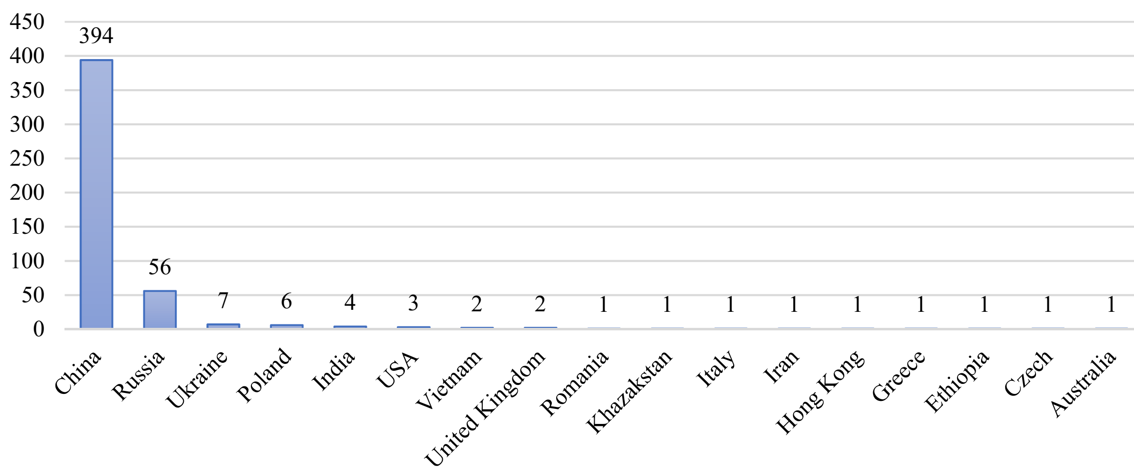

Fig. 1 Total frequency of papers by origin of the first author across nations

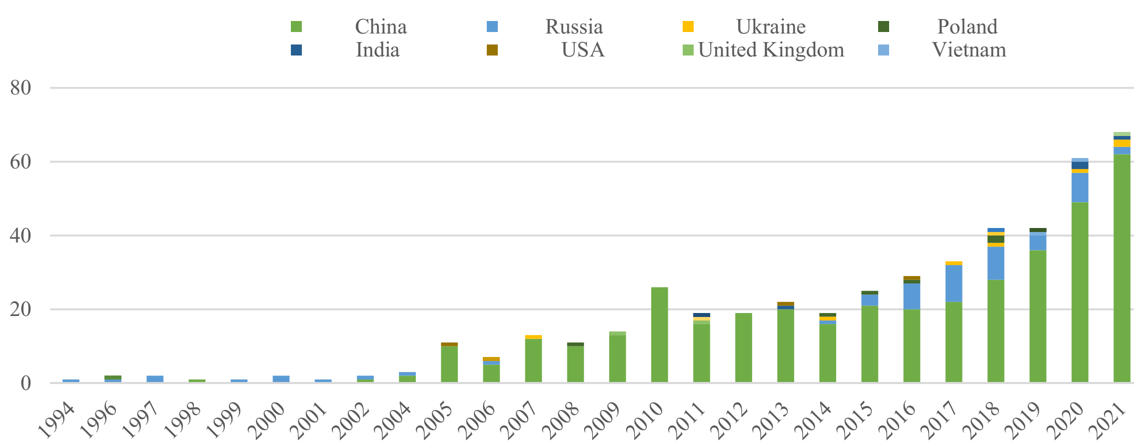

Fig. 2 Stacked bar plot of frequency of papers in the review pool across years by nation of origin of the first author

paradigms. In our study, we applied the search criteria to searches for these similar concepts. This produced a literature library several times larger than the one we utilized that focuses exclusively on ecological security. Given the trade-offs between a focused exploration of ecological security and its applications, versus the relationships between the concepts of ecological security, ecosystem health, ecological integrity, ecological resilience, etc., we have chosen to limit our consideration to the pool of papers focused explicitly on ecological security. We felt broadening the scope to a cross-paradigm comparison would be detrimental to the presentation of the topic of this article. Therefore, we decided to focus on ecological security itself in this paper, and intend to produce a follow up comparative study of relevant concepts in the future research.

Results and discussion

Definition

Table 1 lists the key papers that clearly defined ecological security. Two points need to be clarified regarding the definition. First, who is the beneficiary of ecological security? This question falls in the study scope of environmental ethics. Second, to what extent can security be extended (i.e., what is the standard or threshold of ecological security)? These two key points are discussed separately below.

