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Review

Review on Driving Factors of Ecosystem Services: Its Enlightenment for the Improvement of Forest Ecosystem Functions in Karst Desertification Control

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Abstract: Understanding the multi-scale and multi-factor driving mechanisms of ecosystem services (ES) change is crucial for combating the severe degradation of the ecosystem. We reviewed 408 publications on ecosystem structure, biodiversity, and plant functional traits related to ES in forest ecosystems. Strategies were proposed and key scientific issues were pointed out to improve the forest ecosystem in the karst desertification area. The results showed that the total number of publications has increased rapidly since 2014, of which biodiversity studies contributed the majority. China, the USA, and Germany were the top three countries, accounting for 41%, 9%, and 6% of the research, respectively. Further review found that structure, species diversity, and functional traits have an apparent effect on ES at different (macro, meso, and micro) scales. The optimization of tree structure contributes to the improvement in ES provision and the regulation capacity. Species diversity plays an important role in provision services, while functional diversity is equally important in regulation services. Plant root functional traits can not only help regulation services but also determine the species and structure of rhizosphere microbial communities. The response of ES to a certain factor has been extensively reviewed, but the interaction of multiple driving factors needs to be further studied, especially in how to drive the supply capacity of ES in multi-factor and multi-scale ways. Clarifying the driving mechanism of ES at different scales will help to improve the supply capacity of the ecosystem and achieve the goal of sustainable development.

Keywords: biodiversity; ecosystem services; forests; karst desertification; plant functional traits; structure

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1. Introduction

Ecosystem service (ES) has been defined as the benefits for human populations derived directly or indirectly from ecosystem functions [1], which provide essential material and non-material conditions for human existence and development. However, ES and biodiversity have been severely degraded in recent years [2,3]. The Millennium Ecosystem Assessment (MA) evaluated 24 ESs globally and suggested that 60% were degrading. In addition, according to the report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), the average abundance of species in most important terrestrial communities has declined by at least 20%; 14 of the 18 services assessed were declining; and the global species extinction rate was tens or even hundreds of times faster than the average for the past 10 million years [4]. These conclusions indicated that biodiversity loss might lead to a severely negative impact on ES supply [5,6]. Climate change, ecosystem structure, and land use change were the main driving factors of ES change at the macro scale [7–9], with plant functional traits, species invasion, and microbial diversity acting at the micro and meso scales [10,11]. The impact of global climate change and disturbance mechanisms on mountain areas is greater than that of other biogeographic regions [12] and is expected to intensify further [13]. Human activities are the main factors affecting the significant decline in ecosystem service value and ecological problems, and land use change is the most obvious manifestation of human activities [14]. Climate and land use change will cause changes in the structure and process of different ecosystems and ultimately affect the supply capacity of ES. The functional diversity of plant traits is linked to ecosystem function and biodiversity [15]. Plant communities composed of functionally divergent species or traits contain species combinations that enhance productivity through complementary resource use [16]. The impacts of climate change [17] and land use/cover [18] on ES have been summarized well. This study focuses on the role of ecosystem structure, biodiversity, and plant functional traits, which is of great significance to optimizing ecosystem function.

Many researchers have studied the impacts of climate change [19–23], land use [24–27], and landscape structure [28–32] on ES in different ecosystems. The results showed that all these drivers have a direct and significant effect on ES. However, climate change, land use, and landscape structure change do not affect ES directly but by controlling community structure, plant functional traits, and species diversity in the forest ecosystem. Studies have found that both negative and positive climatic impacts have only small effects on forest dynamics compared to silvicultural measures. Only for very few water-limited stands did climate change affect forest growth negatively due to pronounced drought stress and mortality [33]. On the contrary, forests can regulate the climate through their own attributes. Forests efficiently recycle water using several plant traits, such as deep rooting systems, high leaf area, and surface roughness that facilitates upward water vapor transport. These conditions, strongly related to the forest structure, increase rainfall over tropical forests compared to grass in grazing lands or soy crops [34]. In addition to carbon sinks and carbon storage services (biogeochemical processes of climate regulation), forests also provide climate regulation ES through biogeophysical processes [35]. Forests are responsible for an atmospheric cooling effect through transpiration, and surface winds can transmit the cold air beyond the forest boundary [36], which plays a role in regulating the regional microclimate. Furthermore, biodiversity has been considered to be either the basis for ecosystem services provisioning or a service in itself [2,37]. As the terrestrial ecosystem with the highest biodiversity, the forest has been widely recognized for its role in biodiversity conservation and ecosystem multifunctionality maintenance [38–40]. However, many precious studies paid more attention to species diversity and ignored the role of functional diversity. Lyashevska and Farnsworth [41] pointed out that plant diversity consists of multiple dimensions of diversity, including classification (such as species richness), function (such as diversity of wood density), and structure (such as the average height of the community). Different plant diversity indicators can show different relationships with different ecosystem services [42]. For example, forest functional diversity is positively correlated with hydrological regulation services. The increase in land use intensity led to a reduction in niche differentiation of interspecific functional traits, resulting in the degradation of hydrological services in the forest ecosystem [43]. Although some studies have shown the role of functional traits [44], species diversity [45,46], and functional diversity [47] in forest ES, the relationship among them needs further study, and the key scientific issues need to be clarified.

