frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 13 April 2023
DOI 10.3389/fenvs.2023.1115058

OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Land Use Dynamics,
a section of the journal
Frontiers in Environmental Science

RECEIVED 03 December 2022
ACCEPTED 27 March 2023
PUBLISHED 13 April 2023

CITATION
He Y, Wu D, Liu Y and Zhu H (2023), Review of research on evaluating the ecological security of cultivated land. *Front. Environ. Sci.* 11:1115058. doi: 10.3389/fenvs.2023.1115058

Review of research on evaluating the ecological security of cultivated land

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Cultivated land provides fundamental land-related resources, and its ecological security is, thus, an important means of protecting it. The ecological security of cultivated land has emerged as an important and challenging area of research in recent years. In this study, we summarize the progress in research on the evaluation of the ecological security of cultivated land through visual analysis. We review the concepts, characteristics, driving factors, scales and methods of evaluation, technologies, and simulations used in the relevant literature. The results show that while the relevant concept has been preliminarily established, research on the ecological security of cultivated land remains in its infancy, and comprehensive work on the subject is lacking. The Prevalent research has mainly focused on analyzing the current situation, but lacks a dynamic analysis of the driving mechanism of the ecological security of cultivated land based on simulations. This has made it difficult to understand the spatiotemporal mechanism of the ecological security of cultivated land. Future research in the area should discuss the complex driving mechanism of interactions between the social economy system and the ecological system and focus on an integrated model to assess its dynamic spatial and multi-scale characteristics of ecological security of cultivated land because this can inform the theory of protecting cultivated land and the design of plans for land use to mitigate global climate change.

KEYWORDS

ecological security of cultivated land, concept evaluation index system, evaluation scale, evaluation method, model simulation, spatial–temporal evolution, CiteSpace software

1 Introduction

Protecting the area, quality, and ecology of cultivated land is an important aspect of research on land resource management. The area of cultivated land is the basis for producing materials (Tan et al., 2005), its quality is the fundamental guarantee of its productivity (Kong, 2014), and protecting its ecology is the basic requirement of its security. The relevant research has primarily focused on the security of the area and quality of cultivated land instead of its ecology. Assessing the ecological security of cultivated land is not only beneficial for managing the conflict between humans and land to ensure food security and social stability but also important for regional ecological protection and sustainable economic development that can ensure a harmonious society (Zhang and Song, 2012). The ecological security of cultivated land refers to the security of the resource environment, ecological system, and social economy. It is a functional concept relative to the threat posed to the ecology. Researchers have systematically analyzed sustainable land use in various regions at different scales, (Rasul and Thapa, 2003; Beesley and Ramsey, 2009; Aksoy et al., 2022) such as rivers,

construction land, grasslands, and wetlands at the national, provincial, municipal, and district levels (Zhao et al., 2002; Li and Lai, 2011; Wang et al., 2011a; Wang et al., 2011b; Xu et al., 2011; Li et al., 2014; Chen, 2017; Zhou et al., 2018; Li et al., 2019; Yang et al., 2019; Zhang et al., 2019). However, current research has not adequately attended to the ecological security of cultivated land. Even the basic concept of the ecological security of land has not yet been clearly described, and methods to assess it remain in their infancy. No unified system of indices or method is available to this end, and a dynamic, multi-factor system to evaluate the ecological security of cultivated land is still elusive (Zheng et al., 2009; Liu et al., 2017). This requires considering an explanation of the concept and its connotations (Xiao et al., 2002; Chen and Zhou, 2005; Zhu, 2008; Zhang and Song, 2012), developing a system of indices to assess it (Gong et al., 2010; Li et al., 2022), and analyzing the relevant circumstances (Zhang and Song, 2012; Wu and Xie, 2019). Research on evaluating the ecological security of cultivated land can inform policymaking on reasonably using and protecting cultivated land and coordinating the health of the ecosystem with sustainable development.

Industrialization and urbanization have caused a decline in the area and quality of cultivated land, an increase in pollution, and the deterioration of the ecological environment. This affects food security and social stability, thus threatening the survival of human civilization. Former Chinese Premier Wen Jiabao noted that "the management of protection for land resources in developed countries has already undergone two stages—the management of its area and quality—and is now undergoing higher levels of development, while the management and protection of cultivated land in China is still in an early stage of development." The deteriorating ecological environment of cultivated land will lead to a sharp reduction in its area and damage its quality (Li et al., 2001). Protecting cultivated land resources, preventing the contamination and destruction of farmlands, and strengthening the assessment of their ecological security are, thus, major issues of widespread concern and daunting problems in research. Peng et al. (2018) observed that "in developing countries such as China, where natural habitats are under pressure from high-intensity human interference during rapid urbanization, only bottom-line thinking about the ecology can yield a win–win solution that balances ecological protection with economic development." In light of the aforestated, in this study, we define the ecological security of cultivated land, review and summarize the main content of research in the area, and suggest directions for future research.

2 Collecting information on the status of prevalent research

Researchers have conducted preliminary studies on the ecological security of cultivated land that provide a sound foundation for evaluating and simulating it. As the amount of literature on the subject continues to grow, much of it can be downloaded for free. We used CiteSpace software to visually analyze research in the area. It is used widely for literature reviews as it can provide useful results (Chen, 2012, 2020; Chen and Song, 2019).

We constructed a dataset of the literature on the ecological security of cultivated land by using multiple sources. It contained publications ranging from December 1994 to March 2023. The papers were drawn from the Web of Science, Scopus, Dimensions, and PubMed databases, which are the most widely used bibliographic databases in research (Visser et al., 2021). Table 1 summarizes the database, which contains information on 1,288 studies.

The results of executing CiteSpace are shown in Figure 1, the overview highlighting the most active areas of the relevant research.