Environmental ethics

The beneficiary of ecological security should be initially identified. The ethical basis of ecological security can be divided into three broad categories: nature-centric (e.g., Ma et al. 2019), eclectic (e.g., Yang et al. 2018), and human-centric (e.g., Xu et al. 2014; Chu et al. 2017). Generally, the studies in our literature pool mostly hold the human-centric perspective.

From the human-centric perspective, the demand for ecological security is one of many security needs of humans. Xu et al. (2014) suggested that ecological security is "a problem regarding the extent to which ecological resource supply satisfies human demand for security." This definition draws on Maslow's theory of needs and argues that security is one of the inherent basic needs of humans. Moreover, Xu et al. (2014) divided human needs for ecological security into material and spiritual needs and believed that the material needs mainly originate from the cultivation, carrying, and storage functions of the ecosystem, while the spiritual needs mainly originate from the landscape functions. This subdivision makes the connotation of the definition clear and facilitates subsequent evaluations. Hu et al. (2019) defined ecological security as "a status in which the structure, function, and ecological processes of the ecosystem are not threatened, and the ecosystem is able to offer sufficient ecosystem services to support the development of the socio-economic system." According to this definition, the beneficiary should be humans or human society.

Cherry (1995) also believed that ecological security could be defined from at least three different philosophical perspectives: nature-centric, human-centric, and eclectic. Among these, according to the nature-centric definition, ecological security requires maximum harmony among species and between organisms and ecosystems. Similarly, Rogers (1997) attempted to avoid confining ecological security stakeholders to humans and to extend them to

Table 1 Key definitions of ecological security in our literature pool

Definition	Ethical perspective	Standard of security	References
Ecological security refers to the overall integrity and health of the ecosystems	Nature-centric	The integrity and health of the ecosystems are ensured	Ma et al. (2019)
A dynamic equilibrium between humans and nature	Eclectic	No significant degradation in the global ecosystem	Yang et al. (2018)
The extent to which ecological resources satisfy human demand for security	Human-centric	Ecological resources are sufficient for human demand	Xu et al. (2014)
The ecosystem provides sufficient services for the development of socio-economic system	Human-centric	Ecosystem services are sufficient for socio-economic development	Chu et al. (2017) Hu et al. (2019)
Ecological supply and ecological consumption remain balanced and can meet the needs of local survival and development	Human-centric	Ecological supply is greater than consumption	Wu et al. (2020)
A necessary condition for maintaining human existence	Human-centric	Development of human society and economy is guaranteed	Wang et al. (2021)
A state in which the complex ecosystem composed of nature, economy and society can meet the needs of human development and maintain the sustainable development	Human-centric	Humans' sustainable development is maintained	Fan and Fang (2020)

the "inhabitants" of ecological communities. Quantifying the well-being of non-human organisms is challenging. Although studies on the intrinsic value of nature that is independent of human will (e.g., Jørgensen 2010; Sandler 2012; Nielsen and Jørgensen 2015) have been conducted, this perspective of ecological security that includes the interests of non-human organisms has not been extensively studied (Vucetich et al. 2021). Thus, for ecological security, the discussion on environmental ethics has been generally limited to the definition, and practical evaluation cases have generally considered human interests.

Standard of ecological security

The definition of ecological security often includes a standard, which is used to evaluate the level of security (Table 1). However, ecosystems are complex and the goods and services they provide are diverse; thus, the security standards for ecological security vary significantly across different definitions. For example, Hu et al. (2019) suggested that the secure characteristics of an ecosystem can be characterized through its structure, functions, and processes which are capable of supporting the development of human socioeconomic systems. Unique and clear standards are required to describe the characteristics of ecological security. Ambiguous semantics and vague standards may not facilitate the understanding of ecological security.

In the Millennium Ecosystem Assessment (2003) framework, ecological security is defined as "the minimum level of ecological stock required to provide supporting services, which are the basis for all other services (provisioning, regulating, and cultural services)." According to this definition, the security threshold of an ecosystem is the capacity to provide sufficient supporting services. The balance between supply and demand of ecosystem services is another popular criterion used to define the lower limit of security. Some scientists suggested that the security threshold should correspond to the minimum critical limit or minimum biocapacity of an ecosystem corresponding to certain human needs, i.e., the supply of ecosystem services must be greater than the demand (e.g., Xu et al. 2014; Hu et al. 2019; Wu et al. 2020).