In the carbonate region, especially in the karst desertification area, the soil layer is shallow and forms slowly because of the binary (aboveground and underground) hydrological structure and process. Serious soil erosion limits vegetation growth, and strong human disturbance leads to the occurrence of karst desertification eventually [48,49]. Further, karst desertification intensifies the frequency of droughts, floods, and other disasters, which seriously damage ecological functions and restrict regional sustainability [50]. For example, water and wind can erode the topsoil easily after vegetation degradation, which reduces the water conservation and nutrient supply capacity [51]. Moreover, the decline in plant coverage also degrades regulation services such as carbon sequestration, oxygen release, and hydrological regulation [52]. Water flow takes nutrients into underground spaces, which limits the growth of ground flora and reduces product provision services [51].

Restoring damaged ecosystems rapidly and effectively and improving ES supply capacity are the primary tasks of the eco-degradation area. According to a study by Duarte et al. [53], landscape composition and configuration significantly affect ES. Hodder et al. [54] believed that conservation, management, and interventions at the landscape scale might enhance the supply of a series of ESs (carbon storage, fiber and food, etc.). Laughlin [55] proposed a quantitative model for ES recovery using trait values (e.g., selecting species with high wood density and low specific leaf area to improve community resistance to drought). Biodiversity and ES loss not only directly affect the livelihood of poor populations but may also further exacerbate a decline in human well-being [2]. The ecosystem structure and landscape pattern lend support to this theory at the macro scale, while tree structure, functional trait, species diversity, and functional diversity at the meso and micro scale can provide specific community construction and species configuration schemes. Although the combination of the two scales can effectively optimize the functions of degraded forest ecosystems, there are few existing studies that have been reported.

The purpose of this study is to provide a theoretical basis for the optimization of forest ecosystem function by summarizing the relationship between structure, functional traits, and biodiversity and ES. A systematic review of 408 publications related to ES driving was conducted. We analyzed the annual, institution, and country distribution of publications and created a co-occurrence network analysis for keywords. The research progress on the driving effect of structure, biodiversity, and plant functional traits on ES change was emphatically summarized, and the findings for improving forest ecosystem function in karst desertification areas were put forward. Specifically, we (i) identify the development trend of ES drivers research, (ii) discuss the enlightenment of ES driving factors for forest ecosystem improvement in karst desertification areas, and (iii) explore some scientific issues and opportunities for future work.

2. Materials and Methods

2.1. Publications Acquisition Source

The web of Science (WoS) is an important database for obtaining global academic information. The three major citation indexes (SCIE + SSCI + A&HCI) of WoS include more than 12,400 authoritative and high-impact international academic journals worldwide, covering natural science, engineering technology, social sciences, and arts and humanities. China National Knowledge Infrastructure (CNKI) is the largest academic resource data platform in China, which includes academic resources in multiple research fields and disciplines. These two databases can provide a large amount of research data for this study, so we chose WoS and CNKI as the literature acquisition sources. On 12 October 2022, "Structure (ST) + Ecosystem services (ES)", "Biodiversity (BD) + Ecosystem services (ES)", "Plant functional trait (PFT) + Ecosystem services (ES)" were used as the search terms, and a document search was carried out in WoS and CNKI databases (Figure 1). To ensure that the retrieved publications were highly relevant to this research topic, the search criteria were set as "title". A total of 521 publications were obtained, and screening and statistics of publications were conducted. It should be emphasized that due to the restrictions of access rights and language barriers, we only accessed the WoS and CNKI databases and read the articles that written in English and Chinese, which makes many publications in other languages unavailable.

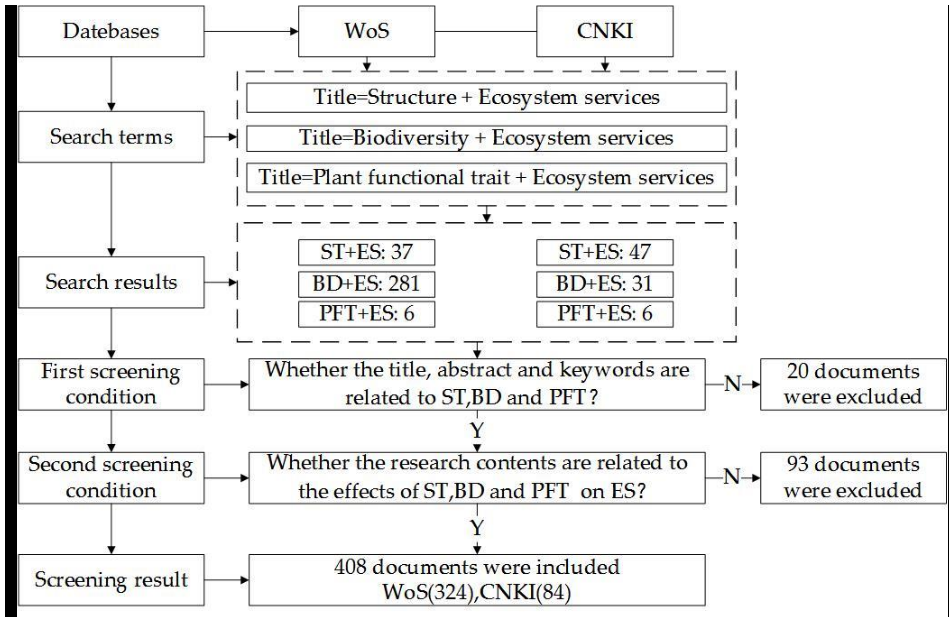

Figure 1. Process of publications' acquisition and screening. This study's systematic mapping process illustrates articles from the initial search to screening for synthesis (identification, screening, eligibility, and inclusion). Publications were found through a database search in the identification stage. Then, the articles captured were screened based on ecosystem services drivers (through titles, keywords, abstracts, and full-text articles) at the screening and eligibility stages. Finally, the publications satisfying the eligibility criteria were included in the study.