Figure 1 provides an overview of the underlying network of references in the area that have often been cited together. The nodes represent the references cited, and the clusters represent concentrations of themes. The degree of concentration may vary widely across clusters, and each cluster is assigned an automatically generated label. The largest cluster, #0 cultivated land protection, is at the center of the network. The second-largest cluster, #1 economic benefits, is located near cluster #0 (see Table 2 for cluster details).

The articles in the constructed database were cited 4,216 times in total, 4,131 times excluding self-citations. Thus, the average number of citations per article was 13.15, and the h-index was 35. These articles belonged to a variety of categories, including environmental sciences, environmental studies, green sustainable science and technology, and ecology and biodiversity conservation. Researchers from China were the most prolific in terms of publication, followed by those in the Americas, Germany, the Netherlands, and India. The Chinese researchers were mainly from the Chinese Academy of Sciences (CAS), the Institute of Geographic Sciences and Natural Resources Research of the CAS, the University of CAS, China Agricultural University, and China University of Geosciences. These authors were funded by the National Natural Science Foundation of China (NSFC), the CAS, the Fundamental Research Funds for Research in Central Universities, the China Postdoctoral Science Foundation, and the National Key Research and Development Program of China. The relevant studies focused on environmental science ecology, science and technology, agriculture, and biodiversity conservation and engineering. The timeline of this research area and important articles on the ecological security of cultivated land are shown in Figure 2 and Table 3, respectively.

The aforementioned timeline of literature on the ecological security of cultivated land shows the area of the circle represents literature records that busted the co-citation rate. CiteSpace identified studies by Liu et al. (2017) in cluster #4 (habitat quality) and Wu et al. (2017) in cluster #5 (land reclamation) as the most noteworthy articles because they had been co-cited by multiple articles. The study by Peng et al. (2018) in cluster #10 (ecological corridors) had the highest citation rate in the ecology of land. The Table 3 shows the publication with the earliest publication date, the highest citation rate, the highest intensity of co-citation, and the most correlation and the latest publication in the field.

2.1 Status of research on the ecological security of cultivated land

Ecological security is an interdisciplinary field involving natural and social sciences. While there is no consensus on the definition of

TABLE 1 Comparison of the sources of data obtained from search queries.

Data source	Website	Articles	Search strategy	Initial
Web of Science	https://clarivate.com/webofsciencegroup/solutions/web-of-science/	368	Full text	1999
Scopus	https://www.scopus.com/search/	530	Title, abstract, and keywords	2000
Dimensions	https://app.dimensions.ai/discover/publication	306	Title and abstract	2000
PubMed	https://pubmed.ncbi.nlm.nih.gov/	84	Best match	1994

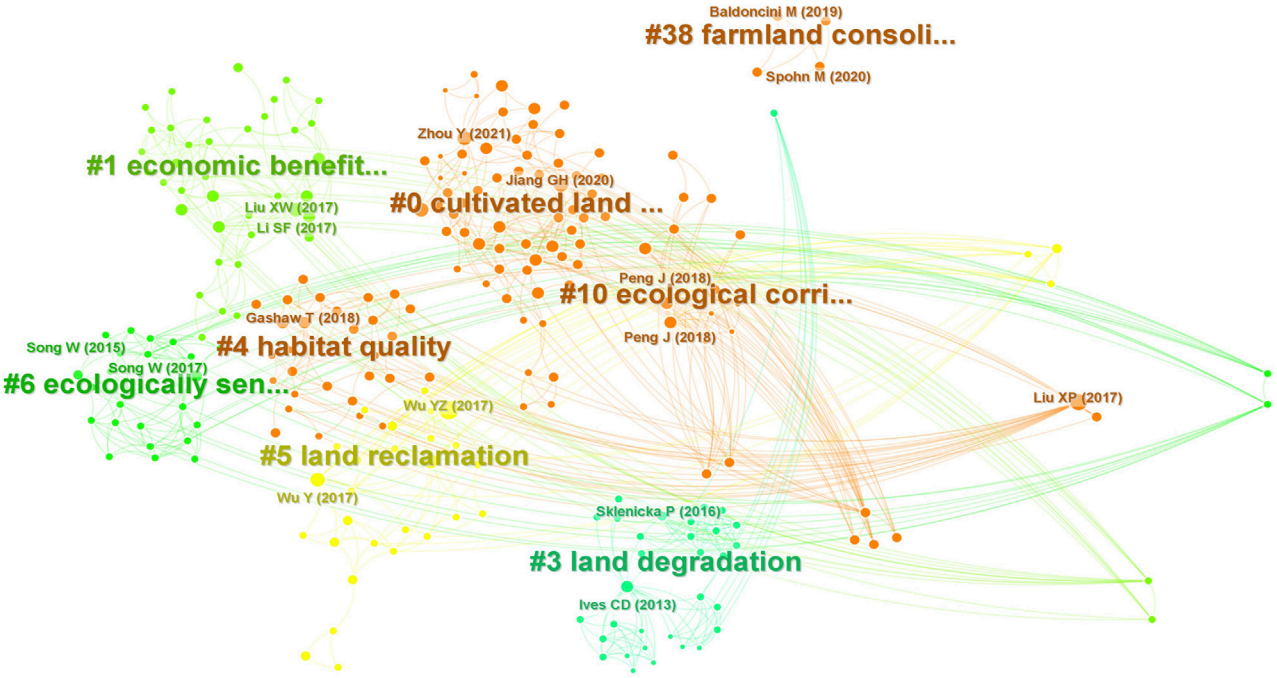

FIGURE 1
Overview of clusters in the ecological security of cultivated land literature.

TABLE 2 Clusters representing themes of research on the ecological security of cultivated land.