Summary of definitions

Based on the aforementioned definitions, ecological security mainly represents the degree to which ecosystem services meet human needs from the human-centric perspective. The utilization of ecosystem services by humans includes not only the production of ecosystem services, but also their flow and consumption (Everard 2017). To ensure ecological security, each cycle process of the ecosystem services has specific requirements (Hu et al. 2019). Mathematically, the requirement for ensuring security is that the supply should not be less than the demand (e.g., Xu et al. 2014). However, due to the limitation of resource allocation and utilization, as well as the existence of uncertainties of complex systems, a surplus is required to ensure that the production and consumption cycles of ecosystem services are not greatly affected or the impact is controllable when unsecure factors interfere (Weinberg 2001; Jorgensen 2016). Therefore, the threshold question regarding security is essentially how much surplus should be retained.

Furthermore, the opposite of security is efficiency, which should also be considered (Marten 2001; Common and Stagl 2005). The pursuit of security emphasizes producing as much surplus as possible (e.g., the precautionary principle). The pursuit of efficiency, in contrast, emphasizes the maximal utilization of resources, thus, compressing or eliminating the surplus. Therefore, ecological security corresponds to the lower limit/threshold of the reserve surplus, or the corresponding surplus requirements under different security degree requirements.

Additionally, some studies have limited the scope to one or more specific ecosystems or categories of ecological resources, e.g., urban land ecological security (Xu et al. 2014), forest ecological security (Lu et al. 2018; Cai et al. 2021), and water ecological security (Xu et al. 2019). The corresponding definitions and study methods do not differ considerably from those of general ecological security.

Evaluation method

The body of ecological security research has mainly used three evaluation methods: quantitative comparison, composite indicators, and spatial analysis. Quantitative comparison implies that the supply and demand of ecological resources or ecosystem services can be calculated and compared. Additionally, a set of key indicators can be used to represent the security level of ecosystems. Here, we divided these articles into composite indicator evaluations. With the development of remote sensing, global positioning systems, and GIS technologies, evaluation of ecological security is increasingly utilizing these technologies. Because these studies analyze ecological security from the perspective of landscape configurations or patterns, they are classified as spatial analysis methods. Table 2 lists the main characteristics of the three methods. Subsequently, the details, advantages, and disadvantages of each method are discussed. Notably, as mentioned in the definition section, nearly all studies on ecological security have considered the well-being of humans, and studies that measured or evaluated ecological security from a nature-centric or eclectic definition were not found in the pool of publications we reviewed.

Table 2 The main characteristics of the three evaluation methods of ecological security

Method	Rationale	Main processes	Representative theoretical bases or measurements
Quantitative comparison	Supply and demand relationship	Identify key ecological resources. Calculate and compare the supply and demand quantity	Ecological footprint (Chu et al. 2017; Guo and Wang 2019)
Composite indicators	Ecological security is represented by indicators reflecting the characteristics of natural and social systems	Select representative indicators, calculate scores and weights of indicators, integrate the scores and weights to a composite, and grade the security degree according to the composite value	PSR (Ke et al. 2020) DPSIR (Liu et al. 2021b)
Spatial analysis	Spatial configuration affects ecological processes and thus, has an influence on ecological security	Calculate the spatial configuration attributes, e.g., landscape index	Landscape index (Liu et al. 2021a)

Quantitative comparison method

This method involves quantifying the supply and demand of resources that human society requires or desires. Generally, ecosystem services, ecological footprint, and/or biocapacity is used to calculate the balance between supply and demand and examine whether the given ecosystem meets all human needs. The ecological security evaluation results indicate the difference or ratio between supply and demand. The paradigm for answering the question of ecological security is “enough or not.”

For example, Guo and Wang (2019) employed the ecological footprint theory to measure the demand perspective wherein human demand for living goods is expressed in terms of the type and extent of land use required to produce these products (Wackernagel et al. 2002). The supply indicator was biocapacity, which was also transformed into the land use form. The quotient of ecological footprint and biocapacity was calculated in the form of land use area as ecological pressure index (EPI). According to the EPI values, ecological security was graded into six levels. Xu et al. (2014) believed that the human demand for ecological resources can be approximately divided into material and spiritual demands. They conducted a questionnaire to clarify the demand materials and their amounts. Subsequently, the supply amounts of all materials were subtracted by the demand amounts after standardization, to refer to the degree of ecological security, which was divided into four levels.

Generally, the theoretical basis of quantitative comparison is clear and non-controversial. However, the supply and demand may be calculated differently among studies; moreover, the most significant difference lies in the grading of security. Nevertheless, after suitable adjustments, the evaluation results of ecological security could be comparable.

Composite indicator method

In this method, the performance and weight of multiple factors are aggregated into a comprehensive index to indicate the state or degree of ecological security. Alternative terms for composite indicators are composite indices (Greco et al. 2019), synthetic indicators, multi-indicators, or multi-attributes (Qiu and Liu 2021). The methodology has been extensively explained previously, e.g., in the handbook on “How to Construct Composite Indicators” by the Organization for Economic Co-operation and Development (OECD) (Giovannini et al. 2008). Some indicators lack absolute reference or criteria; thus, this method evaluates the quality aspect of ecological security. The paradigm to answer the question is “good or bad.”