2.2. Publications Screening and Statistic

After searching, we selected and exported all publications to excel sheets. Then, publications were preliminarily screened by reading titles, abstracts, and keywords. The title, abstract and keywords that did not contain "ecosystem services" or did contain but had nothing to do with "ecosystem services" were not considered. A total of 20 articles were excluded that were not relevant to the research topic. After that, 501 remaining full-text publications were read. Excluded publications included those in which there were "ecosystem services", "structure", "biodiversity", "plant functional traits" in the text, but the text did not involve research on the driving force of ecosystem services. A total of 93 articles which were uncorrelated to the purpose of this study were excluded. Eventually, 408 publications were retained, including 84 (21%) for structure, 312 (76%) for biodiversity, and 12 (3%) for plant functional traits. The included 408 publications (84 in Chinese and 324 in English) were read entirety to extract useful information. MS Office excel 2016 was used for statistical analysis and drawing. We graphed the number of publications in each year from 2005 to 2022 to identify the specific year in which there was the co-occurrence of ES and drivers and development trends in ES drivers research. We then used ArcMap 10.5 to map the publications' distribution in countries and institutions to analyze major ES research countries and organizations. Finally, the keywords of all articles were exported as "ris" files in WoS and CNKI and imported into VOSviewer 1.6.16 software to create a co-occurrence network of keywords.

3. Results and Discussion

3.1. Distribution of Documents

The annual distribution of literature (Figure 2) shows that the research on biodiversity and plant functional traits occurred later than that on structure. In terms of quantity, the research on biodiversity has increased significantly, while the research on structure and plant functional traits has increased slowly. From 2005 to 2014, the total amount fluctuated, but the growth rate was slow. Therefore, we divided the period from 2005 to

2014 into the initial stage of ES research. In 2015, the total amount of literature increased significantly, so we named the period after 2014 the mature stage, mainly due to the outstanding contributions of biodiversity research.

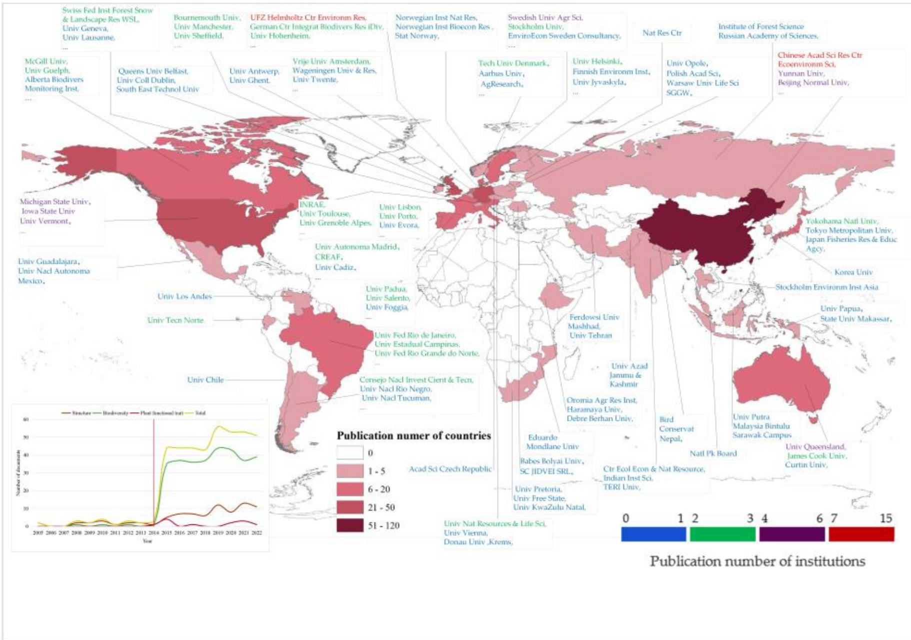

Figure 2. Distribution of documents.

The global distribution of literature was analyzed based on the country where the first author's organization was located. The area distribution is shown in the red map in Figure 2 (after sorting out 408 publications). China has the largest number (112), accounting for 27% of the total number of publications, followed by the United States with 47 (12%), and Germany tied for third with 32 (8%). The reason for the large differences in the international distribution of publications may be that there are few databases, and many publications cannot be obtained. It may also be that there are differences in expressions at home and abroad, so some publications are missed.

Based on the organization of the first authors, the organization distribution analysis was carried out. There was a wide range of research institutions (303 in total), but the chart space was limited. Therefore, only the top three organizations of each country were listed here. Among them, the top 10 institutions are Chinese Acad Sci Res Ctr Ecoenvironm Sci, UFZ Helmholtz Ctr Environm Res, Yunnan Univ, Michigan State Univ, Beijing Normal Univ, Iowa State Univ, Swedish Univ Agr Sci, Univ Queensland, Univ Vermont, and Henan Univ. Universities occupied most of the research institutions, indicating that the education organizations paid more attention to ES drivers. Judging from the individual author, the top 10 contributors to the number of publications on the topic are Ricketts Taylor H (5), Sonter Laura J (5), Polasky Stephen (4), Watson Keri B (4), Woodward Guy (4), Ding Shengyan (3), Xue Fengzhi (3), Fu Bojie (3), Wen Zhi (3), Yu Dandan.

