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The scientometric analysis of Karst ecosystem structure and stability: insights for sustainable protection of World Heritage Sites

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Karst ecosystems, characterized by their fragility and sensitivity to disturbances, need structural stability to preserve biodiversity and geological integrity. Despite their ecological importance, systematic reviews on their stability and structure are scarce. This study fills this gap by analyzing 145 papers from Web of Science (WOS) and China National Knowledge Infrastructure (CNKI) through a systematic literature review. It identifies publication trends, keyword distributions, and regional research focuses, synthesizes key findings on ecosystem structure, disturbance types, and functional influences, and proposes three unresolved scientific questions: the structure-function relationship, a stability evaluation framework, and driving factors for stability optimization. The study provides a foundation for enhancing conservation and sustainable management of karst World Heritage Sites (WHSs), offering new insights into ecosystem stability and protection.

Despite their diversity, China's ecosystems are extremely vulnerable to human activity because of their climate and geographic location. Ecosystems have been greatly damaged by economic growth-driven population pressure and resource overexploitation, with degradation emerging as a key obstacle to sustainable development[1,2]. Maintaining ecological functions depends on the stability and resilience of ecosystems to disturbances, which are based on the integrity of their structure and function[3,4]. Ecosystem stability is a major global environmental problem[5,6], and as the demand for earth's finite resources increases biodiversity loss and environmental complexity become more noticeable[7,8]. Degradation and loss continue despite continuous efforts, threatening ecosystem services and biodiversity[9]. Thus, a major problem with immediate attention is the preservation of ecological health.

The structure and function of ecosystems are fundamental characteristics that define the identity and ecological roles of these systems[10–12]. Well-structured ecosystems not only enhance species diversity and function but also promote the flow of energy and matter[13]. Because structural changes have a direct impact on stability, which in turn affects ecosystem functions and service capacity, studies have indicated that improving ecosystem structure has become a study emphasis[14–16]. Restoring lost ecosystem services, structure, and function through structural alterations is a crucial topic of ecosystem stability study, intending to restore a site to its native state before disturbance[17]. The structure and function of lake and river ecosystems have been the subject of increasingly thorough investigation in recent years, while studies on terrestrial ecosystems have frequently concentrated on particular land use types, such as farms, forests, and grasslands[18]. 3S technologies—remote sensing, geographic information systems, and global positioning systems—have shown themselves to be useful instruments in these land use studies, especially when it comes to examining the variety and fragmentation of the landscape[19–21]. Landscape connection preserves environmental stability by aiding in the maintenance of biodiversity[22,23]. These studies highlight how land-use patterns affect ecological services and ecosystem processes[24]. Additionally, studies on trophic interactions, food webs, and ecological networks form the theoretical basis for understanding ecosystem composition, structure, and dynamics[25–27]. Both natural environments and human activities have significant impacts on ecosystem structure. Human activities mainly affect landscape spread and patch connectivity, while natural factors such as temperature, soil temperature, rainfall, and elevation have broader effects on structure[28]. Biodiversity loss, particularly species extinction, is a primary driver of ecosystem function decline, mainly influenced by human activities[29,30]. Climate change is expected to exacerbate these impacts, leading to further degradation of ecosystem stability and function. Notably, there may be a time lag between human disturbance and ecosystem response, which is crucial for planning conservation and restoration measures[31]. Therefore, a deep understanding of the relationship between ecosystem

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structure and stability, and enhancing resilience to disturbances and environmental changes, is key to achieving ecosystem conservation and restoration.

Because of their distinct developmental circumstances, the areas in South China Karst (SCK) are now a typical example of tropical-subtropical karst ecosystems worldwide. These areas have worldwide significance in geology and ecology in addition to being crucial windows displaying China's distinctive karst landscapes. Nonetheless, it is impossible to ignore these regions' ecological vulnerability. Karst ecosystems are weakly resilient and extremely vulnerable to external perturbations; this trait is impacted by both natural and transient human economic activity. Ecosystems' structure and function are essential to preserving their stability, and the combined effects of extreme weather events and inappropriate land use frequently lead to vulnerability, which further impairs the delivery of ecosystem services[32]. Rocky desertification and other environmental degradation problems may result from the vulnerability of karst ecosystems.

A balance between conservation value, tourism potential, and sustainable development is necessary for the preservation and sensible use of SCK World Heritage Sites (WHSs). This problem is now a focus of academic investigation. However, there is still a lack of research on the environmental stability of these natural sites. This work uses a Systematic Literature Review (SLR) to thoroughly examine international research findings on the stability and structure of karst ecosystems to close this knowledge gap. This study intends to provide a scientific foundation for the management and stability enhancement of WHSs in southern China by evaluating the current condition of ecosystems in World Natural Heritage Sites and identifying important scientific questions pertaining to the structure, stability, and interactions of karst ecosystems. This will guarantee the long-term preservation and sensible use of these priceless historical assets and aid in the creation of sustainable development plans.