Figure 3 shows the major steps of this evaluation method (PSR model as the example to select indicators). Generally, the composite indicator evaluation method follows the procedure of multi-criteria evaluation (MCE), which consists of these steps: selecting suitable indicators, scoring and weighting each indicator, integrating the scores and weights of all indicators to a composite index according to a specific rule, building the relationship between the index and security, and finally grading or ranking the security degree (Carver 1991; Jiang and Eastman 2000). As each key step of this method influences the evaluation results, they have been discussed separately below.

Selecting indicators This step requires splitting the objective (analysis) and assigning different indicators to each aspect or link. The selected indicators should reflect the essence of the proposition or consider the stakeholders’ primary considerations. The splitting method can be roughly divided into aspect distinction and logical distinction approaches. The presence of high correlation between the indicators differentiates the two distinction methods.

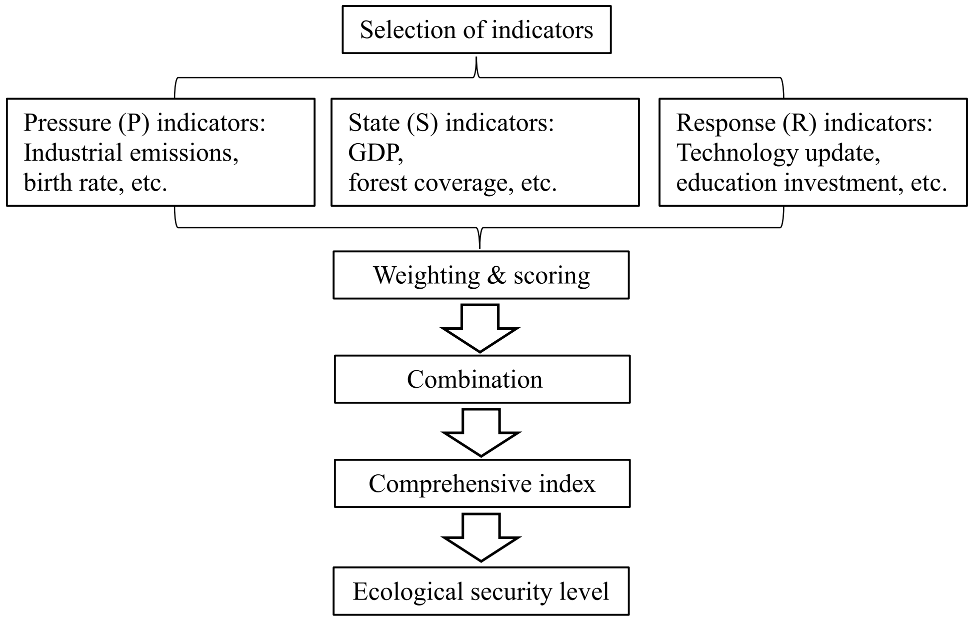

Fig. 3 Composite indicator method to evaluate ecological security (PSR model for indicator selection)

The aspect distinction approach divides the objective into relatively independent small targets; thus, the relationship between indicators is relatively parallel. For instance, Zhang and Xu (2017) first divided ecological security into water security, land security, air security, and biodiversity security and assigned different factors to each. The principle for selecting indicators in this method is that the indicators should be as independent as possible, and their sum should reflect the entire scope of the objective. In the logical distinction approach, the causal relationship of socio-ecological systems is analyzed using conceptual frameworks, such as PSR (e.g., Xu et al. 2019; Ke et al. 2020), DPSIR (e.g., Du et al. 2021; Ma et al. 2021), and PSIR (Lu et al. 2014), wherein indicators are set to measure the state of each component of the framework.

Weighting indicators Weight calculation is usually bound with factor selection; that is, the indicator selection method determines the calculation method of weights. Similar to the indicator selection method, the weight calculation method can also be divided into two types: one method is for parallel (independent) indicators and the other is for interacting indicators, implying that logical or functional correlations widely exist between indicators. For parallel indicators, only one importance ratio exists between each pair of indicators. In contrast, for indicators with logical correlations, at most two correlations exist between an indicator pair: the effect of A on B and the effect of B on A.

Pairwise comparison is the most common method employed for both parallel and interacting indicators. Thus, the correlation matrix is widely used for calculations. Analytical hierarchy process (AHP) is a suitable solution for the parallel indicators because the selection process requires these indicators to be independent of each other (Saaty 2005). For example, Xu et al. (2019) used expert opinions to assign different importance points to the indicators in the AHP model. For interacted indicators, a more complicated process is usually needed to address the complex logical relationship among indicators. For example, the DEMATEL method determined by the DPSIR model was introduced to calculate the indicator weights among indicators that are not independent (Du et al. 2021).

