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Review

Research Progress on Ecological Carrying Capacity and Ecological Security, and Its Inspiration on the Forest Ecosystem in the Karst Desertification Control

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Abstract: Social progress and the improvement of living standards are often accompanied by the intensification of ecological crises. The long-term abuse of natural resources has led to the accumulation of ecological liabilities, which in turn seriously hinders economic development. This has prompted all sectors of society to recognize the importance of ecological carrying capacity (ECC) and ecological security (ES). Remarkable progress has been made in karst desertification control (KDC), which has helped reshape the ECC and ES pattern of forests. Currently, the research field of ECC and ES is experiencing rapid development. Further studies in these areas have immeasurable value in promoting regional sustainable development strategies and strengthening ecological civilization construction. The objective of this paper is to provide an overview of the current research status and potential challenges in the field of ECC and ES, with a view to optimizing the program of forest restoration and protection in KDC. This study systematically analyzed 350 relevant studies and found that (1) research on forest ECC and ES has shown a strong growth trend overall, especially after 2017, with a growth rate exceeding 75%; (2) the literature predominantly focuses on the assessment of forest ECC (40.58%) and the enhancement of forest ES (23.42%); and (3) geographically, research findings are heavily concentrated in Asia, representing 95.40% of the total. Notably, China emerges as the primary contributor to research in this field, accounting for a substantial 94.12%. Based on the above analysis, this review summarizes the significant advancements in forest ecosystems, ECC, and ES, while also delving into the key scientific issues that need to be addressed. Furthermore, it offers valuable insights from forest ecosystems in tackling KDC, with the goal of offering guidance and strategic recommendations for future research and practices in managing delicate ecological environments.

Keywords: ecological carrying capacity; ecological security; karst desertification control; forest

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1. Introduction

The rapid advancement of science and technology has led to the accumulation of significant material and spiritual wealth for humanity. However, the Earth is currently grappling with severe ecological issues, as ecosystem degradation poses threats to human food sources and natural resources, endangering the survival of around 40% of the global population [1]. In such a scenario, the sustainable development of human society is confronted with notable challenges [2]. To tackle this issue, China is actively promoting green development and intensifying efforts to safeguard ecosystems, taking the construction of ecological civilization to unprecedented levels [3]. Ecological carrying capacity (ECC) refers to the inherent ability of natural ecosystems to sustain their service functions and overall health under specific socio-economic conditions [4]. Its assessment is a crucial tool in advancing ecological civilization construction, serving as a metric to gauge the harmony between socio-economic activities, resources, environment, and ecosystems. The integration of sustainable development principles into ECC evaluation methods has been extensively studied across various disciplines such as geography, ecology, environmental science, and resource science [2,5,6]. Despite numerous valuable insights into the concept, research methods, and regional single-factor ECC, the current body of research falls short of meeting the practical demands of sustainable development. The complexity of ecosystems presents challenges in developing theoretical frameworks and quantitative methods for assessing ECC. There is a need for a scientifically unified evaluation system and accounting model to further enhance research and understanding in this area.

Ecological security (ES) refers to the level of protection humans have from ecological harm and environmental pollution [7]. Since the Industrial Revolution, there has been rapid economic development, enhancing the utilization of Earth's resources and the environment. However, this progress has also significantly impacted the Earth's ecosystem [8,9]. Global concerns regarding ecological security (ES), including environmental pollution [10], fossil fuels [11], and radioactive substances [12], have garnered significant attention worldwide. International research has even connected these issues to human food safety [13]. Ecological and environmental issues such as sustained global warming [14], poor ecosystem quality [15], soil erosion [16], karst desertification (KD) [17], and the destruction of wildlife habitats [18] are increasingly severe. The significance of ecosystems' functions and services in ES has gained more attention. Current research on ES assessment primarily emphasizes creating indicator systems that combine various static elements from the natural environment and socio-economic dimensions. However, this approach often falls short in showcasing the comprehensive and systematic nature of ecosystems, overlooking the detailed examination of the fundamental issues that underpin ES. This limitation impedes ongoing research on ES and obstructs the execution of national strategies for constructing ecological civilization and safeguarding ES.

Karst landforms cover 15% of the world's land area and are predominantly found in Guizhou Province and Chongqing City in China and other regions [19,20]. KD occurs in fragile karst environments due to unsustainable human activities, leading to conflicts between humans and the land, soil erosion, vegetation damage, and a loss of land productivity [17]. In southwestern China's karst region, KD is a significant issue, resulting in the reduction in or loss of ecosystem functions amidst challenges of ecosystem degradation and economic underdevelopment [21,22]. Forest restoration plays a crucial role in karst desertification control (KDC) [23], with the establishment of a three-dimensional composite structure of forest shrub grass and optimized spatial allocation being a key focus for restoration efforts [24]. Uneven and unstable regional development, especially in China's western region, poses the biggest challenge to forest ES [25]. Despite various ecological policies, the fragility of forests has hindered the achievement of desired results.

Numerous studies have revealed that forest ecosystems can significantly contribute to the enhancement of regional ECC, optimize the pattern of ES, and improve overall sustainability after undergoing the restoration process [26]. This contributes to the ecological restoration of KD areas and provides important decision-making ideas for the protection and improvement of forest ecosystems in current and future KDC. Nevertheless, a notable gap exists in the current research system, in that few scholars have conducted an in-depth exploration of karst areas from the perspective of karst landscapes, drawing on global research on forest ECC and ES. Therefore, the main objectives of this paper are as follows: (1) to describe the research progress and potential challenges of ECC and ES; and (2) to explore the revelation of forest ECC and ES research on KDC forests. The aim is to provide other ecological restoration regions with portable reference programs for the evaluation of ECC and the enhancement of ES, and to provide scientific references for the sustainable development of ecologically fragile regions.