Clusters	Label
#0 Cultivated land protection	Sustainable development; ecological security; spatiotemporal variation; driving mechanism; Enshi Autonomous Prefecture | land protection; differentiated control measures; multi-functional assessment; fuzzy set; arable land protection cooperation
#1 Economic benefits	Land use efficiency; sustainable land use; Jiangsu province; coupling coordination; impact factor | threshold model; land utilization; economic belt; Yangtze River
#3 Land degradation	Two-step cluster analysis; peri-urban agriculture; risk identification; environmental management | mountain agriculture; urban growth; environmental perception; central Andes; landscape change
#4 Habitat quality	Human footprint index; landscape model; multi-scenario analysis | scenario simulation; ecosystem service; spatiotemporal analysis; Yellow River basin
#5 Land reclamation	Rapid urbanization; food security; requisition–compensation balance policy; ecosystem services | land protection policy; AHP—entropy method; effect evaluation
#6 Ecologically sensitive suburban area	Karst mountains; land use change; scenario simulation; ecosystem services; influence degree | ecosystem services value; sensitive suburban area; influence degree
#10 Ecological corridors	Ecological security patterns; landscape connectivity; network connectivity assessment; Chongqing municipality; ecosystem services | environmental function; driving forces; spatiotemporal characteristics; landscape pattern evolution; land cover change
#38 Farmland consolidation	Land quality; basic physical; chemical properties; heavy metals | land quality

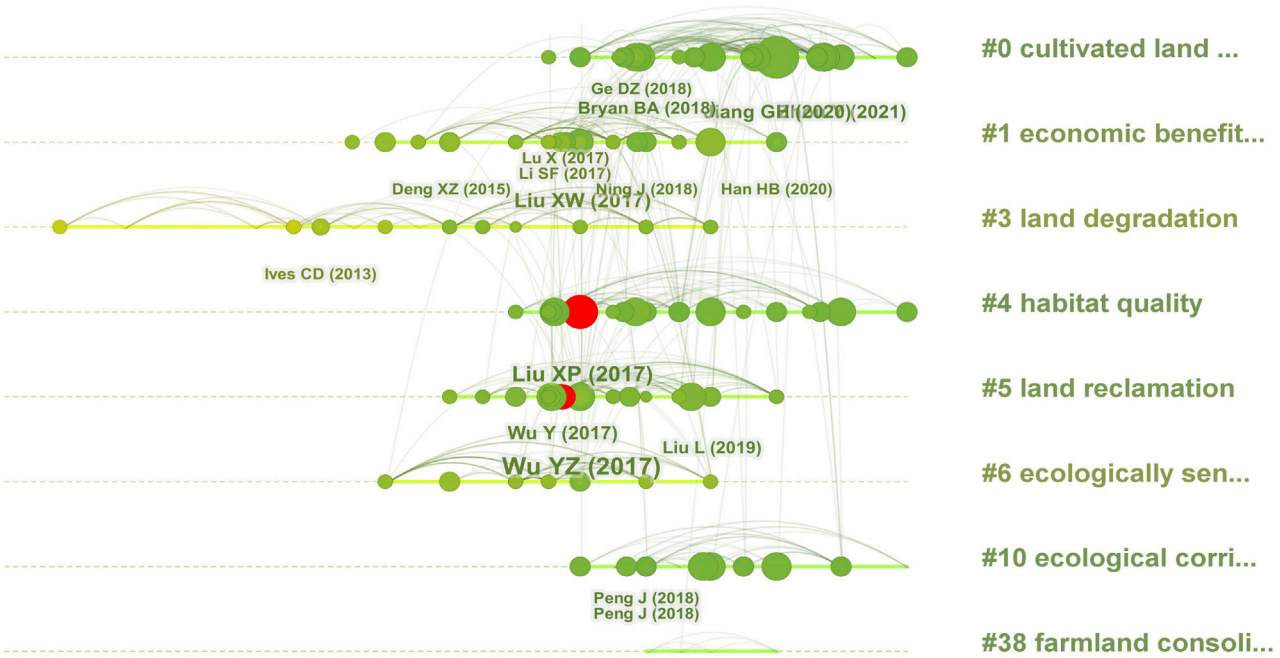

FIGURE 2
Timeline view of literature records on ecological security of cultivated land.

TABLE 3 Overview of important articles.

Author	Article	Journal	Characteristic
Talla, 1994	Population and environment. The era of ecological refugees	Pop Sahel	The earliest relevant literature
Peng et al. (2018)	Linking ecosystem services and the circuit theory to identify ecological security patterns	Science of the Total Environment	The highest-cited literature
Song and Pijanowski (2014)	The effects of China's cultivated land balance program on potential land productivity at a national scale	Applied Geography	The strongest co-citation literature
Liu et al. (2017)	A future land use simulation model (FLUS) for simulating multiple land use scenarios by coupling human and natural effects	Landscape and Urban Planning	The co-citation burst literature
Wu et al. (2017)	Cultivated land protection policies in China facing 2030: Dynamic balance system versus basic farmland zoning	Habitat International	The co-citation burst literature
Wu and Xie (2019)	The variation differences of cultivated land ecological security between flatland and mountainous areas based on LUCC	PLOS One	The most relevant literature
He et al. (2017)	Construction and evaluation of cultivated land ecological security system: A case study in Zhuhai City	6TH ICEESD	The most relevant literature
Li et al. (2022)	Optimizing the use of cultivated land in China's main grain-producing areas from the dual perspective of ecological security and leading-function zoning	International Journal of Environmental Research and Public Health	The latest relevant literature
Zhu et al. (2021)	Land use evolution and land ecological security evaluation based on the AHP–FCE model: Evidence from China	International Journal of Environmental Research and Public Health	The latest relevant literature

ecological security, most scholars claim that it can be understood in both a broad and a narrow sense. The broad sense of ecological security encapsulates people's lives, health, happiness, basic rights, security of living, access to the necessary resources, and their ability to adapt to environmental changes and social order. This, in turn, includes natural ecological security, economic security, and social

ecological security that constitute a composite system of ecological security. The narrow sense of ecological security is defined as the safety of the natural and semi-natural ecological systems and pertains to their integrity and overall level of health (Xiao et al., 2002; Chen and Zhou, 2005). The health of an ecosystem is a new concept in environmental management. Normally functioning ecosystems are considered to be healthy, stable, and sustainable because they can maintain their organizational structure, autonomy, and resilience to stress. Unhealthy ecosystems are those with incomplete or abnormal functions and those that are under stress.