Scoring factors To produce scores of ecological security from indicators, usually an indicator's extreme values (i.e., upper and lower thresholds) are determined initially, after which the final score (i.e., normalization or standardization) is calculated by comparing it with the previously determined extreme values. The changing rules of different indicators differ, and the applicable scoring methods may also differ. Most commonly scoring is done using linear scaling within a specified range. However, frequently studies directly determined the thresholds without adequate explanation. For example, Guo et al. (2020) subdivided a province into different counties and then used the maximum and minimum values of factors, such as population density and forest coverage, in each county as the thresholds to normalize the attribute values of other counties. Similarly, Xu et al. (2014) selected the maximum values in different years of their study period as the criteria and the normalized values of other years as the proportions of the maximum values. Thus, scoring indicators based on the values of specific dataset of the study rather than other widely accepted reference criteria may limit comparability of these studies with other studies.

Combining the indicator performance After calculating the scores and weights of each indicator, a comprehensive index can represent the evaluation results. Most studies used the weighted linear combination (WLC) method wherein the comprehensive index is the sum of the products of the scores and their corresponding weights (Eastman 1999). The WLC method asserts that the factors should be mutually compensable. In practice, factors may not compensate for each other, and the limited availability of one factor may collapse and disable the entire system (Jiang and Eastman 2000). Su et al. (2016) introduced the "cask principle," according to which the capacity of a cask is determined by the shortest board; thus, the minimum value of the product of the scores and weights is used to represent the indicator performance.

Grading ecological security level An area's ecological security level is commonly classified according to its comprehensive evaluation index. For example, Huang et al. (2014) employed the unequal-interval classification method to rank composite index values into five security levels. Similarly, Liu et al. (2021b) used the K-means clustering method to classify the ecological security indices into four levels. However, dividing ecological security levels based on the dataset characteristics instead of objective or universal criteria makes it difficult to compare the grading of levels with other studies.

Spatial analysis method

With the development of spatial technologies, studies that evaluate ecological security using spatial analysis are emerging. The rationale for this approach is that ecological processes are strongly influenced by the spatial configuration of landscape elements (e.g., Wu and Hobbs 2007; Ricklefs 2008). Thus, ecological security is highly dependent on specific landscape configurations. Various disciplines, including landscape ecology, social science, economics, and graphical theories, are involved in answering the question of ecological security.

However, a knowledge gap exists in the logical or quantitative relationship between spatial configuration and ecological security. Further, the application of geospatial technology in ecological security evaluation is challenging. In our literature pool, calculating metrics of landscape structure (e.g., Cushman and McGarigal 2008; McGarigal et al. 2012) was the most popular method, wherein landscape indices were compared to evaluate ecological security. For example, Zhou et al. (2014) used the following five landscape metrics to reflect ecological security: patch density, mean shape index, area-weighted mean patch fractal dimension, contagion, and Shannon's diversity index, each of which represents a different landscape characteristic. Similarly, Rao et al. (2021) used both class-level metrics (percentage of patch type, shape index, and patch density) and landscape-level metrics (mean patch area, edge density, aggregation index, and diversity index).

Although increasing numbers of studies have used spatial techniques to evaluate ecological security, there has been relatively little research directly linking spatial characteristics and ecological security. This, notably, is an area of extensive and long-term research in the related fields of "ecological sustainability" and "ecological resilience" (e.g., Chambers et al. 2019; Cushman and McGarigal 2019). Thus, when spatial analysis methods are used to evaluate ecological security, a plausible theory relating the spatial characteristics of a landscape and ecological security should be provided. For example, drawing from the field of ecological resilience, Cushman and McGarigal (2019) used spatially dynamic landscape simulation modeling to describe ranges of variation in ecosystem structure under natural conditions and used landscape metrics to quantify the departure of the current system state from that range, providing several measures of the degree of departure, resilience and resistance of the system. Methods such as these, which integrate simulation modeling, landscape pattern analysis and ecological effects assessment would be fruitfully incorporated into the research in the field of ecological security.

Summary of the evaluation methods

Presently, most studies used the above three methods. Additionally, some studies used a combination of multiple methods to evaluate ecological security (e.g., Feng et al. 2017; Hu et al. 2019; Xu et al. 2019). For example, in the quantitative comparison method, several elements that connect supply and demand are normalized using the composite indicator method, and weights are calculated to sum them (Xu et al. 2014).