Methods

We chose to use the SLR technique, which is defined by a methodical, explicit, and repeatable methodology and consists of several steps, including search, assessment, synthesis, and reporting. This approach may be used by practitioners and researchers to find, assess, record, and synthesize previous work[33]. The SLR, which originated in the health sciences, is likewise a thorough and methodical framework for evaluating articles. It may be applied to literature evaluations in a variety of fields because of its methodical and logical approach[34,35]. As a result, we employed the SLR framework to thoroughly aggregate the body of literature on the variables influencing the stability and structure of karst ecosystems, as well as the quantitative scientific evaluations associated with these elements (Fig. 1).

The following are the research questions: 1. How are publications distributed by area and year of publication? 2. What categories of study subjects receive the most and least attention? 3. What are the most significant developments and noteworthy findings from the research that has been done thus far? 4. What are the main scientific problems that require further investigation? 5. What knowledge may be acquired about karst ecosystem enhancement? By using the SLR methodology, this study seeks to answer these issues.

Search

The CNKI core database was the main source of Chinese literature throughout the search phase, whilst the WOS database provided worldwide literature. The CNKI and WOS core datasets served as the basis for the literature search, which had a June 30, 2024, cutoff date. The majority of the publications that were retrieved were theses, conference papers, and journal articles.

Appraisal

47 papers were found in the CNKI database using the search criteria "subject" and the keywords "Ecosystem" + "Structure" + "Stability" + "Karst," with synonym expansion chosen. These comprised 37 graduate theses and 10 journal articles. Using the same set of keywords and "Topic" as the search criterion, 98 papers were found in the Web of Science core database. These included 94 articles and 4 other kinds of papers. The CNKI and WOS databases yielded a total of 145 articles.

Synthesis

At this stage, after a thorough analysis, we extracted and categorized relevant variables and derived knowledge and conclusions from the methods and themes of 145 publications. The concepts of ecosystem structure and stability encompass interdisciplinary research, including landscape ecology, geography, and human adaptation and utilization of the environment. However, current studies on ecosystem structure and stability continue to explore definitions, community characteristics, and structural features while neglecting the influence of human disturbances, climate, and other disruptions on specific aspects of ecosystems. We argue that focusing on the driving factors is a prerequisite for fully understanding ecosystem structure and enhancing stability. Furthermore, we aim to integrate and optimize the structure while improving its stability.

Report

Reporting the analysis results is the fourth stage in the SLR architecture, and this phase completes it. We separated the two subjects into service management and generating aspects. First, the published findings derived from the SLR framework are presented in the quantitative categorization found in Sections "Annual Distribution" to "Regional Distribution of Research". Second, to better convey the significant milestone findings and important scientific challenges that require attention, the two primary topics are further subdivided into sub-themes in Sections "The major advancements and milestone achievements" and "Key Scientific Problems to Address", respectively. Based on this, suggestions are made for enhancing the ecosystems of karst WHSs.

Results

Annual distribution

Figure 2 shows the distribution of publications from 1994 to 2024. The overall trend in research on the structure and stability of karst ecosystems is upward, with some fluctuations. Based on an analysis of the time distribution of published literature, the trend can be divided into three phases: 1994–2007: Only a small number of related publications were produced each year, with an average of fewer than 3 publications annually. This phase represents the exploratory stage, during which the research spanned various topics, from microbial ecology to forest ecosystem management and preliminary studies on ecosystem structure. These early works provided valuable insights into karst ecosystems and forest soil characteristics[36,37]. 2008–2016: During this phase, the volume of publications increased, though still at a slow pace. The research covered multiple aspects of karst ecosystems, including soil microbial diversity, the impact of human activities on ecosystems, and plant community dynamics in specific habitats[38–40]. Overall, the publication trend shows a slow upward trajectory, marking the beginning of more focused research. 2017-present: From 2017 onwards, there has been a rapid increase in the number of publications. The research on ecosystem structure and stability has deepened, and the attention to karst ecosystems has intensified. This phase has seen the incorporation of studies on functional optimization and capacity enhancement of karst ecosystems, as well as the spatial and temporal dynamics of land use and community succession[41–43]. This stage is characterized by diversified development. Understanding and protecting biodiversity and ecosystem stability in karst regions are of significant importance.