Research in developed countries has focused on assessing the ecological health of land and provided a well-defined and complete concept and relevant systems and methods of evaluation. These contributions can be viewed as related to work on assessing the ecological security of land, but most such research has ignored the ecological security of cultivated land. Research on the ecological security of cultivated land in China has roughly undergone three stages of development. It started in the 1990s, but the importance of ecological security truly came to the fore after the heavy floods in Sanjiang in 1998 and the dust storm in northern China in 2000. During this period, such scholars such as Yu et al. (1999) investigated regional patterns of ecological security. This can be regarded as the first phase of research on the ecological security of cultivated land. Subsequently, Peng et al. (1996) and other scholars reported basic research on assessing the ecological environment, constructed a system of evaluation to this end, and conducted empirical analyses on China. This can be viewed as the second stage of research in the area. With the growing realization of the importance of the ecological environment of cultivated land, research has gradually come to focus on the security of cultivated land (Zhang, 2006). This includes assessing the ecological security of cultivated land (Li and Lai, 2011; Wang et al., 2011a; Wang et al., 2011b; Xu et al., 2011; Peng et al., 2018) and making predictions based on simulations (Xu et al., 2007). This is the third and current stage of research in the area.

2.2 Status of research in developed countries

It is generally acknowledged that the concept of "ecological security" appeared in the 1980s. Earlier studies on the subject focused on analyzing the concept and its significance (Wen, 2008). The relevant research in developed countries began with assessments of the health of the ecosystem. As early as in 1941, Aldo Leopold presented the concept and connotation of the health of land and applied it to assess its function. Since then, research on the ecological system and problems of environmental safety has gradually developed (Xiao et al., 2002). The meaning of changes in ecological security was first given by Lester R. Brown, a famous American environmentalist. He redefined the concept of national security in 1977 by claiming that "now, the threat to security is less from relations between countries, and more from the relationship between man and nature" (Brown et al., 1981). From 1983 to 1987, the United Nations World Commission on Environment and Development formulated its report called "Our Common Future," which systematically analyzed the major economic, social, and environmental problems facing humanity. The report set "sustainable development" as the basic platform to protect and develop environmental resources and meet the needs of current and future generations. It recommended a series of policy objectives and action plans and used the term "environmental security" (World Commission on Environment and Development, 1987). In 1989, the International Institute for Applied Systems Analysis formally proposed the concept of ecological security (Chen and Zhou, 2005). In the early 1990s, the United States, Russia, the European Union, and other countries added "environmental security" or "ecological security" to the main targets of their national security strategies. In August 1991, the "National Security Strategy Report" of the United States was the first to incorporate environmental security into the national interest. Steve Lonergan and Norman Myers developed and promoted the concept of ecological security at a very early stage. Lonergan discussed the relationships of the environment and ecological security with sustainable development (Lonergan, 1999). Myers claimed that ecological security is ecological degradation caused by wars for regional resources and global environmental threats, which, in turn, are linked to a lack of economic and political security (Myers, 1989). Gro Harlem Brundtland, the former Norwegian prime minister and chair of the World Commission on Environment and Development, Boutros Boutros-Ghali, the former secretary general of the United Nations, and Al Gore, the former vice president of the United States, are all pioneers of the development and promotion of ecological security as well. They claimed that ecological security arises from the concepts of ecological threat and risk. Humans bear the main responsibility for this ecological threat, and ensuring ecological security is necessary for society, political powers, and the global community and is an important part of social stability, national security, and public security (Herrmann et al., 2003; Foley et al., 2005). The "Global Ecological Security Civic Treaty" was mooted at the 1996 Earth Convention and has since been signed by more than 2 million people from over 100 countries. It is the first international consensus on ecological security. The treaty is based on ecological security, sustainable development, and ecological responsibility and strives for coordination among the benefits and obligations of members and organizations. The United Nations organized the World Summit on Sustainable Development in 2002 in Johannesburg, South Africa. It focused on the problem of global ecological safety and promoted research on the issue (Espejel et al., 1999; Lee, 1999; Smith et al., 1999). Research on the microcosmic analysis of ecological security in developed countries has focused on two aspects. One is the risks posed to ecological security by genetic engineering, and the other is the influence of the use of chemical fertilizers on the health and security of the agricultural ecosystem (Alipbeki et al., 2020a; Alipbeki et al., 2020b). Research in the 21st century has shown that direct measurements, network analyses, and model simulations are necessary to assess ecological security. These need to be wedded with technologies to assess the ecology of the landscape, such as remote sensing and the Geographic Information System, to comprehensively understand the functional process of ecological security.

In conclusion, research on ecological security in developed countries has focused on regional ecological security and sustainable land use at the macroscopic and microscopic level. It

has covered the relevant concepts, theoretical systems, methods and indices of evaluation, and dynamic monitoring.