The advantages and disadvantages of all evaluation methods are summarized in Table 3. The case study approach was widely used for the evaluation of ecological security. Comparability is essential for drawing general conclusions from various case studies. In this regard, quantitative comparison methods are advantageous given they provide directly comparable metrics, assuming they are defined in consistent ways. Rigorous and comparative analysis of ecological security levels of different countries or regions would be valuable, for example, for each nation or region to formulate their own ecological conservation policies in the context of the broader distribution of ecological security among peers. Without comparability, whether relative or absolute, the clarity and applicability of ecological security assessments to policymaking will be reduced. However, our literature review showed that the composite indicator method was predominantly used and often limits the comparability of results. Inconsistencies in indicators (e.g., data availability)

Table 3 Advantages and disadvantages of evaluation methods of ecological security

Method	Advantages	Disadvantages
Quantitative comparison	The theory is simple and direct Results of different areas even scales are comparable	Ecological processes are eliminated; thus, large-scale key information is lost The application efficiency of ecological resources is not considered The security thresholds are not clear
Composite indicators	Several aspects or dimensions can be involved to provide a comprehensive evaluation	Evidence for the selection, scoring and weighting of indicators is insufficient Evaluation results are usually incomparable
Spatial analysis	Two (even three) dimensional analysis provides information that is more practical	A large knowledge gap exists between spatial configuration and ecological security Constructing quantitative relationships is largely difficult

are common and further limits comparison. Procedures that are more effective, consistent, and transparent are required for scoring indicators and grading ecological security levels. Further, the prospects for spatial analysis are promising, but the challenges are large in linking spatial patterns to ecological processes and outcomes for ecological security. Thus, interdisciplinary collaboration may be necessary to fill the knowledge gaps.

Approach to identify measures

Another important research topic is implementing measures to ensure or enhance ecological security. Complexity and heterogeneity are two characteristics of both ecological and social systems (Ricklefs 2008). Complexity determines that a solution to a problem may require multiple measures, and a measure can have various consequences. The degree of heterogeneity of a system is positively related to the number of specific issues that require analysis and quantification. These two principles can also be used to solve ecological security problems. In this review, we extracted the proposed approaches instead of only listing the specific measures. The general study process is to analyze the mechanism, find the crux of ecological security problems, and propose measures. Therefore, building a causal chain is fundamental. However, establishing a causal relationship between certain driving factors and ecological security is difficult. Therefore, regression analysis is usually used to determine the influence of factors. Moreover, apart from determining the key factors, areas that are significant to ecological processes can be identified to ensure ecological security, namely landscape ecological security pattern (LESP) (Yu 1996). LESP mainly comprises ecological source areas and ecological corridors, and protecting them is equivalent to ensuring ecological security. Table 4 describes the three major approaches to propose measures.

Causality approach

Analyzing the specific problems is the key to propose solutions, wherein causal chains and major driving factors are identified. This approach generally includes the following three steps: (1) Analyzing the problem to identify the independent and dependent variables and the relevant intermediate variables. (2) Establishing quantitative relationships and expressing the logical chain in the form of equations. (3) Estimating the parameters for the equations using existing data or referring to other relevant studies. Here, the independent variables represent the drivers, and the dependent variables are the indicators of ecological security level. Once the causal chain is established, the relationship between drivers and ecological security (e.g., positive, negative, or irrelevant) and its strength (or sensitivity) can be calculated or simulated. Accordingly, it becomes clear what measures should be taken to regulate the drivers and ultimately change the ecological security level in the desired direction.

Research methods that model results using possible policies or measures directly as drivers can draw conclusions

Table 4 Key information on the three major approaches to propose measures to ensure ecological security

Approach	Key processes	Representative procedures and references
Causality	Find driving factors (causative agents) and build the causal relationship with ecological security	Scenario analysis and system dynamics (Zhang et al. 2019)
Correlation	Find correlated factors and build correlation relationships with ecological security	Stochastic impacts by regression on population, affluence, and technology model (Guo and Wang 2019)
Landscape	Clarify suitable landscape configurations for ecological security	Identification of ecological resources and corridors (Li et al. 2019)

rapidly. Scenario analysis is a method that combines the advantages of scenarios and models (IPBES 2019). Zhang et al. (2019) considered China's forests as the research area, established future scenarios using conditions and constraints under different policy assumptions, and used system dynamics to simulate the changes in ecological security in the next few decades. By comparing the future trends of ecological security across different scenarios, they found that a comprehensive forestry policy could significantly improve forest ecology security in the short term. Li et al. (2015) believed that forest ecological security is mainly represented by three factors: total forest stock volume, forest per unit land area, and forest coverage rate. Four policy scenarios (medium-speed socio-economic development, strengthening environmental management, developing rational forest management policies, and establishing a mixed policy that integrates all the above measures) were developed to identify their influences on the factors reflecting security by comparison with a baseline scenario. Moreover, causal feedback relationships between these scenarios were built for three main subsystems: forest resource, socio-economic, and environment subsystems. They found that only the mixed policy could guarantee significant improvements in ecological security in the study area.