3.2. Co-Occurrence Network of Keywords

Keywords are the condensed key information of a paper, and we can determine the research focuses of each field by analyzing the keywords. A co-occurrence network clustering analysis was performed using the keywords of 408 publications (Figure 3). Each keyword must appear in at least 5 publications or will not be counted; a total of 162 keywords were extracted. The larger the label and shape in the figure, the higher the frequency of the keyword, and the thickness of the connecting line is proportional to the co-occurrence frequency of the keyword. The most frequently used keywords were ecosystem services (150), conservation (125), biodiversity (97), management (81), diversity

(62), climate change (49). It can be seen in the figure that cluster 1 (green) is centered on ES, with conservation, biodiversity, patterns, etc., as auxiliary research; cluster 2 (blue) focuses on diversity and land use; cluster 3 (red) pays close attention to management and values. In addition, keywords such as climate change, natural capital, and agriculture were widely used.

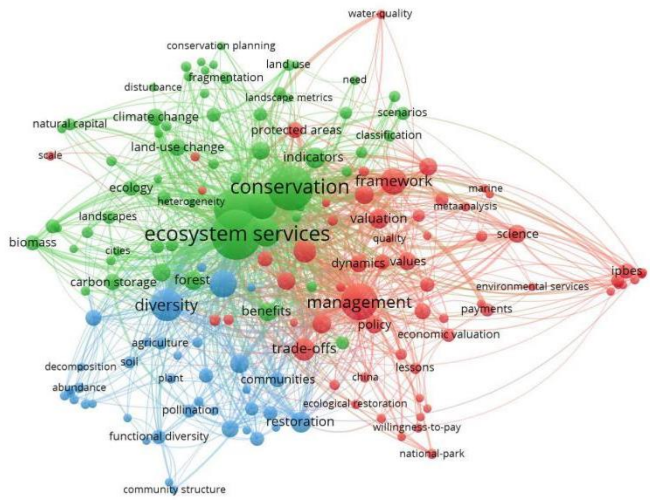

Figure 3. Co-occurrence network of keywords.

3.3. Main Developments and Landmark Achievement

(1) Ecosystem structure determines ecosystem processes and functions

Landscape structure not only affects the biodiversity [56] and vertical structure [57] of urban plants but also has a significant impact on the diversity of plant communities, the structure of agroecosystems [58], and pollination [59]. The composition and configuration of the landscape are considered key factors when explaining the changes in plant species diversity at different spatial scales [60]. Habitat loss and fragmentation, such as the reduction in patch size and loss of connectivity, have adverse effects on plant species diversity [61,62]. Habitat fragmentation leads to patch area reduction, connectivity loss, and edge effect increase, which may lead to a loss of ecosystem functions related to carbon and nitrogen conservation, ecosystem productivity, and pollination [63]. Fragmentation of the watershed landscape leads to a decline in soil conservation services [64]; a reduction in forest area and an increase in impervious surfaces are the main reasons for the decline in regional ecosystem service value [65]; landscape heterogeneity directly affects various attributes of the ecosystem, such as seed propagation, animal movement, population maintenance, the interaction between species, and dynamics and basic functions of the ecosystem [66]. In other words, landscape structure, including composition (quantity of each land use/cover type) and configuration (spatial arrangement of land use/cover type), can affect the supply of ES [67].

(2) Forest spatial structure influences water regulation and species diversity

Forest spatial structure refers to the spatial relationship of trees in the forest (such as size and distribution), which reflects the spatial relationship among species in the forest communities [68]. It also determines the competition between trees, the spatial niches, and the stability of the stand structure. In forest ecosystems, the density, spatial arrangement and canopy structure of vegetation exert strong control over many ecosystem functions that depend on the scale of the ecosystem [69]. The forest structure plays an important role in regulating water and air circulation. Canopy coverage, leaf characteristics (area, biomass, morphology), and branching characteristics (density, quantity, length) are considered key factors affecting the canopy water storage capacity [70,71]. Tree height not only affects canopy fluctuation and energy exchange with the atmosphere [72] but also affects soil splash erosion by water. In addition, the stand density can regulate the species diversity under the forest. The species diversity of the shrub and herb layer under the high-density *Eucalyptus robusta* Smith forest is significantly less than in low-density forests [73]. The shrub layer diversity of the *Cupressus funebris* Endl. plantation in Yunding Mountain showed a single peak change of first increasing and then decreasing with the decrease in stand density, while the herb layer diversity showed a double peak change [74]. Tending and cutting can effectively regulate the spatial structure of the forest, but the cutting intensity should be different according to different forest types [75]. The more reasonable the structure of the stand is, the higher its stability will be and the more functions it will play [76].

(3) Biodiversity is a crucial driver of the nutrient cycle

Some researchers believe that losing plant diversity will reduce soil microbial diversity [77]. High plant diversity will increase the carbon input from the rhizosphere to the microbial community, thereby increasing microbial activity and carbon storage [78]. Increasing plant diversity can increase the accumulation and use efficiency of soil total nitrogen [79,80], improve plant productivity and pollination media, and inhibit weeds and pests [81]. Some researchers believe that the impact of plant diversity on dryland ecosystem functions and services (i.e., multi-functionality) is indirect but is the result of the positive impact of plant diversity on microbial diversity [11,82]. Most microbial species are heterotrophs, which can produce specific extracellular enzymes to decompose fauna, plant, microbial residues, and various complex organic substances into inorganic substances (such as CO_2, H_2O, NH_3, $SO^{2-}{}_4$, and $PO^{3-}{}_4$). These inorganic substances can be used by primary producers to participate in the material cycle again [83,84]. The increase in soil biodiversity from a very low level to a medium level may also accelerate nutrient cycling [85]. In addition, microbial species are also involved in the mineralization of organic matter, biological control of pathogens, and remediation of ecological environmental pollution [86,87]. Therefore, some researchers claimed that microbial diversity determines the productivity of ecosystems (especially in nutrient-poor ecosystems) and plant diversity. On the other hand, when soil microbial species compete for nutrients with plants as pathogens or convert nutrients into forms unavailable to plants, they may also harm plant productivity [88]. However, the driving mechanisms of plant diversity and microbial diversity on ecosystem functions and services lack sufficient empirical evidence and need further study.