Keyword cluster analysis

Using CiteSpace software to analyze the keywords in these literatures (Fig. 3), it was found that the key topics in the CNKI literature focused on karst, stability, and vegetation restoration. Functional characteristics, community structure, ecological restoration techniques, succession in various structural contexts, and human perturbations are the main areas of research. In contrast, the main areas of research covered by WOS

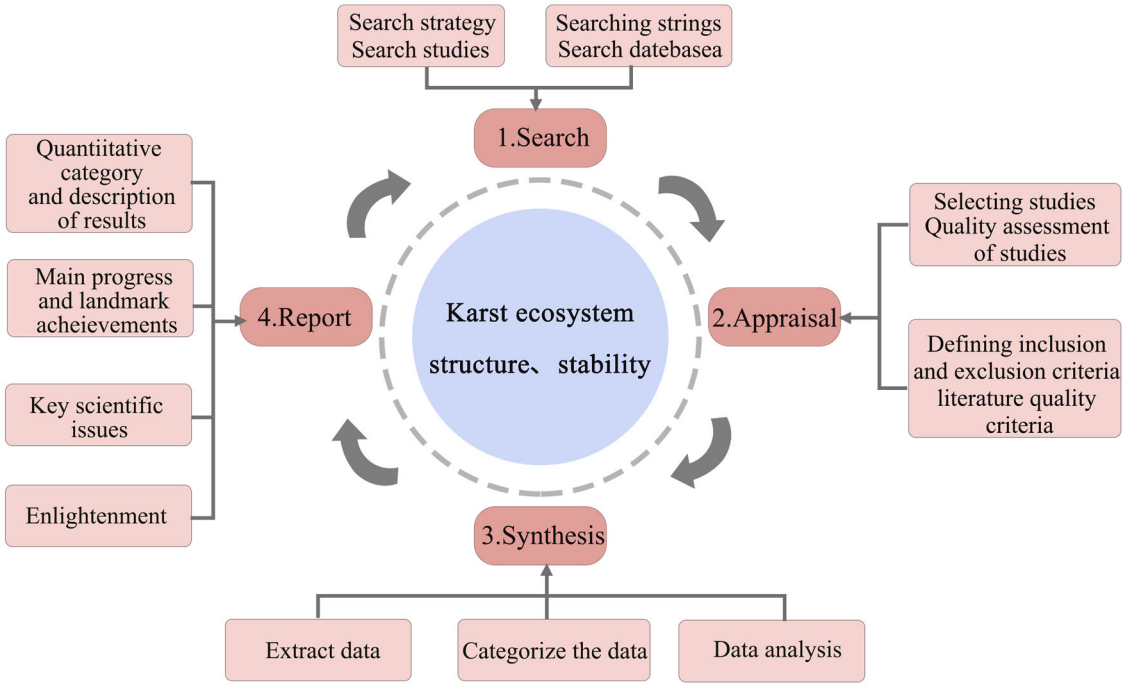

Fig. 1 | Process and Steps of Systematic Literature Review.