2.3 Status of research in developing countries

2.3.1 Definition of the concept

The concept of the ecological security of cultivated land was proposed only recently. Many researchers have provided varying accounts and interpretations of it based on their academic background. Zhao et al. (2002) proposed that the environmental effects of the security of land use should be used as a prototype of the ecological security of cultivated land, where this includes soil erosion, land desertification, and degradation in the quality of soil. Such negative environmental effects are caused by the development and use of cultivated land. Zhang (2006) noted that the ecological security of cultivated land refers to a scenario in which the ecological environment, which is the reliable basis for the existence and development of humankind, unthreatened, or less threatened, by damage and imbalance. Under this condition, the ecological system is stable and balanced and has an abundance of natural resources such that the ecological environment of cultivated land is pollution free, unmolested, and unthreatened. Zhu (2008) further developed the concept by noting that the ecological security of cultivated land resources, including the security of resources and the environment, the ecological system, and social and economic security, means that the ecosystem has a normally functioning structure that can ensure sustainable development to satisfy social and economic needs. The environmental security of cultivated land means that the resource and biological environments of cultivated land are safe or unthreatened. The security of the ecosystem of cultivated land includes the safety of its internal structure. The socioeconomic security of cultivated land involves the functions and features of cultivated land resources to realize the security of society and the economy. The social and economic safety of cultivated land is the ultimate target of ensuring its ecological security (Peng et al., 2004; He et al., 2017). Wang Jun (2009) claimed that the ecological security of cultivated land means to ensure that the ecological environment is less affected, or unaffected, through the mutual coordination of the natural, economic, and social systems at a certain time and spatial scale. The ecological system of cultivated land functions normally in this case. We define the ecological security of cultivated land as the organic unity of its area, quality, and ecological environment at a certain time and spatial scale. Because the recycling of materials, energy conversion, and the flow of information change constantly between the biological and environmental systems of the ecological security of cultivated land, they are always interrelated (Figure 3). The ecological security of cultivated land is a higher direction of security and development than area, quality, and ecological environment. The ecological security of cultivated land is a state of functions related to ecological threats and is a relative and dynamic concept. It has the features of regionalism, systematics, dynamics, imperceptibility, regulation, externality, publicity, and strategies. The concept of the ecological security of cultivated land can promote high-quality development to achieve environmental and social economy benefits (see Table 4).

2.3.2 Analyzing features of the ecological security of cultivated land

The ecological security of cultivated land has its own distinctive features. Zhang (2006) pointed out that cultivated land has the features of artificiality, irreversibility, chronicity, and integrality. Zhu (2008) observed that it also has the features of commonality, crypticity, and strategy. The commonality of the security of cultivated land resources is largely determined by externalities. Because cultivated land has the function of ensuring food security, it is considered to be a kind of public product. Changes in its ecological security are slow and subtle. It takes a long time for cultivated land to change from a safe state to an unsafe state, because of which this transition is difficult to detect. By the time we identify this process, the land already undergoes a qualitative change. Ecological security is an important part of the national security system as it has strategic significance for sustainable social and economic development. The ecosystem of cultivated land plays an important role in the overall ecosystem as well. Wang Jun (2009), noted the comprehensive and important features of the ecological security of cultivated land. They include many aspects as well as influential, natural, ecological, economic, and social factors. These factors interact with and influence one another to render ecological security complex. Analyses at different temporal scales have shown that it undergoes dynamic evolution.

2.3.3 Analyzing factors driving the ecological security of cultivated land

In their analyses of the factors driving the ecological security of cultivated land, Chinese researchers have paid special attention to theoretical analyses but have ignored comprehensive, systematic, and empirical analyses (Zhu, 2008). Zhao et al. (2002) concluded that the main factors influencing the ecological security of cultivated land are population growth, social and economic development, patterns of land use, technological development, environmental optimization, and environmental policy. Zhang (2006) claimed that regional topography and natural disasters influence the ecological safety of the Three Gorges Reservoir Area in Chongqing. Zhu (2008) proposed dividing the factors influencing the ecological security of cultivated land in China into direct and indirect factors. Economic is the direct factor referring to the financial support for agriculture, and the social awareness of protecting cultivated land is the indirect factor. The indirect factor also plays a key role in influencing the ecological security of cultivated land and determines the degree of ecological security. Wang (2009) claimed that factors influencing the ecological security of cultivated land include natural, economic, and social factors. He analyzed factors influencing the ecology of Shijiazhuang based on dynamic changes in the area, quality, and ecological environment of cultivated land. Prevalent research has shown that the ecological security of cultivated land is affected by many aspects of natural and human activities at different scales. Separately analyzing the relevant conditions, their ranges of influence, and their dynamic processes can help reasonably explain and predict the mechanism of changes in the ecological security of cultivated land.

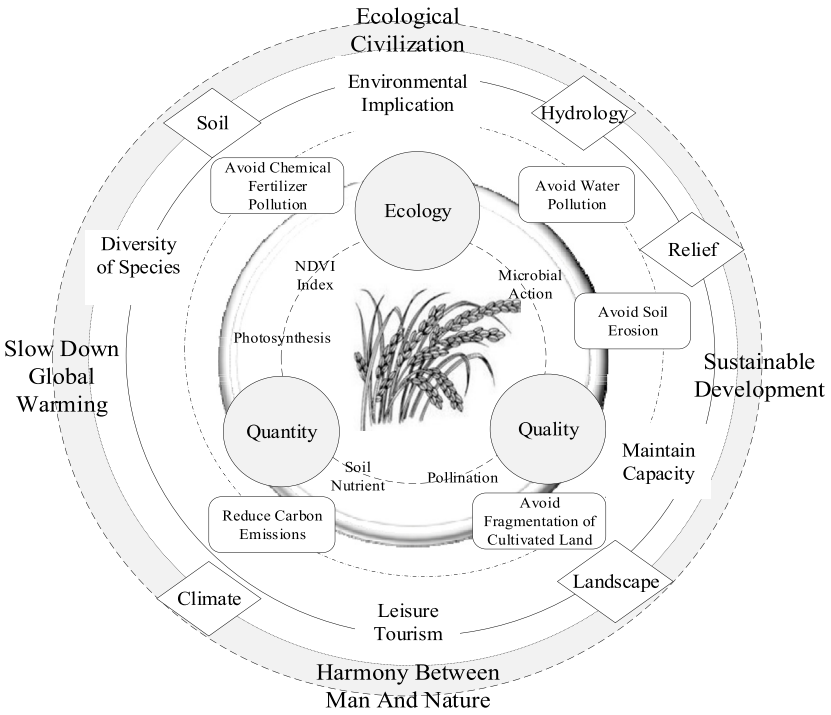

FIGURE 3
Composition structure of a system for ecological security of cultivated land.