Correlation approach

The research process of the correlation approach is similar to that of causality approach. The difference is that the causality approach aims to establish a direct and clear relationship between independent and dependent variables, relationships in the correlation approach may be indirect. Establishing a causal relationship between certain driving factors and ecological security is generally difficult. Thus, regression analysis can be used to determine the relationships between drivers and impacts and the relative influence of different factors. Moreover, various models have been developed and applied to extract critical drivers. The model of stochastic impacts by regression on population, affluence, and technology (STIRPAT) proposed by Dietz and Rosa (1997) can be used to judge the importance degree of each driving factor. Guo and Wang (2019) selected five driving characteristics from economic, social, and technological aspects and calculated their relative importance using the STIRPAT model.

Furthermore, development of GIS technology has facilitated spatial correlation analysis. For example, Liu et al. (2021b) constructed an ecological security evaluation system that involved 25 different factors. The key factors affecting ecological security were identified by the Geo-detector, a tool that can reveal the driving factors of stratified spatial heterogeneity. Based on the geographically weighted regression model, Rao et al. (2021) analyzed the impact of urban growth patterns (characterized by elevation, population density, and gross domestic product) on ecological security (characterized by landscape indices).

In summary, analyzing the causal or correlational relationship between drivers and ecological security can assist in implementing specific and valuable policy recommendations.

Landscape approach

A common assumption for the landscape approach to ecological security is that, for a particular region, a potential landscape pattern (LESP) exists that is sufficient to ensure ecological security (Yu 1996). LESP can be defined as a spatial pattern comprising vital ecological components (e.g., patches and corridors) that are critically important in controlling the ecological processes (Su et al. 2016). Additionally, the authors believed that to ensure ecological security, ecological source areas and corridors in the ecosystem must be protected (e.g., Li et al. 2021). Ecological sources refer to locations that provide significant ecosystem services (Wu and Hobbs 2007) and ecological corridors (or habitat corridors or green corridors), which are defined as passages between critical ecological patches (that are equivalent to ecological source areas according to this approach), play a vital role in many ecological processes, such as wildlife population connectivity (e.g., Rudnick et al. 2012; Cushman et al. 2013). Thus, they are gaining increasing importance (Yu 1996). Notably, the identification and protection of the supply side of ecological resources is the most prominent feature of this approach.

For example, Li et al. (2019) calculated three ecosystem services in their selected study area, i.e., carbon fixation, soil conservation, and water production. Subsequently, all grids were divided into five grades according to the supply capacity of these three ecosystem services, and two regions with the highest grades were regarded as ecological sources. Further, ecological corridors represented the paths of least accumulated resistance between ecological source areas. Therefore, a resistance surface was created based on the habitat quality analysis (the better the quality, the lower the resistance). The corridors were extracted using the resistance surface and ecological source areas based on the circuit theory, which predicts the current flow between source areas across a continuous resistance surface. Su et al. (2016) divided the landscape pattern that was used to ensure ecological security into five categories: geology, hydrology, atmosphere, biodiversity, and farmland patterns. Critical ecological patches, corridors, and buffers were identified for each design and graded into three ranks.

Most studies that have used the landscape approach to assess ecological security followed the procedure of identifying ecological sources, establishing resistance surfaces, and generating ecological corridors, with differences in the specific methods used to implement these steps. Among these steps, the most critical and foundation is the determination of ecological sources. However, a strong reference for its screening criteria is still lacking, and a strong theory or empirical evidence is still required to support its relationship with ecological security. Furthermore, defining functional resistance surfaces appropriately and source locations for connectivity modeling are also major challenges in producing meaningful corridor predictions.

Summary on the approaches

The aforementioned analyses and examples emphasize that while although establishing a causal chain with ecological security as an objective function is the best way to solve problems (e.g., Li et al. 2015), it is challenging. As a result, few studies have used the causality approach andthus, further comprehensive investigations are needed. A large number of studies have used correlational approaches to associate indicators with ecological security outcomes. Given the challenge of directly ascribing causality in studies of ecological security, rigorous correlational methods using large empirical samples of meaningful indicators and strong analytical methods are recommended. The potential prospects of this approach can increase as more geographic correlation analysis tools become available (Wang et al. 2010; Guo and Wang 2019).