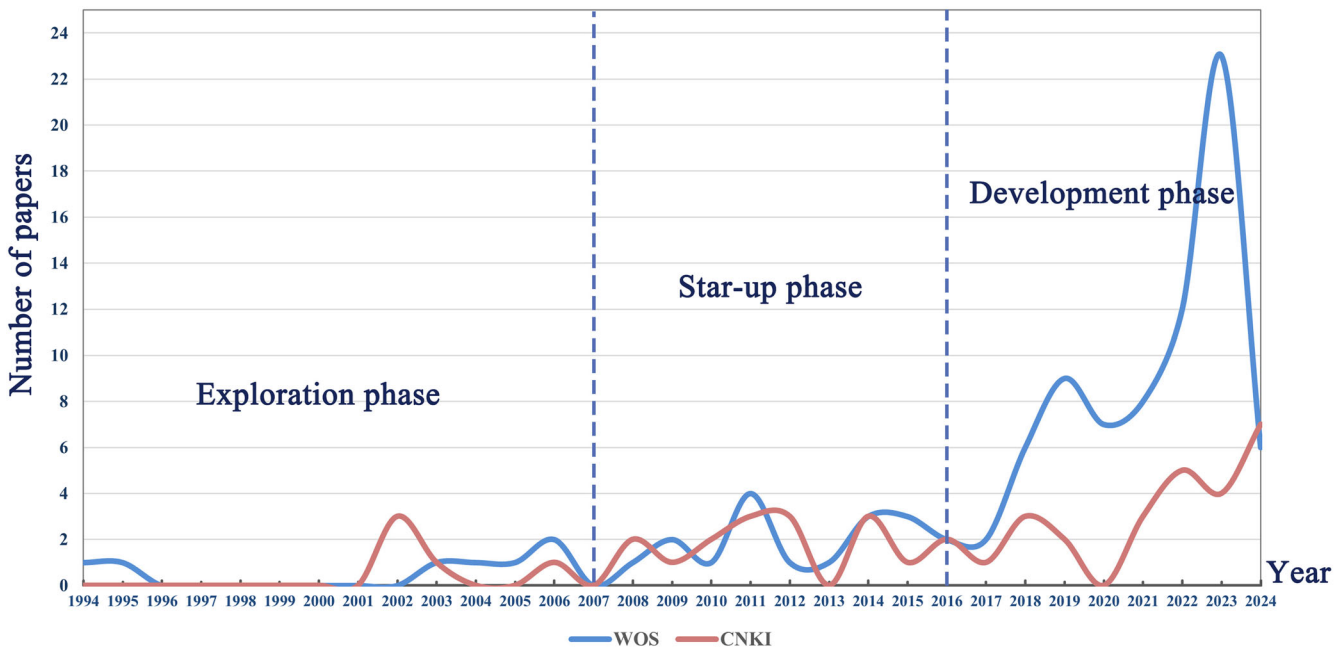

Fig. 2 | Annual Distribution of CNKI and WOS Literature.

include kinetics, diversity, bacterial community dynamics, Ecosystem services and carbon. Key topics also include the impacts of land use, hydrological characteristics, soil quality and biodiversity, as well as the impacts of climate change on the water cycle, vegetation dynamics and biodiversity in karst environments.

Figure 4a shows the seven terms with the biggest citation surges from 1994 to 2024 in CiteSpace, with the burst detection strength set at 0.2. Between 2002 and 2011, "soil quality" saw a spike in citations with a strength of 0.87. From 2008 until 2019, "community structure" continued to receive citations. From 2022 to 2024, "Stability" likewise showed a high citation strength of 2.31. According to the continually high citation rates for "stability" and "structure" between 2022 and 2024, ecosystem structure and stability are the key areas of present study interest and are probably going to continue to be significant research topics in the future.

The 17 terms with the highest increases in citations in WOS from 1995 to 2024 are displayed in Fig. 4b. Between 2017 and 2021, "microbial biomass" and "karst region" saw concentrated citation bursts, suggesting a concentrated interest in these subjects. Citations for the terms "afforestation," "karst ecosystem," and "bacterial community" increased significantly between 2020 and 2024, indicating a strong and contemporary interest in these topics, especially in relation to microbiology and environmental protection. The terms "land use" and "management," which have citation bursts spanning from 2016 to 2024, show current research interests that are essential to environmental management and sustainable development.

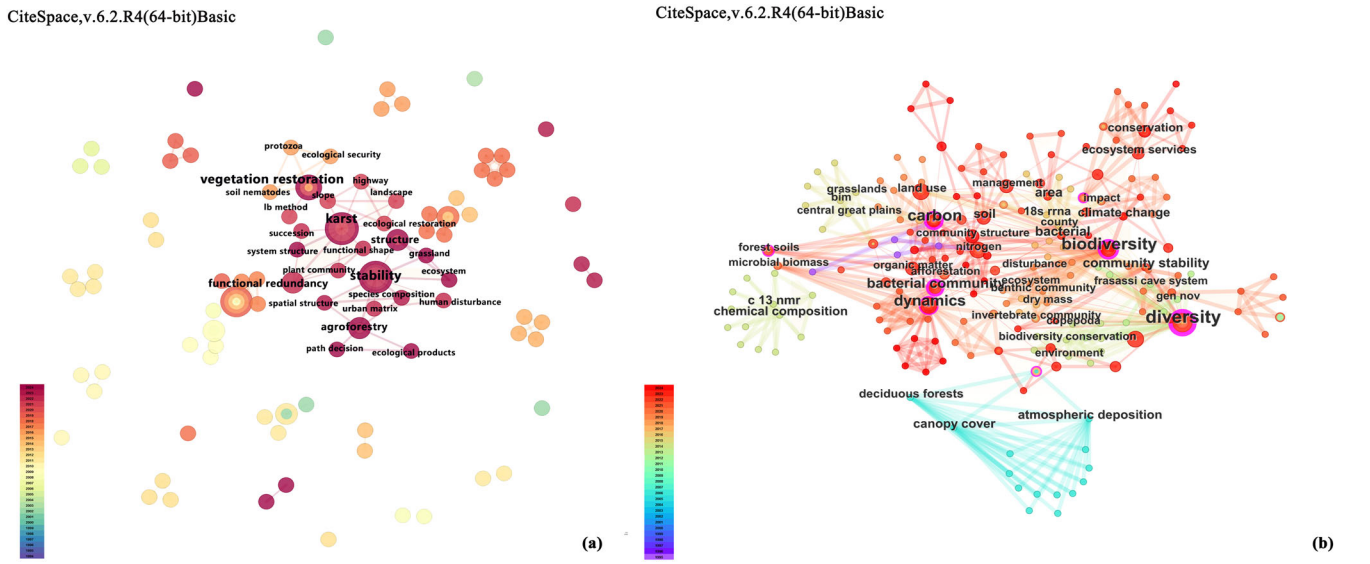

Fig. 3 | Keyword cluster analysis. a for CNKI; (**b**) for WOS. The circle in the figure represents a keyword, and the size of the circle indicates the frequency or importance of the keyword within the analysis period. The color gradient represents the time of occurrence of the keyword, with red indicating a more recent occurrence.