TABLE 4 Benefits of ecological security of cultivated land to the environment and social economy.

Benefits to environment	Benefits to social economy
• Ecological life support	• Leisure tourism
Circulating and purifying air and water	• Culture of farming
Fixation and circulation of nutrients	• Education and research
Formation and maintenance of soil • Diversity of life Growth of plants Growth of animals	• Use-related benefits Production of food • Non-use-related benefits
	Interest in land Aesthetic Spiritual
• Global climate change Carbon storage Decomposition of microorganisms above and below the ground Improved absorption of fertilizers	• Future value Food security guarantee Sustainable development Social stability

2.3.4 Scales of evaluating the ecological security of land

Scale refers to the size of the ecosystem (spatial scale) or its temporal dynamics (temporal scale) (Fu et al., 2001). Using different scales yields different levels of patterns and processes and their rules of interaction. This ultimately influences the scientific and practical aspects of research (Lu and Fu, 2001; Ma et al., 2005). Ecological security can be considered at multiple scales. Understanding the scales of the ecological security of cultivated land is the most effective means of evaluating it and an important prerequisite for establishing a system for it (Lee, 1999). The health of the ecosystem of cultivated land differs at various temporal stages of the evolution of its structure and function. Energy flow and the recycling of materials in each component in different stages maintain a stable and dynamic balance, and the health of the ecosystem of cultivated land changes with the environment (Cui and Yang, 2003). Research

that uses "time points" can be used to quickly evaluate the status and characteristics of cultivated land, but different reference indexical values often create wide differences in the results. Research characterized by "time periods" can be used to easily define the dynamic changes in cultivated land, but this strategy yields uncertain results when the data are incomplete (Cui and Yang, 2003). Research on the ecological security of cultivated land at different spatial scales considers different objects, such as the individual, the overall population, the community, the ecosystem, and the landscape. This, in turn, requires a suitable spatial scale to establish relations with macroecological and microecological problems (Zhang and Ren, 2005). Large-scale studies help better understand the status of ecological security in general, while small-scale research helps explore the mechanisms of ecological security and their specific performance in great detail. Therefore, the relevant research should not only consider the spatiotemporal unity of the ecological security of cultivated land but also examine the spatiotemporal differences in it based on the characteristics of the object of study to improve the authenticity of the evaluation. Scale conversion is connected at different levels by time or space and involves transforming data from one scale to another. From the perspective of evolution, conclusions from relatively large-scale studies can be applied to small-scale studies. Assessment at the spatial scale involves the transformation of data from the national, provincial, and regional levels (Zhao et al., 2002; Zhu, 2008) to the prefecture level at the mesoscale, as well as at the county level and lower levels (Wang, 2009). The temporal scale of evaluation ranges from a single year to a continuous period of several years (Zhu, 2008). However, if the research scale of ecological security of cultivated land is too large, many details may be lost. This also leads to a lack of consideration of regional differences (Li et al., 2001).

2.3.5 Methods and technologies of evaluation

Studies assessing the ecological security of cultivated land have evolved from conducting qualitative to quantitative research in China in recent years. Qualitative research provides a theoretical basis to this end, while quantitative evaluation can identify the state and level of the ecological security of cultivated land to render it measurable. Using both qualitative and quantitative methods to assess the ecological security of cultivated land is, thus, the natural direction of development of prevalent research. Currently used methods include fuzzy comprehensive evaluation, the comprehensive index-based method, system dynamics-based methods, methods to determine the ecological carrying capacity, and those based on artificial neural networks (Zuo et al., 2002; Liu et al., 2011). Wang Jun (2009) quantified indices to assess the ecological security of cultivated land by using a linear dimensionless method according to data obtained from statistical yearbooks and field surveys. The BP neural network was used to evaluate the ecological security of cultivated land in Shijiazhuang City, and the results were simulated in MATLAB 6.5. The authors divided states of the ecological security of cultivated land into five levels: poor, middle, good, very good, and ideal. Wu and Xie (2019) used the pressure support framework as a system of indicators of assessment and used an improved BP neural network model to capture dynamic spatiotemporal changes in the ecological security of cultivated land in Yuxi City from 2005 to 2015. However, Most of the research studies on the ecological security of cultivated land in China still use statistical yearbook data for quantitative analysis, and the combination of 3S spatial analysis technology and geo-statistics for evaluation is relatively rare.

2.3.6 Systems of indices for evaluation

The main idea underlying the formulation of a system of indices to assess the ecological security of cultivated land is to identify the relationship between the ecological environment and society. Such a system of indices is a large and complex system. Social consensus on a standard system of indices of evaluation to this end remains elusive. The most frequently used methods include the pressure–state–response indexical system, the exposure–response analysis system, the system of indices of the landscape, and the system of indices of sustainable development. The system of comprehensive indices, which is integrated into the aforementioned systems, was built on the basis of ecological and soil sciences, thus attending to social, economic, and landscape-related data. This is believed to represent the future direction of development in research on the evaluation of the ecological security of cultivated land (Liu et al., 2011). The choice of indices of evaluation is based on the principles of scientificity, integrity, dominance, availability, operationalism, universality, dynamism, and stability. Zhu Hongbo created a system of indices to assess the ecological security of cultivated land according to the factors influencing its connotations. It consisted of six indices representing directly influential factors, five representing indirectly influential factors, and five indicators of socioeconomic impact. Wang Jun (2009) created a system of indices for evaluation based on a target layer, an index layer, levels of indices, and 22 indices of evaluation. The natural factors influencing the ecological security of cultivated land included the *per capita* area of cultivated land and unused area of land *per capita*, forest coverage, and the area occupied by paddy fields. The economic factors considered included the GDP growth rate, the ratio of expenditure on agriculture, the *per capita* net income of farmers, and the use of chemical fertilizer on units of cultivated land. Social factors influencing the ecological security of cultivated land included the level of urbanization, the index of pressure of cultivated land, population density, and the rate of population growth. Wen et al. (2007) proposed a system of indices that considered the quality of the climate and soil, geologic landforms, and the area of cultivated land through 19 indices. The authors proposed one factor of ecological safety to comprehensively account for important factors. Social and economic factors alone cannot satisfy the need for assessing the ecological security of cultivated land. Researchers, thus, need to pay more attention to the area of cultivated land and factors related to the quality of the ecological environment.