(4) Functional diversity promotes the maintenance of ecosystem multi-functionality

Species require different conditions for seed production, propagation, and germination [89]. They can promote species coexistence by adjusting lifestyle or phenology habits (such as the growth rate, shade tolerance, crown retention time, and reproductive capacity), thus forming different ecosystem functions [90]. As the foundation, changing ecosystem functions directly affects ES and human well-being [91]. Ecosystem multi-functionality (EMF) was first proposed in 2004 [92]; since then, the maintenance of EMF has gradually become one of the focuses of researchers, and substantial progress has been made. Gamfeldt et al. [93] put forward a conceptual model to explore the impact of species loss on the comprehensive functions of the ecosystem (i.e., EMF). They found that the overall function is more vulnerable to the impact of species loss than a single function due to the complementarity between the multiple functions. Xu et al. [94] emphasized that maintaining multiple functions requires not only higher species richness but also diversified community types. Because different functional traits of coexisting species can increase the overall utilization efficiency of resources and thus promote ecosystem functions. The functional traits of dominant species strongly affect the ecosystem functions of communities. Therefore, functional diversity is considered the key driver of ecosystem versatility [95,96]. Though species diversity is also considered an important influencing factor of EMF, the positive correlation between species diversity (especially species richness) and ecosystem function may be due to the increase in species number leading to the increase in trait diversity [97]. Functional traits are related to the resource utilization (including selection effect and complementary effect) of species [98]; it may be a better predictor of ecosystem functions [99]. Therefore, functional diversity may be more conducive to maintaining EMF than species diversity [100,101].

(5) Plant functional traits of both aboveground and underground parts affect ESs simultaneously

Functional traits reflect the adaptation of organisms to physical and biological environment change and the trade-offs among different functions [102], which is a core concept of functional ecology [103]. Many studies have shown that plant functional traits play an important role in ES. For example, high leaf nitrogen content can promote soil organic carbon storage [104]. Plant canopy density and fine root percentage have an important impact on ecosystem hydrological regulation services [43]. Different traits affect services differently. Root traits are mainly related to erosion control, climate regulation, and biomass production; flower traits are concerned with aesthetic attraction and pollination; and stem and whole plant traits are associated with biomass production [105]. Dennis et al. [106] believed that the type and quantity of root exudates determine the type and quantity of rhizosphere microbial species, as well as affect the structure of the rhizosphere microbial community and carbon utilization. As a key aspect supporting plants' ability to stand and nutrient absorption, the root system continuously secretes various substances to promote the absorption of mineral elements by plants and provides carbohydrates, sugar alcohols, amino acids, and phenols for rhizosphere microbial species as nutrients and energy supply [107]. At the same time, root-related microbial species can directly affect plant growth and population dynamics and indirectly affect nutrient cycling by controlling plant litter input and root nutrient absorption [88,108], forming a mutual feedback mechanism among plants soil microbial species. The plant root system also has an important effect in promoting material circulation and hydrological regulation [109]. Under specific conditions, plant roots can transfer soil moisture in the deep layer to the dry surface soil through conduction tissues, thereby completing water redistribution [110]. The interlacement of underground roots can effectively improve the soil shear strength and soil permeability, which can reduce soil erosion [111]. Plant functional traits are important driving forces for ES changes, both aboveground and underground.

3.4. A Systematic Review of ES Drivers for Forest Ecosystem Improvement in Karst Desertification

(1) The optimization of stand spatial structure helps improve the quality of the ecosystem

The regulation of forest spatial structure and distribution pattern by manual measures is conducive to promoting interspecific interaction and improving ecosystem functions. Pruning significantly increases the light intensity, temperature, understory biomass, and Shannon Weiner index of species [112]. The intercropping of forest and grass can promote the regulation of soil quality and microclimate and increase forest products [113]. This shows that reasonable management measures can not only improve the forest structure and productivity but improve the carbon fixation capacity of vegetation. Thinning and replanting can significantly improve the forest layer index and mixing degree. The increase in individual differences between trees can expand the growth space of young and middle-aged forests, which reduces the competitive pressure between trees and significantly improves the stand structure (Figure 4) [114,115]. There are more problems in the spatial structure of the karst desertification forest ecosystem compared with non-karst desertification. Common situations include sparse understory vegetation and incomplete hierarchical structure of arbor, shrub, and grass; broken patches and a lack of a large, connected forest landscape; and a single species disposition, which is not conducive to resisting diseases and pests. Therefore, implementing artificial management in this area to optimize the forest spatial structure is conducive to improving the forest ecosystem function and service supply capacity. According to the characteristics of karst desertification forest, the optimization of stand spatial structure can be carried out horizontally and vertically. In the horizontal space, natural forests can be thinned, replanted, and renewed manually. Intercropping of trees and cereal/grass and mixed plantation can be implemented to regulate the composition and the proportion in the artificial forest. In the vertical space, trees can be pruned and reshaped to control their height and crown width [116] so that the lower trees can fully absorb solar energy and improve the community' productivity. In short, during planting and ecological restoration, the layers of trees, shrubs and herbs should be intact to improve the self-regulation ability of the ecosystem in terms of nutrient decomposition and circulation [117].