Distribution of research content branches

Research on karst ecosystem structure and function, ecosystem stability and service capacity, biodiversity and karst groundwater, soil microbiology and ecological restoration, and fauna and disturbance are the five categories into which the 145 publications that were thoroughly examined can be divided (Fig. 5a). Overall, 41.38% of the articles are devoted to research on ecosystem structure and function, making it the primary topic. In order to investigate how structure affects ecosystem functioning, many researchers first define community structure from an ecological viewpoint and landscape structure from a land use perspective. The majority of researchers concentrated on soil properties and the stability of soil structure in karst ecosystems during the exploratory phase, which saw the greatest number of studies on karst stability, soil microbiology, and ecological restoration. Research on ecosystem structure and function grew steadily during the early and varied stages of development, as more researchers looked at ecosystem stability, functions, and service capacity from the viewpoints of community structure, trophic structure, and landscape structure. Research on karst animal populations is now somewhat limited, with a greater focus on soil microbiology. This might be because associated issues are not given enough attention.

During the exploratory phase, research on ecosystem stability and service capacity, soil microbiology, and ecological restoration was the most prominent, with four relevant publications each. At this stage, the research mainly focused on the fundamental ecological processes and restoration mechanisms in karst regions, aiming to deepen the understanding of ecosystem functions and the role of soil microbiology. As research progressed into the initiation and development phases, the focus gradually shifted toward ecosystem structure and function. In these stages, studies began to delve deeper into the internal structure of karst ecosystems, their functional diversity, and the impacts of human activities and natural changes on ecosystem stability. Such research has laid the theoretical foundation for the protection of karst ecosystems and the enhancement of their service capacities. The study of karst ecosystem structures, the improvement and optimization of ecosystem functions, and the expansion of service capacity are anticipated to be the main areas of ecosystem research in the future (Fig. 5b).

Regional distribution of research

With 66 articles or 67.35% of the total worldwide output, China leads the world in the number of publications pertaining to ecosystem structure and stability studies, according to a statistical analysis of published literature. Germany comes in third place with a total share of 4.21%, followed by the United States with 9 publications, accounting for 9.18% of the global production. 19.26% of the global production comes from other nations with pertinent publications, such as France, Austria, Canada, the Czech Republic, Belgium, Brazil, Croatia, Italy, the Netherlands, and Poland (Fig. 6).

China is one of the most developed and typical countries in terms of karst landforms, with a wealth of karst landscape materials, which explains the large number of publications from China. In addition, China's policies prioritize scientific research and ecological environmental conservation, including a large investment in resources and labor for karst ecosystem research. Additionally, managing water resources and land use presents several difficulties because of the distinctive features of karst landforms, such as subterranean rivers and caverns. Thus, China's karst ecosystem study is motivated by pressing practical demands.

The major advancements and milestone achievements

To comprehend karst ecosystems, it is necessary to identify and measure the stability and composition of ecological structures. Because species interactions have a direct impact on the processes of energy flow and material cycling among various ecosystem components, structure has an impact on the stability and functionality of ecosystems. As a result, ecosystem stability and functioning are intimately linked to ecosystem structure[44]. To further develop research in this area, a systematic assessment of the advancements and significant successes in the study of karst ecosystem structure and stability was carried out based on the previously described research material.

Study on the structure of karst ecosystems. The structure of karst ecosystems can be divided into four distinct aspects: 1. Composition Structure: This describes the species composition, their abundance, and the relationships between them. 2. Trophic Structure: This represents the nutritional relationships established through the food chain, linking biotic and abiotic components, producers and consumers, and consumers and decomposers into a cohesive system. 3. Temporal Structure: It refers to the diverse use of space and time by different components within the system. 4. Spatial Structure: It refers to the vertical stratification and horizontal mosaic distribution of different system components in terms of arrangement[45,46].