2.3.7 Simulation and prediction

As the current status of the ecological security of cultivated land cannot meet the needs of society, research on predicting its state through simulations has become prevalent. Xu et al. (2007) proposed an early warning system for the ecological security of cultivated land. This involves a qualitative evaluation of the ecological environment, forecasts of its expected status in the future, and the generation of a warning if detrimental changes in it are expected that can hinder the coordinated development of the

ecological environment and the social economy. The authors used Microsoft Visual Studio.NET as the platform to develop an early warning system of this kind for Anhui Province in China. They also developed indicators of early warning and a method to set the level of warning based on four considerations: the fertility of soil in farmlands, the quality of the environment, its health, and output. However, this system is merely a prototype and requires further research and development. Moreover, it is based only on a single index such that it does not consider the complicated relations between the factors of assessment. Furthermore, it cannot simulate the regional ecological security of cultivated land resources or the trends of changes in them owing to a lack of support based on 3S technology. Therefore, the simulation and prediction of the ecological security of cultivated land should actively absorb research achievement of related disciplines and aim to develop from single-factor to multi-factor comprehensive simulation.

2.3.8 Measures to protect the ecological security of cultivated land

As developing countries are in a period of rapid economic development, protections for cultivated land play an important role in ensuring national food security, social stability, security of the regional ecological environment, and the overall coordinated development between urban and rural areas for them (Cai, 2001; Song and Ouyang, 2012). This determines the state of the ecological security of cultivated land. Song et al. (2014) noted that protections for the ecology of cultivated land should be guided by the multi-functional demands of urban and rural residents for cultivated land, and more attention should be paid to conserving resources and protecting the environment through a series of measures related to land use and land management. This can ensure that the area, quality, and spatial pattern of cultivated land are suitable for the protection of farmland ecology and coordinated development. Fu and Tan (2005) considered problems related to the ecological security of cultivated land in Hubei Province in China from 1995 to 2004. Peng (2013) considered the comprehensive ecological security of cultivated land in the Jianghan Plain in China from 2001 to 2010. He noted that measures to ensure the ecological security of cultivated land are designed to publicize them and improve public awareness, influence the relevant regulations, establish early warning systems for them, strengthen the ecological restoration and reconstruction of cultivated land, prevent agricultural pollution, establish a mechanism for ecological compensation, control the population, encourage people to coordinate and develop reserved resources of cultivated land, carry out land consolidation and mining, and achieve a balance between the area and quality of cultivated land. Chen (2011) developed five measures according to the state of risk to the ecological security of cultivated land in Shandong Province in China from 1999 to 2008: increasing funds for the ecological protection of cultivated land, improving the level of agricultural mechanization, strengthening the management of investment in agricultural and ecological security, and establishing a legal system for the conservation of cultivated land. Zhang (2006) proposed a system for protecting the regional ecology of cultivated land. He applied it to a reservoir in Fengdu County in Chongqing Province of China by considering institutional guarantees, funding, and technological security. Protecting the ecology of cultivated land involves satisfying multi-functional demands for its utilization, natural and socioeconomic conditions, and multi-level and multi-dimensional spatial and functional forms to develop the corresponding measures.

3 Progress of research on evaluating the ecological security of cultivated land

The importance of research on the ecological security of cultivated land is widely recognized in both developed and developing countries. Researchers have analyzed problems related to the ecological security of cultivated land by using theories and methods with the aim of sustainable development. These research studies have laid an important foundation for further systematic work in the concerned area. However, due to the complexity of the object of study and the limitations incurred by an imperfect theoretical system and methods of research, the problems described in the following section continue to require attention.

3.1 Focus on mesoscale research of cultivated land ecological security

Owing to the different spatial and temporal scales used in research, the various mechanisms of assessing the security of the ecosystem of cultivated land yield different results. Due to the complexity of the ecological system of cultivated land, many studies in the past focused on studies conducted at the macroscopic spatial scale and short temporal scales. Furthermore, the observations and scale of research used are singular, and there is a lack of research at the mesoscale, which makes it difficult to understand the regional ecological security of cultivated land based on its overall dynamic characteristics and mechanism of evolution. With the development of high-resolution remote sensing technology and depth-monitoring technology, it is now possible to study synchronous data from a large area at multiple scales (Zuo et al., 2003; Li and Pan, 2010). The mesoscale may be the most suitable to research the ecological security of cultivated land.

3.2 Establishing a system of indices to assess the ecological security of cultivated land

Researchers have proposed several systems of indices to assess the ecological security of cultivated land according to their aims in different areas of study (Gao et al., 2008; Gao et al., 2017; Lai et al., 2023). These systems involve a number of natural elements, such as the topography, vegetation, landscape index, landscape function, and ecological indicators, as well as non-natural factors, such as the society, economy, and pressure from human activities. However, an evaluation system with a large number of indices complicates the problem of ecological security and impedes its evaluation. Thus, as few indices as possible should be used as representatives so that they can be controlled to focus on the most important issues. The evaluation indices should be chosen by attending to social and

economic factors, the area and quality of the cultivated land, and the ecological environment. Future studies need to discuss the complex mechanism of interactions between the social economy system and the ecological system according to the chain of "risk identification–external influence–degree of safety–mechanism of influence—regional prevention" to build a system of indices to assess the ecological security of cultivated land.