(**a**)

(**b**)

Figure 4. Comparison of different stand structures: (**a**) Worse stand structure with Tectona grandis L.F. only. (**b**) Better stand structure with Quercus fabri Hance, Lindera glauca (Sieb. et Zucc.) Bl, Arthraxon hispidus (Trin.) Makino, etc. (Source of the pictures: Photoed by Lingwei Kong.).

(2) Building plant functional groups based on functional characteristics and environmental conditions is conducive to improving ecological functions

Plant functional types combine a series of plants with certain plant functional traits, which are the basic units for studying the dynamic changes of vegetation along with the environment [118,119]. They link plant morphology, community science, and ecological processes, and are a very useful tool for studying the dynamic changes between climate and vegetation. Environmental heterogeneity (such as soil, light, and terrain) shapes the characteristics of individual plants to a certain extent, it also affects the interactions between species and their proportions in different spatial ranges. The aim of community structure optimization can be achieved by making full use of the adaptability of species characteristics to the environment to dispose of species [120,121]. In karst desertification areas, due to exposed bedrock and a lack of surface water, adaptive plants are usually drought resistant, lithophytic, and calciphilous [122]. The existing research found that the soil enzyme activity, soil nutrients, and microbial community diversity index of forest grass intercropping in karst mountain areas were significantly higher than in wasteland and farmland returning to grassland [123]. Therefore, since few species are included in afforestation for karst desertification control (Figure 5a), multi-species interplanting can play an important role in promoting ecological restoration. In addition, in forest gaps with enough sunlight, short-lived and shade-intolerant species have higher growth rates than long-lived and shade-tolerant species [124]. In forests with high canopy density and insufficient light, shade tolerant species can be selected for planting, which can enhance the integrity of the stand structure (Figure 5b). The characteristics of herbaceous plants are mostly similar—weaker than most trees and shrubs, but they can also be appropriately added to enhance the overall stability of the community.

(a) (b)

Figure 5. Comparison of communities comprising different species in Guizhou, China: (**a**) Single species with *Zanthoxylum bungeanum* Maxim. only. (**b**) Multiple species with *Pinus massoniana* Lamb, *Quercus fabri* Hance, *Populus alba* L., etc. (Source of the pictures: Photoed by Lingwei Kong.).

(3) Biodiversity conservation is the foundation for maintaining EMF

Biodiversity determines ecosystem functions and processes [125,126]. Higher biodiversity can produce higher levels of ecosystem functions [127,128]. The plants are more abundant in karst habitats than in non-karst habitats in South China karst (accounting for 30%–40% of the total local species). Many species are rare, endangered, protected groups, and endemic species (10% are endemic karst species, and 20%–30% are characteristic karst species) [129]. However, the change and degradation in the ecological environment in karst desertification have led to the fragile karst ecosystem becoming more unstable and biodiversity declining [130]. The degradation of plant communities led to reduced biomass and soil organic matter, which affected microbial diversity. The evolution of habitat toward drought accelerated the decomposition rate of soil organic matter [131]. As a result, the content of soil organic matter and water permeability decreased, and finally, a fragile ecosystem with poor ecological structure and functions was formed. The assessment and protection of biodiversity loss should be one of the core tasks in this area. Unfortunately, few researchers have carried out assessments and proposed feasible protection plans so far. Under the threat of climate change, Hylander et al. [132] proposed two forest biodiversity conservation tools (Resistance and Transformation) at the landscape scale, including eight specific implementation measures. In addition, Lindenmayer [133] also proposed four general principles from the perspective of natural forest restoration. We believe that these are of great significance for biodiversity conservation in karst desertification areas. However, due to the differences in natural conditions, it is better to seek local protection schemes based on others' measures. Here, we proposed some suggestions, hoping to help the biodiversity conservation of karst desertification forest ecosystems. (1) In response to the loss of biodiversity caused by climate change, the endemic species in this region can be transplanted to other regions with suitable conditions, or the characteristics of species can be improved to adapt to climate change. At the same time, it is important introduce new species from other regions that do not exist in this region, but the scale should be controlled to prevent the occurrence of biological invasion. (2) To address the loss of biodiversity caused by human activities, supervision should be strengthened, and arbitrary logging, mining, and hunting should be prohibited. In addition, people ought to be encouraged to carry out relevant protection work, such as artificial afforestation, breeding instead of killing wild animals, and anthropic management of natural forests (Figure 6). (3) In the face of the loss of biodiversity caused by niche change, manual intervention can be carried out (cultivate endangered species and appropriately remove excessive species) to prevent the food chain from breaking. In a word, biodiversity conservation of karst desertification ecosystems is a long-term job, and there is still a long way to go.

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

Figure 6. Biodiversity conservation measures in Guizhou, China: (**a**) Close hillsides to facilitate afforestation. The dominant species include *Toona sinensis* (A. Juss.) Roem., *Pyracantha fortuneana* (Maxim.) Li, *Cladrastis platycarpa* (Maxim.) Makino, etc. (**b**) Artificial afforestation. The dominant species include *Zanthoxylum bungeanum* Maxim., *Juglans regia* L., *Prunus salicina* Lindl., etc. (Source of the pictures: Photoed by Kangning Xiong.).