2. Materials and Methods

A literature search was conducted using databases such as CNKI (China National Knowledge Infrastructure) (https://www.cnki.net (5 March 2024)) and WOS (Web of Science) (https://webofscience.clarivate.cn/wos/woscc/basic-search (5 March 2024)). Literature searches were conducted by entering "Forest Ecological Carrying Capacity" for the first search and "Forest Ecological Security" for the second search. The search deadline was 31 December 2023. The following inclusion criteria were employed: (1) search terms should be present in at least the title, abstract, and keywords of the studies; (2) studies are included in the CNKI and WoS databases; (3) studies are related to forest ECC or ES; (4) studies are written in English or Chinese; and (5) the types of studies include journal articles and reviews, conference papers, newspapers, editorials, serials, scientific results, books, doctoral dissertations, and Master's theses. The following exclusion criteria were applied: (1) duplication in the literature; (2) studies of non-forest ecosystems; and (3) unavailable literature.

Firstly, 819 articles in Chinese and 430 articles in English, amounting to a total of 1249 articles, were sourced from the CNKI and WoS databases, respectively. Secondly, following a review of the title, abstract, and keywords, only 869 articles were deemed to meet the inclusion criteria. Subsequently, following a detailed examination of the full text, a total of 350 valid documents were retained (Figure 1). Finally, the retrieved literature was analyzed in terms of annual distribution, issuing institution, and other measures.

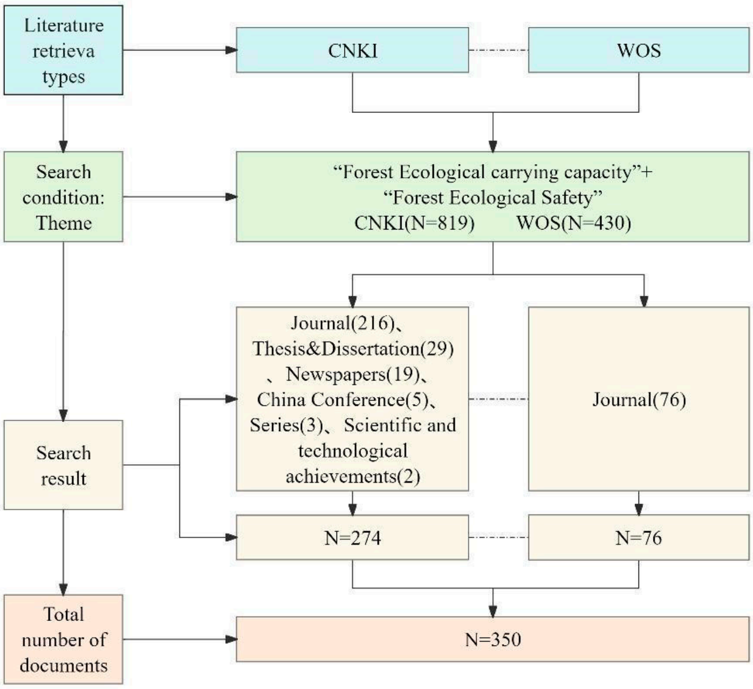

Figure 1. The process of literature retrieval.

3. Results

3.1. Annual Distribution of the Literature

A change in the number of research studies is a significant indicator of the evolution of the research field, and can reflect the development trend in the field. Research on forest ECC and ES can be categorized into three stages, showing an overall upward trend (Figure 2). The first stage, from 2000 to 2006, saw a total of 15 articles. This initial phase had a slow start, with an average annual publication of fewer than three articles, representing the sprout stage. The second stage, from 2007 to 2016, comprised 122 articles, with an average annual publication of over 12 related studies, marking the fluctuating growth period. The third stage, from 2017 to 2023, experienced rapid growth, with a total of 213 publications, indicating the field's significant research potential.

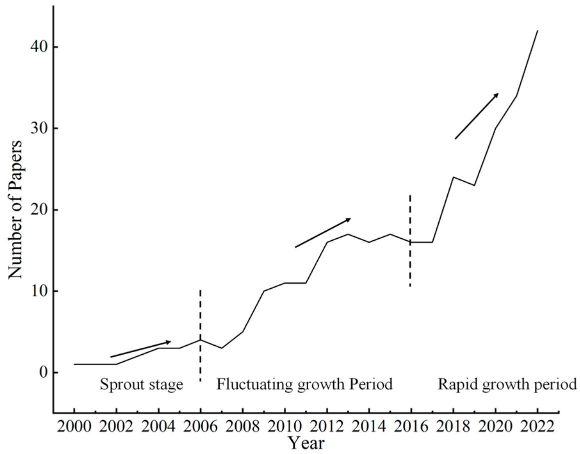

Figure 2. Annual distribution of the literature.

3.2. *Regional and Institutional Distribution of the Literature*

Figure 3 illustrates the distribution of institutions engaged in research on forest ECC and ES. The analysis reveals that research efforts are predominantly concentrated in Asia, accounting for 95.40% of the total, underscoring the region's substantial contribution to this field. Following Asia, North America and Europe represent 2.28% and 1.63%, respectively, while South America and Africa exhibit lower participation rates, at 0.35% each. Notably, research activities in Asia are primarily concentrated in countries such as China, Vietnam, and Japan; North America is represented by the United States and Canada; and Europe sees significant contributions from institutions in Russia and Italy. Chinese institutions lead in terms of research output in this field, surpassing other countries by a considerable margin, with Canada, the United States, and Italy following behind.