Composition structure. Under the impact of functional fluxes between populations and their surroundings, karst ecosystems—natural complexes with distinct structures, functions, and self-regulatory abilities—are created. The forest, river, and cave ecosystems are all very different from one

Fig. 4 | Keywords with the strongest citation bursts. (The red and green bar charts next to each term show the citation intensity and time window for that keyword in certain years. The red bars represent periods of strong citation bursts, suggesting years when the keyword garnered more attention in the literature, whereas the green bars represent periods of fewer citation activity).

another[47,48]. The community composition of forest ecosystems has been the main focus of research, with a particular emphasis on the role that species variety plays in biomass[49]. In-depth research on the karst ecosystems in the Shibing and Libo-Huanjiang areas has been done by academics like Wen. These studies have covered a variety of ecosystem types, such as rivers, forests, and caves. In order to represent the richness and ecological flexibility of these systems, they classified vegetation types into coniferous forests, broadleaf forests, mixed coniferous-broadleaf forests, and shrublands. Mid-subtropical evergreen broadleaf forests and evergreen-deciduous broadleaf mixed forests are the epitome of plant succession in these areas, signifying the ecosystem's stability and maturity[47]. In-depth investigations into the composition of plant communities in the Maolan karst region have also been carried out by researchers such as Tian, who have highlighted the significance of topography in forming plant community structures and exposed the intricacy of forest communities[50]. Researchers have quantified the significance values of component species and concentrated on species diversity and composition within ecosystems in tropical regions[51,52]. Different patterns of plant development impact these ecosystems' structural features. By highlighting the adaptive reactions of communities to their surroundings, research on the species composition and structure of communities provides a greater understanding of the mechanisms behind species maintenance in karst environments. For ecological conservation and restoration initiatives, this information is crucial.

Trophic structure. Ecological research is greatly influenced by the trophic structure, food webs, and ecological networks of ecosystems. Through food webs and chains, producers, consumers, and decomposers create trophic levels[45]. Both upward and downward interactions between species are responsible for the construction of food webs[48]. The movement and cycling of matter and energy among the different ecosystem components, as well as the processes of community assembly, are directly impacted by the varied interactions among species within ecological communities. The stability and functionality of ecosystems are intimately related to these interactions[44]. By changing interspecies connections, global changes may pose a danger to ecosystem stability and biodiversity[53].

Soil microorganisms are currently the main focus of most research on the trophic structure in karst environments. As decomposers, soil microorganisms are extremely sensitive to ecosystem deterioration in karst environments and are essential to ecosystem restoration[54]. Soil stability is adversely affected by the degradation process, which results in a decrease in soil organic carbon, microbial biomass, and carbon content[55]. Communities with a single trophic level and those with many trophic levels have different