(4) The combination of macro-scale landscape structure optimization and micro-scale biodiversity improvement can effectively increase the supply of ES

As a result of ecological degradation, the landscape in karst desertification areas shows high heterogeneity and fragmentation (Figure 7a) [134]. Meanwhile, the loss of plant and microbial diversity has also caused great damage to the EMF at the micro scale [81,85]. However, the relationships of services have obvious spatial scale dependence [135]. Research on a single scale may miss or even distort the interaction rules between ESs, which is not conducive to a comprehensive and objective understanding of ESs [136]. The fragmentation of landscape in karst desertification areas not only leads to a loss of biodiversity but also reduces the sustainability of land use [137]. Research showed that after implementing a series of afforestation and forest cultivation measures, the landscape diversity increased by 8%, and fragmentation decreased by 25% [138]. Therefore, it is necessary to adjust the type, number, and spatial distribution pattern of landscape components and patches at the macro scale (Figure 7b) so as to make each component harmonious and orderly, ultimately restoring the damaged ecosystem and achieving regional sustainable development [139]. For example, according to the ecological vulnerability characteristics of karst desertification areas, steep slopes and gentle slopes can be planned as forests/grasslands and farmland, which can improve soil and water conservation capacity and make full use of soil nutrients [140,141]. The configuration of patches (such as forest land, grassland, and water) around farmland can help to increase landscape diversity and biodiversity, improving the EMF [142]. The coupling of water and fertilizer in poor soil regions can help to increase the content of soil organic matter and the number of microorganisms, improving plant productivity [143]. Therefore, at the micro scale, plant and microbial diversity can be increased by artificial afforestation [144] and organic matter addition.

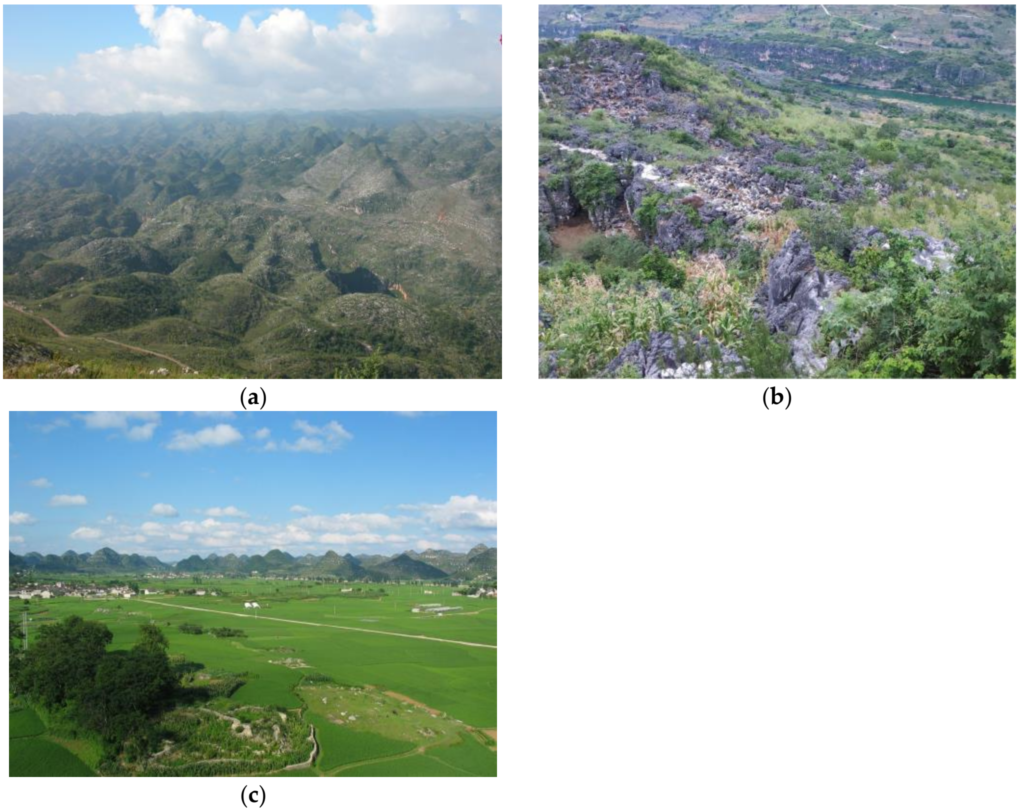

Figure 7. Comparison of landscapes configured by different patches in Guizhou, China: (**a**) Single patch configuration landscape with karst desertification. (**b**) Small vegetation patches and large stone patches in the process of ecological restoration. (**c**) Multiple patch configuration landscape without desertification. (Source of the pictures: Photoed by Kangning Xiong.).

3.5. Key Scientific Issues to Be Solved and Prospects

(1) How do ecosystem functions respond to structural changes? Research on interspecific relationships and functional differences in ecosystems with different structures can be carried out.

Understanding the response of ES and functions to the change in ecosystem structure is crucial for the efficient allocation of environmental resources and rational formulation of environmental policies [145]. An unreasonable landscape structure will lead to an overall decline in ESs and functions [146]. In the stand structure, interspecific interactions not only directly affect the flow and circulation of matter and energy among different components of the ecosystem but also affect the process of community construction, making the network structure closely related to ecosystem functions and community stability [147]. Mixed forests and multi-storied forest have stronger disease and pest resistance than monoculture forests and single-storied forests; natural forest have a better stand structure and biodiversity than artificial forests, as well as stronger overall ecological function [148,149]. Although more and more evidence show that landscape structure and stand structure are crucial to the supply of services, there are still some important questions to answer about the mechanism and process behind this role, including the key question about how to configure them to improve the ecosystem function. There are detailed results on the impact of a certain ecosystem structure on services, but few researchers have focused on the interspecific relationships and ecosystem functions driven by different ecosystem structures. In the future, research on biodiversity and ecosystem function differences within different structures should be strengthened, and the role of structures in ecological processes, functions, and services should be revealed.