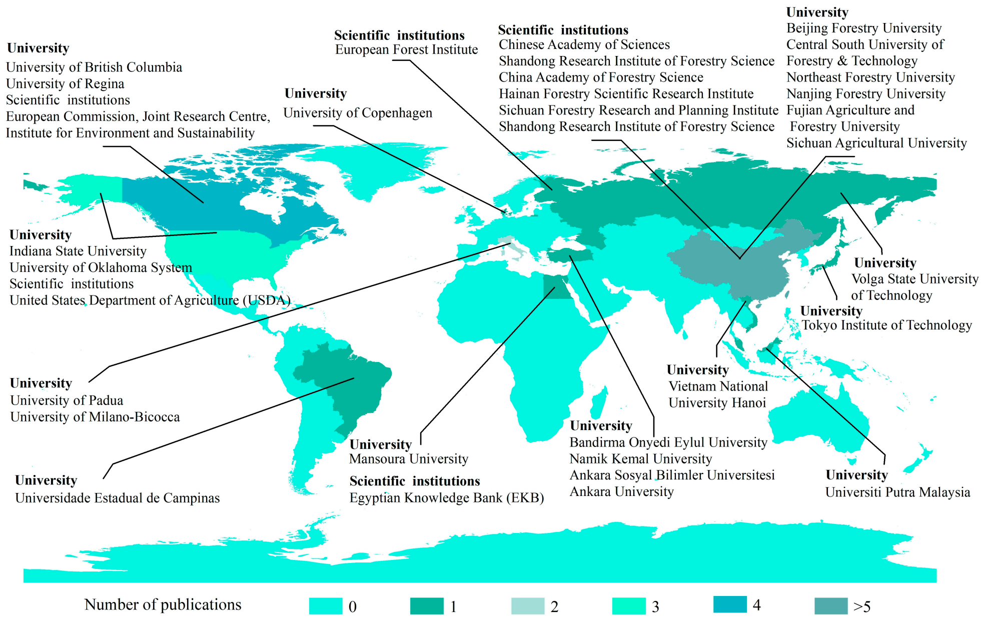

Figure 3. The breakdown of the institutions and nations described in the study.

This study focuses on the top 20 publishing institutions with over two articles each (Figure 4). Analysis reveals that all institutions with over 10 articles are based in China, with the University of British Columbia (4 articles) and Indiana State University (3 articles) representing foreign institutions. The leading institutions can be categorized into two groups: universities specializing in forestry research, such as Beijing Forestry University (35 articles) and Central South University of Forestry and Technology (18 articles), and national and local scientific research institutions like the Chinese Academy of Sciences (24 articles). Additionally, forestry- and agriculture-related universities have also made notable contributions, such as Fujian Agriculture and Forestry University (11 articles). The distribution of the literature is influenced by various factors including research funding, geographical location, and academic focus.

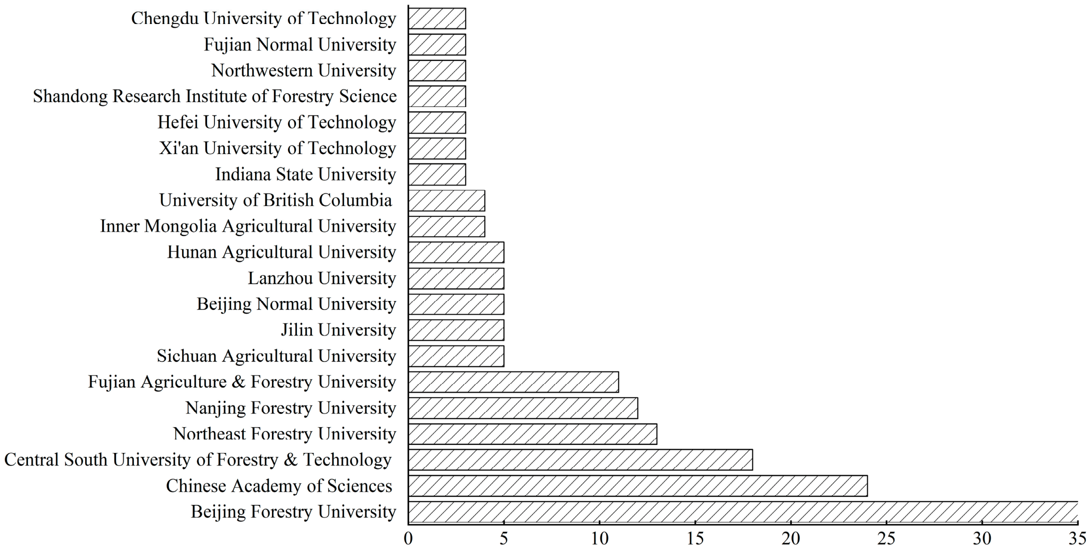

Figure 4. Top 20 units in total literature research volume.

3.3. Distribution of Research Topics in the Literature

This study categorizes the screened literature into five main categories: forest ecosystems, assessment of forest ECC, regulation of forest ECC, enhancement of forest ES, and other (Figure 5). The results showed that forest ecosystems accounted for 11.15% of research, focusing on their structure and function. The assessment of forest ECC literature is the most abundant, reaching 40.58%, covering indicator screening, system construction, and innovative evaluation methods. The regulation of forest ECC literature accounts for 15.32%, with a focus on exploring the internal regulatory mechanisms of forests; the enhancement of forest ES literature accounts for 23.42%, mainly related to the construction of ES patterns; and the rest belongs to other. This classification reveals the mature trend in the assessment of forest ECC research, while the fields of regulation of forest ECC and enhancement of forest ES are still actively exploring and developing.

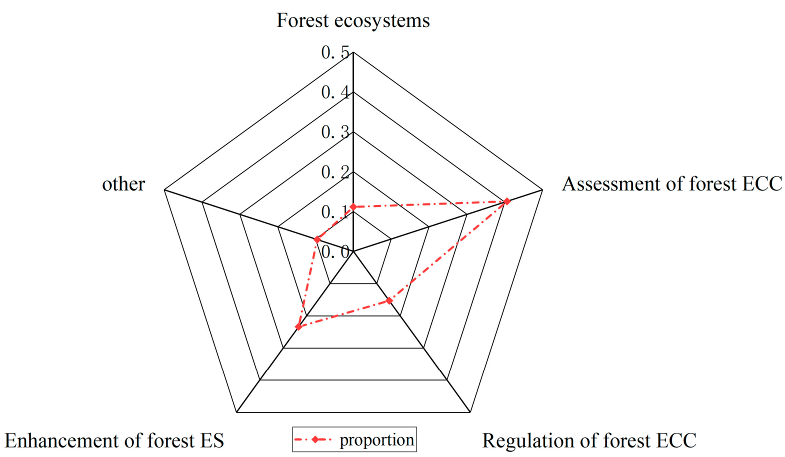

Figure 5. Distribution of research themes in the literature.

3.4. Main Research Stage Division

The relevant research on forest ecosystems began in 2000 and has continued for over 20 years of study (Table 1). Over this period, there have been significant developments in the evaluation and regulation of ECC, as well as enhancements in ES. The research progress on forest ECC and ES can be divided into three stages: the sprout stage, the fluctuating growth stage, and the rapid growth stage.