However, the identification of ecological sources and corridors in the landscape approach has to date been mainly based on existing land use land cover (LULC) (e.g., Su et al. 2016; Li et al. 2019), which may be insufficient for ensuring ecological security. For example, Cushman et al. (2008) showed that classified land cover maps were poor predictors of biodiversity and that higher resolution gradient methods (e.g., McGarigal and Cushman 2005; Cushman et al. 2010) quantifying multiple scales of ecological heterogeneity were a stronger basis for ecological assessment than LULC maps. Accordingly, the configuration of these ecological sources and corridors identified based on the existing LULC is not reliable. Theoretically, we believe that under the given target conditions, a potential optimal landscape configuration exists to ensure ecological security in a particular area. The keys to provide this meaningful optimal landscape configuration lie in (1) establishing an appropriate landscape definition, (2) measuring appropriate landscape metrics for that landscape definition, and (3) associating those measurements with meaningful indices and ranges of variation reflecting system dynamics, resilience, and security. Current research suggests that adopting a multiscale gradient framework (e.g., Cushman 2010; Cushman et al. 2010) using surface metrics or spatial entropy measures (e.g., Cushman 2016, 2018) often provides more rigor and information for determining the dynamic state of ecosystems that traditional landscape analysis with patch metrics (McGarigal et al. 2012). Determining the potential optimal landscape configuration and comparing it with the existing pattern maybe a suitable approach to determine landscape adjustments to ensure ecological security.

Future perspectives

Different studies in our review held different viewpoints and used different evaluation methods for ecological security. First, highlighting the emphasis of ecological security and avoiding excessive overlap with other concepts is necessary. Additionally, whether ecological security should cover non-human interests should be considered. For example, Vucetich et al. (2021) introduced efficiency frontiers to maximize utility for human and non-human members of biological communities. Such perspectives seem critical to broaden the currently highly anthropocentric focus of recent ecological security research. Second, the definitions and evaluation methods of ecological security are strongly correlated. Although definitions that considered the interests of living organisms other than humans were proposed (e.g., Cherry 1995; Rogers 1997), specific evaluations in this regard were mostly unavailable. There may be two alternatives: one is to consider that ecological security is entirely human-centric; accordingly, its definition and evaluation are undoubtedly based on human interests. The other is that the interests of living organisms other than humans should also be recognized; therefore, developing a calculation method that can include their interests is necessary. Third, irrespective of the evaluation method, quantifying the evaluation results and ensuring their comparability is the only solution to fill the knowledge gap. We cannot increase the level of ecological security indefinitely because a cost or price (explicit or implicit) exists to ensure security. We must balance security and efficiency. To do this reliably we need quantitative, repeatable, transparent, and theoretically sound evaluation methods. Fourth, the complexity and heterogeneity of ecosystems hinders the development of universal measures to ensure ecological security (Weinberg 2001; Jorgensen 2016); thus, subdividing the problem and establishing logical chains for each subdivided issue is usually required. In this case, shorter logic chains may help solve particular problems in suggesting the measures to improve ecological security. Ultimately, for the landscape approach to identify improvement measures, mechanistic relationships between ecological patterns and ecological security outcomes across multiple spatial scales are needed.

Conclusions

This paper reviewed nearly three decades of research on ecological security based on three aspects: definition, evaluation methods, and approaches to propose measures to ensure or enhance ecological security. Nearly all ecological security research published to date has adopted a human-centric view, which focused on the well-being of humans and the development of socio-economic systems. We believe that a broader, non-anthropocentric perspective that incorporates the intrinsic value of non-humans in the context of cost–benefit, security–efficiency evaluations is essential for future work. The primary security standard is that the supply of natural resources must be larger than the demand. However, different views exist on the required extent of security margin. The relative balance of security and efficiency in different ecological security contexts and goals requires additional investigation. Furthermore, we found that three main evaluation methods have been utilized in ecological security research: quantitative comparison, composite indicators, and spatial analysis, each having their specific advantages and disadvantages. Ensuring the comparability of the evaluation results of different studies remains a priority, because it is currently not feasible to reliably integrate or compare results from most studies of ecological security. A convenient method applicable to different areas or scales is required. To determine measures to ensure or enhance ecological security, three main approaches exist, namely, causality, correlation, and landscape approaches. Establishing causality or correlation between factors and ecological security deserves further investigation, although complexity and heterogeneity of ecological and social systems makes it difficult to well achieve. Lastly, instead of identifying ecological sources and corridors based on the existing LULC, identifying the potential optimal landscape configuration may be more valuable and useful.

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Data availability The data are available on the request from the corresponding author.

Declarations

Conflict of interest The authors declare no competing interests.

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