(2) Species diversity or functional diversity contributing more to ESs; comparative studies on species and functional traits of different communities are needed.

Functional traits determine ecosystem functions, and species are considered a collection of functional traits [150]. Species provide many material products for human beings, and functional traits can affect regulating services such as the water cycle. They are indispensable carriers of ES. However, it is unclear who contributes more to ES supply between species and functional diversity. At present, research on the driving mechanism of biodiversity to ES is mostly focused on a single scale or dimension, and different conclusions will be drawn in different ecosystems [151,152]. Thus, the impact of species diversity and functional diversity on ES change needs to be further studied. In addition, aboveground and underground biodiversity, as well as their comprehensive impact in different scales or dimensions, can effectively explain more variations in EMF [153,154]. Researchers should pay more attention to the synergistic effect of above- and below-ground biodiversity in the future, extending the field observation period, enriching the community survey content, and selecting representative functional indicators to construct a long-term, multi-spatial, and multi-dimensional biodiversity-EMF database [155].

(3) The application of relationships between biodiversity and ecosystem service is insufficient. The practical application of existing research results should be strengthened.

Although some studies have paid attention to the interaction between biodiversity and ES, most focused on the impact of biodiversity on ESs. Few studies have talked about how to apply the relationship between biodiversity and ES at the practical level, and there is a lack of effective ways to realize relevant cognition. An important research direction is thus to explore ways to improve ESs according to the relevant knowledge of biodiversity and ESs, as well as diminishing the leap from theory to the application of the biodiversity ES relationship. In the face of the continuous impact of human interference and environmental change on ES, maintaining and improving ESs of oceans, forests, grasslands, and agriculture has become a practical problem that many regions must address [156]. Theoretically, it is possible to formulate management measures to improve and restore ES from the perspective of biodiversity, and the implementation of ecosystem management measures can, in turn, improve biodiversity and ESs. For example, forest restoration can increase species diversity and ecosystem productivity at the same time [157]. In practice, some studies have explored and verified the feasibility of applying the knowledge of biodiversity-ES relationships to policy-making and natural reserve management, forest ecosystem management, degraded ecosystem restoration, and agricultural ecosystem improvement, but the application of existing research results still needs to be strengthened in future studies.

(4) Few pieces of research integrate multiple driving factors of ES change; the research on the co-influence of natural and human factors should be strengthened.

In addition to climate change and human activities, ES changes are also affected by various drivers, such as ecosystem structure, biodiversity, and landscape. There are complex interactions between these driving factors [158]. Most existing research mainly focuses on the role of a single driver, while research on the synergy of multiple factors and their contribution rate is scarce. In the future, we should not only continue to deeply explore the mechanism of impact of climate change and land use on services but also strengthen the driving force of population, economy, policy, culture, and other social factors, as well as natural factors, such as ecosystem structure, biodiversity, landscape pattern, regional differentiation, and the interaction of multiple factors on service change. Meanwhile, it is necessary to reveal the contribution rate of different driving factors on the service change to manage the environment in the development, utilization, and protection of ecological resources. This will provide scientific guidance for ecological restoration in ecologically vulnerable areas and promote the realization of sustainable development goals.

(5) There is no case study on improving ES through landscape pattern optimization. Long time-series sample plot monitoring should be carried out to explore the optimal landscape pattern.

The landscape composition and configuration affect the ecological process. Understanding how landscape composition and configuration affect the supply of ES is the key to improving landscape management [67]. Most researchers have focused on the response of ESs to landscape structure changes, there are few reports on how to improve ES via landscape composition and configuration. Thus, effectively configuring the landscape to promote ESs and function is a difficult problem for landscape ecology, especially in areas with high spatial heterogeneity and changing land cover. Core area and grid size are important determinants of ecosystem service trade-offs and synergies, which affect ES interactions [159]. Future research needs to include a long-term dynamic observation of the field landscape configuration to determine an optimal landscape composition and configuration scheme and provide scientific basis for improving regional ecosystem functions and services.

4. Conclusions

A total of 408 publications were reviewed, and the annual distribution of publications showed a significant growth trend, in which biodiversity research accounted for the majority. The driving factors of ESs mainly focused on biodiversity, ecological protection and management, land use, and climate change. The role of structure, species/functional diversity, and functional traits is still unclear. Further review found a progressive synergy among structure, biodiversity, ecosystem function, and ES. A complete ecosystem structure has higher biodiversity and ecosystem stability. The increase in biodiversity can accelerate the material cycle and improve the ecosystem's productivity. Multifunctionality of the system helps to improve the supply capacity of ES. The combination of macro-scale ecosystem structure optimization and micro-/medium-scale species disposition is helpful for the ecological restoration and management in karst desertification areas. Specifically, land use types and landscape structures can be planned according to actual conditions, such as soil erosion, rock exposure rate, and soil quality, which is conducive to vegetation restoration and biodiversity protection. Management measures (such as plantation) can optimize the forest structure and promote the improvement of ecosystem functions. In addition, constructing forest communities according to plant characteristics can help to retard water and soil loss, accelerating nutrient cycling and improving the EMF.

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