Table 1. Division of research stages.

Study Phase	Development Background	Main Features
Sprout stage (2000–2006)	In the 1990s, China entered the stage of sustainable development, and researchers regarded ECC as an important basis for sustainability.	The average number of related articles per year was fewer than three, suggesting a preliminary exploration of ECC and ES. The main focus was on the derivation and development of the concepts of ECC and ES, with a exploration of forest ecosystems as the research subject.
Fluctuating growth period (2007–2016)	In 2007, the 17th National Congress of the Communist Party of China introduced the concept of building an ecological civilization. This initiative was prompted by the increasing issues of environmental pollution, degradation of ecological quality, and inadequate ECC. As a result, ES was incorporated into the national security agenda.	The integration of ECC and ES with urban areas (clusters) and tourism expanded in research depth and scale, moving beyond natural areas. More studies focused on the ECC and ES of urban forests, forest tourism, and urban agglomerations, leading to significant developments in this field.
Rapid growth period (2017–2023)	The 19th National Congress of the Communist Party of China in 2017 emphasized the importance of ecological civilization as a key component of modernization and highlighted the need for an ES pattern.	The annual average number of related publications exceeded 33, with a significant increase in the literature focusing on the construction of ES patterns for forest ecosystems in various levels such as provincial, national, and national parks.

3.5. Main Research Developments and Landmark Achievements

3.5.1. Forest Ecosystems

(1) Forest restoration has different effects on ecosystem services and ECC.

Artificial intervention in restoring degraded land facilitates community succession in ecosystems, significantly improving the regulatory functions of forest ecosystems such as water conservation and disaster prevention [27,28]. This intervention also promotes biomass accumulation, enriching resources like wood, food, and medicine [29], thereby enhancing the supply capacity of ecosystem services and increasing ECC. However, variations in forest types and restoration levels can impact the trade-offs and synergies between these services [30]. For instance, afforestation in degraded areas may enhance carbon sequestration and water conservation, but could potentially reduce food and forage supply [31]. Afforestation in non-degraded areas can enhance timber production and esthetics, but may have negative impacts on water sources and climate regulation [32]. Forest restoration also contributes positively to meeting the demand for ecosystem services by improving human quality of life, health, and economic conditions, leading to increased demand for these services [33]. The restoration of degraded areas has boosted farmers' income and stimulated higher demand for food and forage [34], while the restoration of non-degraded areas has enhanced urban residents' quality of life and increased demand for recreational and leisure services [35].

Following the mitigation of KD in karst areas, the vegetation pattern has been enhanced to optimize the forest ecosystem (Figure 6). The introduction of tree and broad-leaved species, including *Cupressus duclouxiana* Hickel 1814 and *Koelreuteria bipinnata* Franch 1886, into plantation areas serves to balance the structure of the forest stand, thereby taking into account both ecological and economic benefits [36]. This approach has significantly improved the provision of forest ecosystem services, contributed to the restoration of natural ecosystem stability and integrity, and ultimately strengthened the overall ECC.

(a) (b)

Figure 6. KDC forms a stable forest ecosystem: (**a**) forest ecosystems before KDC; (**b**) forest ecosystems after KDC.

(2) Forest ecosystems exhibit a high level of connectivity among patches in various source areas.

Ecological source areas are crucial for maintaining ES both within and outside a region [37,38]. Forest ecosystems play a key role in regulating ecological resources and services, as well as enhancing biodiversity through connectivity mechanisms. Forest restoration projects in degraded areas expand regulating services like water conservation and carbon sinks, while promoting biological exchange and strengthening genetic diversity [39]. In non-degraded areas, forest restoration aims to improve supply services such as timber supply, create ecological habitats, and support population reproduction and growth [40].

In karst areas, forest ecosystems face challenges in controlling desertification, due to patchy fragmentation and terrain complexity, which hinder ecosystem connectivity. Enhancing forest restoration efforts to expand forest coverage and improve connectivity (Figure 7) is crucial for solving this issue and holds immense value in restoring regional ecological balance.

(a) (b)

Figure 7. Forest restoration promotes source-patch connectivity: (**a**) forest ecosystems before KDC; (**b**) forest ecosystems after KDC.

3.5.2. Assessment of Forest ECC

(1) The comprehensive evaluation model is a standard demonstration of the small-scale forest ECC evaluation model.

The field of ECC research is experiencing a significant shift from a one-dimensional approach to a more comprehensive evaluation system, and from static analysis to dynamic simulation prediction. Various operational method models, such as the Net Primary Productivity (NPP) model highlighted in Table 2, focus on comparing regional biological productivity with benchmark reference values [41]. Wang et al. conducted an evaluation of ECC in the Heihe River Basin [42]. The ecological footprint model introduced by Rees [43] has become a crucial tool for interdisciplinary analysis, by meticulously categorizing ecological productive land types and comparing resource consumption with carrying potential. Yue et al. expanded the scope by integrating ecosystem service assessment [44]. Gao et al. proposed a comprehensive evaluation model that includes quantitative indicators like carrying capacity index and pressure index, providing an accurate depiction of regional ECC [45]. This model's relevance and evaluation precision are widely acknowledged.

Table 2. Common methods and models for ECC evaluation.

Method/Model	Advantages	Disadvantages	Applicable Objects	Citation
NPP	It can effectively demonstrate the disruption of natural systems, particularly the stability of ecosystems, and is both comprehensible and quantifiable.	It may overlook the influence of human socio-economic activities on ecosystems and the responsiveness of natural systems to ecological concerns.	This method is well suited for analyzing extensive regions like natural ecosystems and watersheds.	[42]
Ecological footprint model	The data acquisition methods are diverse and easily accessible, with clear theoretical foundations, relatively simple calculations, an easy verification of results, and strong adaptability.	Neglecting the functional diversity and dynamic changes in land itself hinders the ability to simulate and predict future development trends, leading to low calculation accuracy.	This method is more suitable for ecosystems in larger cities where precision requirements are lower.	[46]
Based on the InVEST model	Integrating ecosystem services with spatial analysis facilitates the zoning of ecosystem spatial functions.	It overlooks the influence of human economic and social activities.	This approach is more suitable for ecosystems in larger cities with lower precision.	[44]
Based on the AHP comprehensive evaluation method	It uses select comprehensive evaluation indicators from the perspectives of resources, environment, and socio-economic factors.	The required number of data is large, and the evaluation results are easily influenced by subjective factors.	This method is particularly suitable for researching medium- and small-scale regions with abundant data.	[45]

In KD areas, land degradation and ecological damage greatly hinder the water and soil conservation capabilities of forests. Furthermore, socio-economic growth, particularly agricultural expansion and rapid urbanization, exert dual pressures on the ecological capacity of forests. Thus, it is essential to establish a comprehensive evaluation framework that effectively captures the dynamic equilibrium between social and economic progress and forest ecological preservation. The goal is to identify a mutually beneficial approach that fosters social and economic advancement while safeguarding the sustainable development of forest ecosystems.