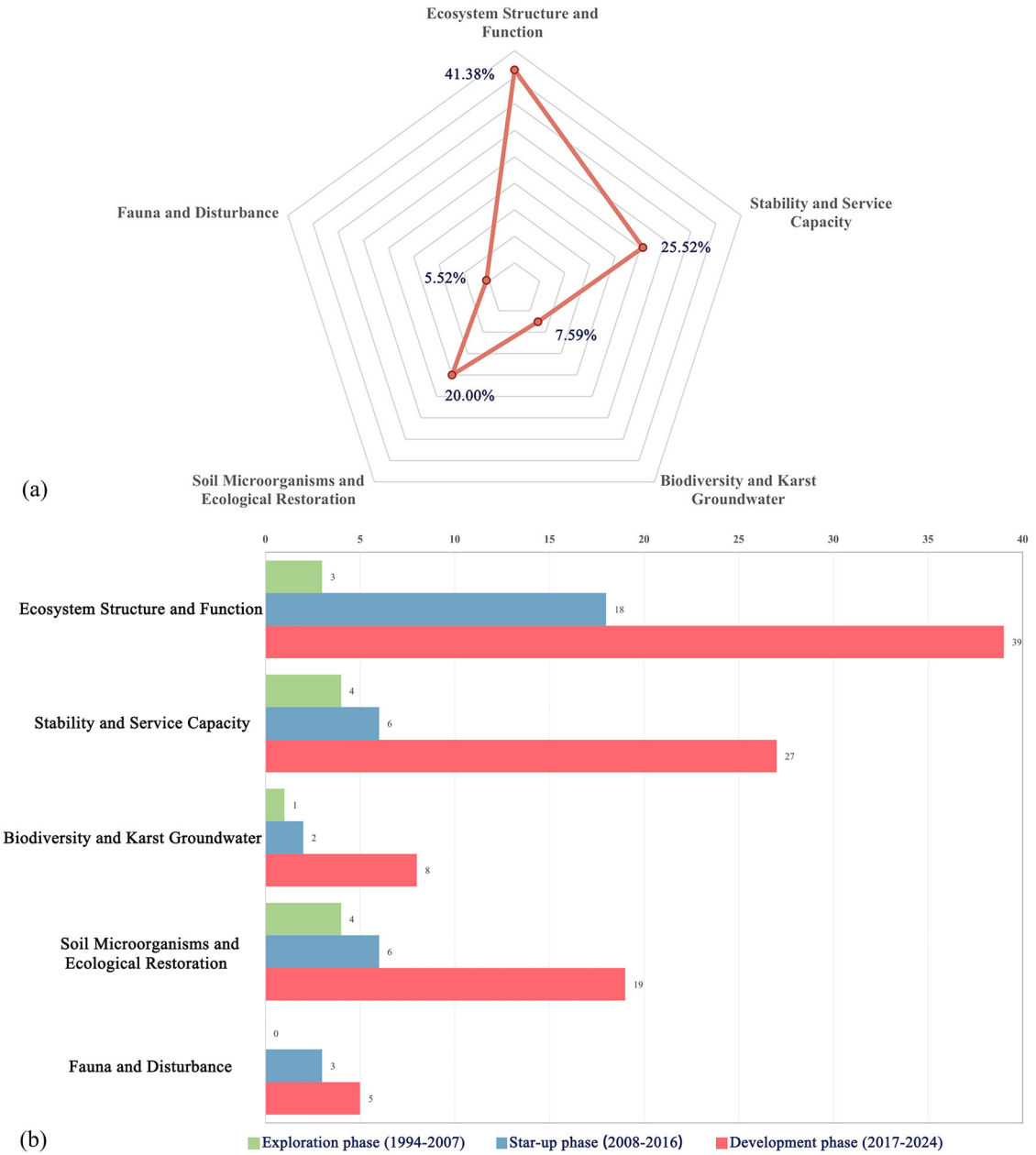

Fig. 5 | Content Distribution of the Literature. a Overall Distribution of Research Content; (**b**) Distribution of Research Content by Stages.

relationships between variety and stability. The diversity-stability connection in multitrophic-level ecosystems shows that interactions between trophic levels are critical to ecosystem stability. Through the exchange of matter and energy, interactions between various trophic levels impact the stability of ecosystems[56].

Consequently, the stability of the ecosystem itself determines the long-term viability of ecosystem services and activities. A deeper comprehension of how groups react to disruptions is possible through the application of a multidimensional stability paradigm[52]. Understanding the structure and stability of ecosystems requires examining intermediary interactions between species and the network-driven mechanisms.

Spatiotemporal structure. Terrestrial ecosystems are continuously influenced by natural and human factors, leading to changes across temporal and spatial scales[57]. In the karst region of the Guizhou Plateau, the InVEST model and geographic detectors were used to analyze the spatiotemporal distribution and evolution of habitat quality. It was found that land use types and annual precipitation are key influencing factors[58]. Time series analyses indicate that extreme conditions, such as changes in temperature and rainfall patterns, can affect forest structure and spatial distribution[59]. Most current studies focus on the seasonal changes and large-scale spatiotemporal dynamics of ecosystems under extreme climate conditions[60], while there is insufficient attention given to seasonal changes and small-scale structural variations under normal climate conditions. Therefore, monitoring landscape and land use changes in karst ecosystems across different seasons and over various time scales is crucial for optimizing ecosystem structure and enhancing stability. While seasonal changes and small-scale structural variations under normal climatic circumstances receive little attention, the majority of current research concentrates on the seasonal changes and large-scale spatiotemporal dynamics of ecosystems under severe climate conditions[60]. In order to maximize ecosystem structure and improve stability, it is essential to track changes in the landscape and land use in karst ecosystems throughout a range of time scales and seasons.

Research on the spatiotemporal evolution characteristics and quantitative attribution of ecosystem service clusters in karst regions is crucial for implementing zonal management strategies based on dominant functions.

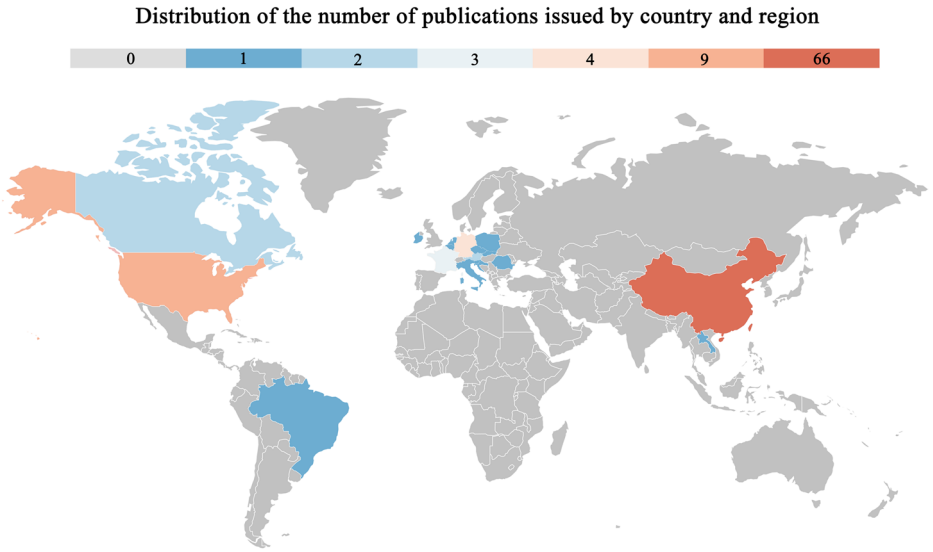

Fig. 6 | Differences in regional distribution of research.