3.3 Improving current methods and developing new ones

Research on and technologies for assessing the ecological security of cultivated land are still in their infancy. Models of evaluation methods to this end, in particular, need to be updated in future works. At present, static methods of evaluation are the main ones, while dynamic methods of evaluation are scarce. Quantitative models of mathematical evaluation are more frequently used than models of spatial evaluation. Therefore, future research on assessing the ecological security of cultivated land should seek to combine mathematical models and 3S technology to build models. Furthermore, methods of dynamic evaluation should be considered based on static evaluation. Researchers should identify the key factors and processes for the ecological security of cultivated land.

3.4 Strengthening research on the ecological security of cultivated land and climate change

The proposal for the ecological security of cultivated land plays an important role in slowing down global warming. According to the 2006 report of the IPCC, different methods of farming influence changes in the carbon pool, for example, irrigation and dryland or greenhouse farming. These farming methods directly affect climate change (Giardina and Ryan, 2000; Simon et al., 2006). The change of ecological security of cultivated land not only affects human activities, but also has a profound impact on climate change. How to quantitatively analyze the impact of ecological security of cultivated land on climate change is not only a scientific problem in the field of climate change, but also a difficult problem in the field of surface system science.

4 Conclusion

Our review of the relevant research here has shown that most studies have considered the security of land resources as the object of research, while few authors have considered the ecological security of cultivated land. Moreover, most studies have used static analyses instead of dynamic analyses based on simulations. Recent works have considered typical regions in case studies from the perspective of the area of cultivated land resources, changes in the quality of land, mechanisms driving these changes, pattern of the landscape, and the relationship between social and economic development. However, these studies have overemphasized the safety of and prevention of damage to the area and quality of cultivated land resources but have ignored the ecological security of cultivated land. Evaluating this is an important means of monitoring risks to the ecological environment, managing ecological resources, and providing early warnings in case of changes in the quality of the ecological environment. With rapid urbanization and modernization in recent decades, the conflict between the ecosystem of cultivated land and human activities has become increasingly prominent. The use of cultivated land for non-agricultural construction, the use of chemical fertilizers, and the pollution of soil by residues from heavy metals are serious problems that deteriorate the quality of cultivated land and fragment its landscape. This enhances the risk of the ecological degradation of the land. The ecological risks of cultivated land will lead to increased carbon emission, water pollution, and soil erosion that affect food security and social stability. Moreover, social progress has led to a transformation in the significance of cultivated land from its traditional function of production to ecological functions. The concept of ecological security has been introduced can improve the quality of cultivated land and achieve sustainable development. Therefore, investigating the ecological security of cultivated land can help relieve the tension between humans and nature, modernize its management, and provide a reference for decision making and future planning in agriculture.

5 Discussion

The evaluation of the ecological security of cultivated land has emerged as a new field of research in recent years. No uniform system of evaluation is yet available as a reference, and few theories and methods have been developed for it. However, the subject is very important. In this study, we systematically reviewed the literature on the ecological security of cultivated land and suggested directions for future theoretical and practical research in the area. We have made the following contributions to research in the area: 1) We introduced the general state of research in the field, including the prominent researchers, countries of origin of research, research institutions, and important studies. This helped determine the status of research on the ecological security of cultivated land in general. We used CiteSpace software to visualize the results of our survey. 2) We identified the concept, phases, and characteristics of the ecological security of cultivated land and the factors driving it. We also systematically discussed the relevant scales of evaluation, methods and technologies, systems of indices, methods of simulation and forecasting, and measures of protection. 3) We provided directions for future research in the area. We believe that the factors of the ecological security of cultivated land are an important basis for the formulation of measures and policies on land resource management, land use structure optimization, land use transformation, and ecological protection.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

YH, DW, YL, and HZ contributed to the conception and design of the study. YH organized the database. YH performed the statistical analysis. YH wrote the first draft of the manuscript. YH, DW, YL, and HZ wrote sections of the manuscript. All authors contributed to manuscript revision and read and approved the submitted version.

Funding

This work was supported by Program of National Natural Science Foundation of China, (No.41971184); Team Project of Natural Science Foundation of Guangdong Province, (No.2018B030312004); Guangdong Planning Office of Philosophy and Social Science under the project "Disciplinary Co-projects for 2020 under the 13th Five-Year Plan" (No. GD20XYJ32); 2022 Guangdong Province Ordinary University Characteristic Innovation Category Project (Humanities and Social Sciences category) (2022WTSCX087); 2022 Tertiary Education Scientific Research Project of Guangzhou Municipal Education Bureau (No. 202235269); the Department of Education of Guangdong Province, under the "2020 Research Project under the 13th Five-Year Plan, Special Research Area on the Construction of Guangdong—Hong Kong—Macao Greater Bay Area" and "The Silk Road" (No. 2020GXJK199); 2021 Curriculum Ideological and Political Education Construction Project "land use planning" of Guangdong Institute of teaching management of colleges and universities (No. x-kcsz2021158); Guangzhou University Project "On-campus research projects (research category)" (No. YJ2021007); 2022 Guangzhou Higher Education teaching quality and teaching reform project (No. 2022JXTD001); and Renmin University of China: the special developing and guiding fund for building world-class universities (disciplines).

Acknowledgments

The authors would like to acknowledge WD and ZH, Guangzhou University, for valuable discussion and assistance in interpreting the significance of the results of this study. They also thank the editor and reviewers for their valuable comments and suggestions.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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