(2) The evaluation of forest ECC depends on ecosystem supply and human demand.

Non-degraded ecological areas, such as the eastern coast and the middle and lower reaches of the Yangtze River, possess favorable natural conditions and high population density. The limitation on their forest ECC is primarily due to the escalating human demand, rather than insufficient forest supply capacity [47]. These areas exhibit a substantial need for the cultural and regulatory services provided by forests. On a global scale, developed countries have a lower forest ECC compared to developing countries, highlighting a significant global imbalance [48]. According to Chen et al. [49], the consumption of natural capital surpasses its contribution, signaling a decline in the global forest ECC. Zhu et al. [50] further underscored that increased human intervention directly contributes to a decrease in forest ECC, leading to significant structural and functional changes.

Degraded ecological areas, such as the arid regions in western China and the KD zones in southern China, are mainly constrained in their forest ECC by the low supply capacity of the ecosystem itself, attributed to harsh natural conditions and sparse populations [51]. The overexploitation and impact of climate change have further eroded the forest resources and ecological functions in these areas [52]. Additionally, Inostroza L et al. [53] identified a direct correlation between the acceleration of urbanization and the decrease in forest ECC, highlighting significant spatial differences.

3.5.3. Regulation of Forest ECC

(1) Forest structure optimization and functional enhancement are the main means of regulating ECC.

Research has shown that simply increasing forest coverage or improving quality in non-degraded forest areas has reached a point of saturation in expanding ECC [54]. The key now lies in finely optimizing and adjusting the structure and function of forest landscapes. By analyzing the balance between regional ecological service supply and demand, it is important to identify ecological-surplus and -deficit areas, and then optimize surplus areas through landscape configuration strategies to achieve overall ecological balance [55]. In eastern China, the introduction of diverse landscapes such as tourist forests and urban green spaces has effectively met the various needs of the public for environmental beautification and cultural and educational services [56]. On the other hand, degraded forest areas are characterized by scarce resources, weak supply capacity, and significant degradation. Therefore, the restoration and protection of forest resources and the implementation of scientific ECC regulation have become top priorities in maintaining ES. For example, in southwest China, initiatives such as returning farmland to forests and grasslands and large-scale afforestation projects have greatly improved issues like soil erosion and biodiversity decline, while also increasing forest coverage and ECC [57,58].

In KD areas, the intricate terrain and severe soil erosion lead to a limited availability of forest resources and a uniform landscape structure (Figure 8). Therefore, when restoring forest resources, it is crucial to focus on optimizing both landscape structure and function, increasing forest diversity and complexity, enhancing stability and adaptability, and effectively regulating the forest ECC of the region.

Figure 8. The forest landscape structure in KD areas is a single one, and is functionally poor.

(2) The adjustment of forest industry structure and strengthening forest management are important regulatory measures for ECC.

The strategic adjustment of the forest industry structure aims to optimize the layout of forest resources for improved economic and ecological benefits [59]. Specific strategies include expanding economic forest planting and promoting sustainable timber industry development [60]. This adjustment enhances resource utilization efficiency, the multi-functionality of forests, ecosystem services potential, and ECC regulation. Strengthening the forest management system involves improving protection policies and promoting rational resource use [61]. Scientific strategies can enhance protection efficiency, maintain biodiversity and vegetation integrity, promote carbon sequestration, and optimize ecological environment quality. Additionally, strengthened management aims to boost forest resilience and recovery capacity, reduce the ecological impact of natural disasters, and solidify the regulation of forests' ECC.

In KD areas, with their distinct arid and semi-arid climate and issues of soil and water scarcity, it is essential to introduce tailored forest management and protection strategies. This involves adapting the forest industry structure, enhancing forest management practices (Figure 9), closely aligning with local natural conditions and economic requirements, and establishing a forest ecological industry system that reflects regional characteristics. The objective of this approach is to harmonize economic progress with ecological conservation, creating a mutually beneficial scenario and paving the way for the effective governance of KD.

Figure 9. The forest industry structure for KDC is a single one.

3.5.4. Enhancement of Forest ES

(1) Constructing an ES pattern is an important strategy for enhancing the external ES of forests.

The field of ES in karst forests has garnered significant academic interest in addressing the escalating degradation of the ecological environment. Gao et al. [62] conducted a study in the karst mountainous areas of Hechi City, Guangxi Province, focusing on constructing a resistance surface by normalizing land cover types. They systematically assessed the ecological significance of forests and outlined ES patterns, suggesting targeted optimization strategies. Li et al. [63] examined the karst forest in Nanshan District, Chongqing, integrating ecological importance, sensitivity, and demand analysis to identify forest ecological source areas. They developed an ES framework to support regional ecological land planning. High-quality forests in karst fragile ecological areas play a crucial role in stabilizing ecological functions, emphasizing the need for their protection and restoration as the cornerstone of establishing an ES pattern. Therefore, it is essential to design a scientifically sound ES framework centered on forest protection and restoration to effectively mitigate ecological vulnerability and reconcile the inherent conflict between economic development and ecological preservation. As an illustration, the Amazon rainforest can attain a mutually beneficial equilibrium between ecological preservation and economic advancement through the establishment of a network of protected areas, the advancement of sustainable agriculture, and the development of ecotourism. This effectively mitigates threats such as illegal logging and facilitates the recovery of biodiversity and carbon storage capacity [64].

In KD areas, land fragmentation worsens soil instability and heightens the vulnerability of forest ecosystems to erosion (Figure 10). To address this issue, forest restoration efforts should be integrated with the development of an ecological grid that considers key factors like land use patterns and slope conditions. Comprehensive planning for forest ecosystems and the establishment of ecological protection zones and key areas are essential steps to reduce resistance to land use changes and enhance ecological construction. This approach aims to elevate regional ES levels in a holistic manner.

Figure 10. Severe land fragmentation in KD areas.

(2) The ES early-warning system plays a protective role in enhancing ES.

The forest ES early-warning system, which relies on the comprehensive monitoring, in-depth assessment, and detailed analysis of forest ecosystems, can sensitively capture and identify potential risk factors that threaten forest ecological balance and even lead to collapse [65]. In non-degraded or mildly degraded areas such as those in northeast and north China, socio-economic pressures drive a surge in human demand for forest resources and services, leading to competition and conflicts between regulatory services, and resulting in supply–demand imbalances and trade-offs [66]. Strengthening monitoring, evaluation, and early-warning mechanisms is crucial for the timely identification of potential risks and the effective prevention of ecological crises [67]. For instance, the forest fire early-warning system, constructed using remote sensing technology in Northeast China, has achieved the real-time monitoring and prediction of fires, providing solid data support for prevention and control efforts [68].

In KD areas with significant degradation, factors like biological invasion and human interference can greatly harm the structure and function of forest ecosystems. This worsens the occurrence of natural disasters such as forest pests, diseases, and fires (Figure 11), ultimately reducing the resilience and sustainability of the system [69,70]. Therefore, there is a pressing need to enhance the restoration and reconstruction of forest ecosystems. This includes establishing a monitoring system for diseases and pests with early-warning capabilities, utilizing a variety of data sources. This will help improve the regulatory services provided by forests and enhance overall ES [71].

Figure 11. Threats to forests: (**a**) forest pests and diseases in KDC; (**b**) forest fires in KDC.

4. Discussion

4.1. Distribution Differences in the Study Area

The development of ECC and ES research has shown significant imbalances globally, due to differences in natural resource base and economic and social development levels among regions (Figure 12). China has stood out in this field, drawing global attention. In 2003, China's State Council released the 'Action Plan for Sustainable Development in the Early 21st Century', prioritizing the sustainable use of forest resources. This policy spurred domestic scholars' interest and investment in this research area. An analysis of the top twenty countries by forest area in 2020 indicates that the top five countries are actively researching forest ECC and ES, while countries ranked sixth to twentieth have made less progress. Interestingly, countries with smaller forest areas like Turkey, Finland, Malaysia, and Japan are actively researching in this field. This reveals the uneven distribution of research areas and suggests that perceptions of resource scarcity may influence research interests. The concentration of research efforts in countries with strong economic foundations and scientific capabilities is also evident.

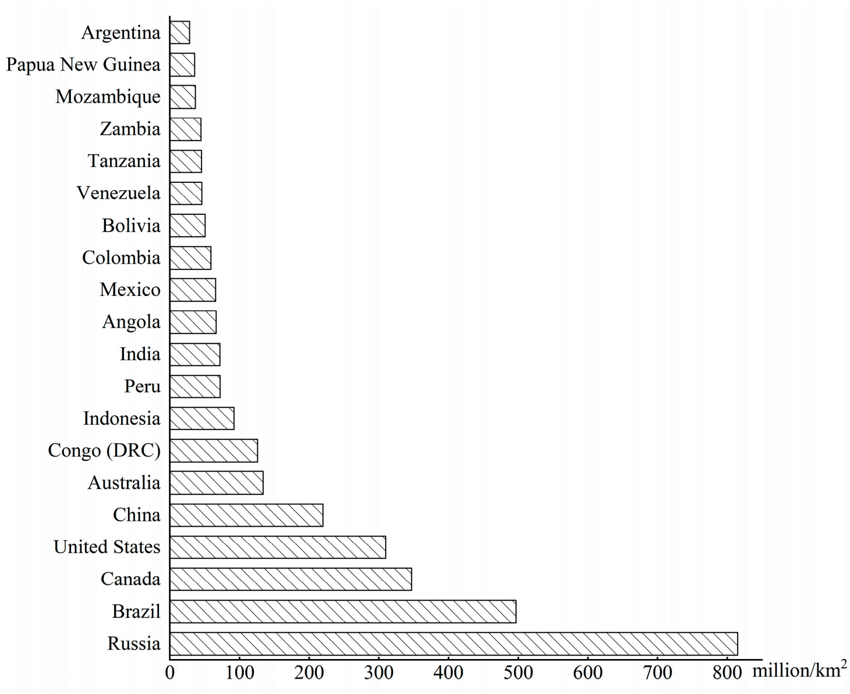

Figure 12. Top 20 countries in the world in terms of forest area in 2020 (data from FAO official database).

4.2. Key Scientific Issues to Be Solved and Prospects

4.2.1. Forest Ecosystems

(1) In response to the key scientific issue of unclear mechanisms affecting the supply capacity of forest ecosystems under complex and variable soil types and moisture conditions, research should be conducted on the internal mechanisms of how the soil–vegetation–atmosphere system responds to and adapts to drought stress.

Soil type and soil moisture conditions are crucial regulatory factors for the supply of forest ecosystem services, significantly impacting the ES pattern [72]. The physical, chemical, and biological properties of soil play a fundamental role in shaping the growth trajectory and water use efficiency of vegetation [73]. Additionally, soil moisture status directly influences the drought pressure experienced by vegetation, thus affecting the provision of ecosystem services [74]. Drought stress leads to a reduction in vegetation biomass and water use efficiency, and challenges its adaptability and resilience [75]. By investigating how soil types and moisture conditions influence forest ecosystem supply, we can uncover the underlying mechanisms of drought response and adaptation in the intricate system of soil–vegetation–atmosphere interactions. This includes exploring the feedback regulation of vegetation on soil moisture [76] and the impact on atmospheric evapotranspiration [77]. However, current research predominantly focuses on two-dimensional interface interactions and lacks integrated three-dimensional coupling models.

KD areas present a unique challenge to vegetation growth due to their sandy and calcareous soil, low moisture content, and high permeability (Figure 13). Understanding the impact of these soil characteristics on vegetation biomass and water use efficiency, as well as the interaction within the soil–vegetation–atmosphere system in arid environments, is crucial for guiding desertification control and improving forest ES. This analysis provides a scientific foundation for developing regional ecological restoration strategies.

Figure 13. Comparison of different soil moisture conditions in KDC forests: (**a**) perennial arid region; (**b**) abundant water volume.

(2) In response to the key scientific issues regarding the differential mechanisms of ECC in different forest ecosystems, restoration models should be clarified, including the uniqueness of vegetation species' composition, differences in functional group classification, and the operational mechanisms that dominate ecological processes under each model.

The restoration of forest ecosystems can be achieved through a variety of approaches, including the establishment of plantation forests. These methods are characterized by a clear purpose and defined phases of forest development. However, they often result in a reduction in biodiversity. In contrast, the restoration of closed forest ecosystems is a low-cost and highly efficient approach that promotes biodiversity and facilitates self-recovery, leading to the formation of more natural and stable ecosystems. Both have the potential to exert a profound influence on the ECC of forests, through the shaping of distinctive vegetation structures and functions [78,79]. These patterns not only govern species and functional diversity, but also directly affect the vegetation's ability to adapt to environmental factors like soil and hydrology [80]. Therefore, delving into the relationship between forest ecosystem models and ECC is essential for understanding the changing dynamics and impacts on ECC [77,81]. Additionally, assessing whether each model's ECC meets human resource demands, ensuring the continuity and integrity of ecological restoration systems, is a crucial research focus [82]. However, current research tends to concentrate on individual models, overlooking the potential interactions and synergies between them.

In KD areas, forest ecosystems possess various ecological, economic, and cultural values, forming a complex symbiotic system. By examining the diverse forest ecosystem model in detail, analyzing its specific influence and internal driving forces on the ECC of KD areas can enhance regional ES (Figure 14). Furthermore, it offers novel strategies and approaches for safeguarding the diversity and stability of forest ecology in KD areas.

(**a**) (**b**)

Figure 14. Different forest ecosystem restoration models in KDC: (**a**) artificial afforestation; (**b**) closed mountain afforestation.

4.2.2. Assessment of Forest ECC

(1) In response to the key scientific issue of an incomplete ECC evaluation system, it is necessary to deepen the simulation and prediction research on evolutionary trends and future scenarios, and construct a universal and scientific evaluation system.

The evaluation of ECC has established a clear research focus and identified key issues within the theoretical framework. However, there is a need to enhance the accuracy and depth of its practical application. Current research tends to concentrate on a single or a few subsystems such as social economy, resource environment, and ecosystem, overlooking the intricate inter-relationships between subsystems within a composite system. Diverse regions and environments exhibit significant variations in the demand for indicator systems and the outcomes of model applications. Even when different models are applied in the same region, disparate conclusions may be drawn [83,84]. Consequently, there is a pressing need to investigate the compatibility and universality of models. ECC, as a comprehensive reflection of the interplay between nature, economy, and society, highlights the dynamic equilibrium between ecosystem supply capacity and socio-economic demand [45]. While existing research methods are varied, there is a scarcity of scenario simulation tools that can holistically forecast future development trajectories. Therefore, there is an urgent call for theoretical innovation and technological advancements to develop a precise, multi-factor coupled ECC evaluation model. This model would enable a scientifically informed assessment and guidance for practical applications.

In KD areas, where water scarcity, poor soil quality, and erosion susceptibility are prevalent, evaluating ECC is essential. This evaluation not only impacts the restoration and sustainable development of forest ecosystems, but also plays a crucial role in ensuring the effectiveness of KDC and the synergistic effect of regional ecosystems.

(2) In response to the key scientific issue of the differential mechanisms of forest ECC at different research scales, it is essential to clarify the intricate patterns of interaction and feedback mechanisms involving multiple factors that influence forest ECC at different scales of research.

The evaluation of forest ECC is currently heavily focused on the macro scale, at and above the city and county levels. However, there is a lack of in-depth exploration at the micro scale below the township level. This includes a deficiency in ecosystem coherence analysis from cities and counties down to townships, villages, and even finer scales. This limitation overlooks the spatial heterogeneity within the region, leading to information loss and unclear spatial distribution. As a result, it hampers the seamless integration and effective guidance of multi-level spatial planning systems, and lacks precision in strategy implementation [85,86]. The diversity of research scales, ranging from global to regional levels, directly impacts the assessment of forest ECC and the development of regulatory strategies [87,88]. Moreover, different scales significantly influence the types, quantities, and distribution of forest ecological services, which in turn affect their contributions to human well-being and socio-economic development [89]. The majority of extant studies are constrained to a single or macro scale, thereby failing to acknowledge the significance of scale effects and any internal spatial discrepancies that may exist. Furthermore, the singularity of the time dimension, the limited temporal span, and the absence of dynamic analyses represent additional shortcomings in the research.

In light of the considerable scale disparities between the natural and humanistic environments in the rocky desertification region, and the abundance and diversity of naturally occurring or human-induced vegetation types, including *Pinus massoniana*, *Pyracantha fortuneana*, and other multi-species, it is imperative to conduct a comprehensive analysis of the interaction and feedback mechanisms between the ECC of forests and ES at multiple scales. Beginning with a multi-scale approach is essential to investigate the correlation between forest ECC and ES in KD areas, including their internal spatial variations. The ultimate goal is to establish a scientific foundation and updated criteria for KDC and ES preservation.

4.2.3. Regulation of Forest ECC

(1) In response to the key scientific issue of balancing and coordinating socio-economic development with forest ECC in KD areas, researchers should prioritize understanding the complex and subtle interaction between the socio-economic development process and ECC.

Socio-economic development, as a key driver and objective of human social advancement, is essential for fostering ecological restoration. Different levels of KD present varying degrees and patterns of socio-economic development [90]. Regions with mild KD are primarily influenced by available resources and market demand, while areas with severe desertification encounter challenges such as environmental limitations and technological obstacles [91]. The advancement of the socio-economic sector not only boosts the demand and financial capacity for ecological restoration, but also establishes a strong material foundation and financial backing, significantly impacting the ECC of forests. It is imperative to thoroughly examine the equilibrium and interaction between socio-economic development and forest ECC across different levels of desertification, to facilitate the coexistence and sustainable growth of forest ecosystems [92]. Nevertheless, current research on this relationship remains insufficient.

Given the unique economic structure of KD areas, it is imperative to implement tailored policies that consider the current social and economic development status and trends at different levels of KD areas. This will help in harmonizing the relationship between social economy and forest ECC, ultimately leading to the effective regulation of forest ECC. This, in turn, will ensure the long-term sustainability of forest ecosystems and regional ES.

(2) In response to the key scientific issue of how land use patterns serve as a key driving force affecting forest ECC, it is essential to investigate the effects of various land use patterns on vegetation structure and function, and the ecosystem services they deliver.

The land use pattern is a crucial factor that significantly influences and shapes the spatial heterogeneity of forest ECC [93]. Different land use patterns have a profound impact on ecological service functions. Moreover, land use changes also lead to a shift in interaction patterns between vegetation, soil, and atmosphere, directly influencing the dynamic changes in forest ECC [94]. This process involves adjusting the vegetation's sensitivity and adaptability to environmental stresses like drought, which in turn affects resilience to environmental changes [33]. Analyzing land use patterns can help uncover spatial patterns, evolutionary trends, and the underlying driving mechanisms of forest ECC under different land use strategies [49,95]. However, current research tends to focus on the impact of individual land use modes, overlooking the complex effects of transitioning between different modes and their comprehensive role in forest ECC.

The adjustment of land use patterns in KD areas is crucial, due to the high proportion of agricultural land and the low proportion of forests and grasslands. Exploring the impact of different land use patterns and their conversion mechanisms on forest ECC and ES will offer innovative paths and a scientific basis for land use planning and ECC regulation in KDC areas.

4.2.4. Enhancement of Forest ES

(1) In response to the key scientific issue concerning the increase in the forest ES threshold under drought stress intensity, researchers should focus on understanding the complex and nonlinear interaction between drought stress intensity and forest ES. It is important to accurately identify the critical turning points in this relationship.

The intensity of drought stress, recognized as a critical factor impacting regional forest ES [96], significantly influences the physiological and ecological functions of vegetation and the ecological services it provides across various levels, ultimately posing a threat to forest ES [97]. Severe drought conditions can diminish the photosynthetic and respiratory activities of vegetation, compromising its resilience and recovery capacity in the face of environmental disturbances [98]. Hence, it is crucial to investigate the existence of a threshold effect in relation to drought stress intensity, where forest ES might rapidly deteriorate or collapse once the drought intensity surpasses a critical threshold [99]. However, there remains a lack of comprehensive understanding regarding the threshold effect of forest ES under varying levels of drought stress intensity.

In order to understand the impact of drought on vegetation growth in KD areas, it is essential to analyze the nonlinear relationship and critical threshold between drought stress intensity and forest ES. This analysis will help in developing effective strategies to enhance ES. The response of different types of vegetation to drought and other forms of stress is not uniform, due to the physiological characteristics of the vegetation in question, the environmental conditions in which it is grown, and the specific type and degree of stress to which it is exposed. By studying the response mechanisms and threshold effects of forest ecosystems under varying levels of drought stress, new indicators can be identified to evaluate forest drought resistance and resilience in KDC areas (Figure 15). This will guide the implementation of ecological restoration and protection measures.

Figure 15. Forest drought stress intensity is high in KD areas.

(2) In response to the critical scientific question of elevating forest ES thresholds across varying levels of soil erosion, it is imperative to delve into the intricate and nuanced relationships and feedback loops between soil erosion and vegetation development.

Soil erosion plays a crucial role in regulating forest ES by significantly impacting soil quality, structure, and function. This process alters the interaction between vegetation, soil, and atmosphere, posing a challenge to the stability of forest ecosystems [100]. Soil erosion leads to decreased soil fertility, changes in soil structure, and disruptions in the balance of microbial communities. These effects create a chain reaction that hinders vegetation root expansion, limits nutrient acquisition, and reduces water use efficiency [101]. A detailed analysis of the degree of soil erosion can unveil its complex impact on forest ES [39,102]. Understanding the changing patterns of ES thresholds in response to varying degrees of erosion is essential for identifying critical points of system collapse and developing effective strategies to enhance ES.

Soil erosion is a significant factor contributing to KD [17]. Investigating the impacts of vegetation roots, soil fertility, and microbial communities across varying levels of erosion enhances our comprehension of the connection between soil erosion and ecological stability. Furthermore, it paves the way for enhancing erosion resistance and ecosystem resilience in regions focused on KDC.

5. Conclusions

This study systematically explored recent trends and hotspots in forest ecosystem research by analyzing 350 relevant studies from databases like CNKI and WOS. The findings indicate the following: (1) a significant increase in research publications since 2017, with a growth rate exceeding 75%. The research process was categorized into a sprout stage, a fluctuating growth period, and a rapid growth period. (2) The research area is predominantly concentrated in Asia, notably China (94.12%), followed by North America. (3) In terms of research content, assessment of forests ECC emerged as the most prominent topic (40.58%), followed by enhancement of forest ES (23.42%), regulation of forest ECC (15.32%), and forest ecosystem (11.15%).

This paper proposes solutions to key scientific questions for future research, including the following. (1) The supply capacity of forest ecosystems in complex environments should be explored, especially the effects of drought on the soil–vegetation–atmosphere system, and the differences in the ECC of different forest ecosystem models and their mechanisms should be elucidated. (2) The evaluation system of ECC should be improved, strengthening the prediction of future scenarios, and the mechanism of differences in ECC at multiple scales and the role of multiple factors should be analyzed. (3) The relationship between socio-economics and ECC in KD areas should be studied, and the influence of land use patterns on the ECC of forests should be explored. (4) The strategy to increase the threshold of ES of forests under drought stress should be defined, and the influence mechanism of soil erosion on the threshold of ES should be explored. These studies will provide an important scientific basis for the sustainable management of forest ecosystems in KDC.

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