This helps in the efficient allocation of environmental resources and promotes multifunctional land use[54]. By identifying the spatiotemporal evolution characteristics of ecosystem service clusters, a better understanding of the trade-offs and synergies between various ecosystem services can be achieved. This provides scientific support for land use governance and sustainable development in karst regions. The composition of landscape structure dominates the prediction of ecosystem service provision. The spatial characteristics of landscape configuration, including the shape of patches and connectivity between different land use/land cover types, have significant impacts on ecosystems[55,56]. However, current research on landscape structure primarily focuses on landscape pattern analysis at the provincial and municipal levels. As research subjects and geographic environments vary, further studies are needed to assess whether these regional findings apply to specific geographic areas, such as the karst WHSs in southern China.

Study on ecosystem stability in karst regions. Two important traits that are used to characterize the behavior of ecosystems are stability and resilience. Resilience is the ability of an ecosystem to return to its initial condition following a disturbance, whereas stability is the ability of an ecosystem to preserve or restore its structure and functions mostly unaltered[57–59]. What makes natural systems appear to be stable? Ecologists have focused heavily on this subject ever since the field's founding.

The evaluation markers for ecological stability have grown more intricate as research has advanced. Aspects including structure, function, external environment, human influence, and single-indicator techniques are the main considerations in the selection of these indicators. In order to assess the energy flow, structure, and function of a system, Odum developed 22 indicators that included topics such as life history, nutrient cycling, community energy, and community structure[60]. Karst ecosystems may now be measured in a variety of ways thanks to advancements in remote sensing technologies. Huang et al. performed a comprehensive assessment of the karst peak-cluster depressions in southern China using Landsat time series data from 1988 to 2018. They identified three elements of ecological stability —resilience, variability, and resistance—using temporal decomposition techniques. In order to investigate the aspects of ecological stability, they also examined the relationships among these elements[61].

Lin et al. reviewed the stability of village ecosystems in karst regions and pointed out that stability is closely related to both internal and external structures of the ecosystem[62]. While the internal structure includes elements like people, energy, and livelihoods, the exterior structure mostly relates to landscape patterns, such as the spatial arrangement of communities and land use. The functions and service capacity of the ecosystem are determined by the interplay between these components. Karst ecosystems can become more resilient and resistant to perturbations by boosting livelihood variety and optimizing landscape patterns, which would improve stability. Xiao et al.'s research demonstrated that the introduction of agroforestry systems in karst regions, such as the combination of perennial woody plants with crops and livestock, can effectively improve soil fertility, reduce soil erosion, and enhance biodiversity[33]. This benefits locals socially and economically in addition to encouraging the regeneration of damaged ecosystems. The contribution of dissolved organic matter generated by the biological carbon pump in karst regions to global carbon sinks was highlighted by Xia et al. in their study of the effects of hydrological processes on the stability of karst ecosystems[63].

Because of their distinct geological and hydrological features, karst habitats are ecologically delicate and extremely vulnerable to human intervention. In order to maintain relative stability in the face of external disruptions, these systems rely on the interactions between structure, the physical environment, and biological activities. In particular, vegetation cover, soil structure, hydrological processes, topography, biodiversity, and climate are important elements that affect the surface stability of natural systems. It is crucial to investigate the stability of ecosystems within particular landscapes as well as to elucidate the connections between various structural types, functions, and stability from a variety of angles and levels while studying ecosystem functions in WHSs. In the end, this will improve the ecosystem's capacity to deliver services and achieve useful advantages.

Study on the types of disturbances in karst ecosystems. The concept of stability is intimately linked to how a system reacts to shocks. Various sorts of disruptions in natural ecosystems have distinct effects on different ecosystem components. Disturbances can be classified as internal or external to the system. External disturbances or perturbations are changes in biotic and abiotic environmental elements that affect the structure and dynamics of ecosystems[64]. These disturbances can be understood and distinguished by their intensity, timing properties (such as frequency and duration), spatial distribution, methods of action, and sources[65]. Traditionally, disturbances are classed as pulse perturbations, press perturbations, and environmental stochasticity (also known as noise).

Common pulse perturbations in karst regions include short-term intense natural phenomena, including torrential rainfall, flash floods, landslides, and forest fires[66]. These disruptions have an immediate and significant impact on plant cover, soil conservation, and species distribution in karst environments. For example, severe rainfall can exacerbate karst erosion, resulting in soil loss and the destruction of local ecosystems[67]. Press

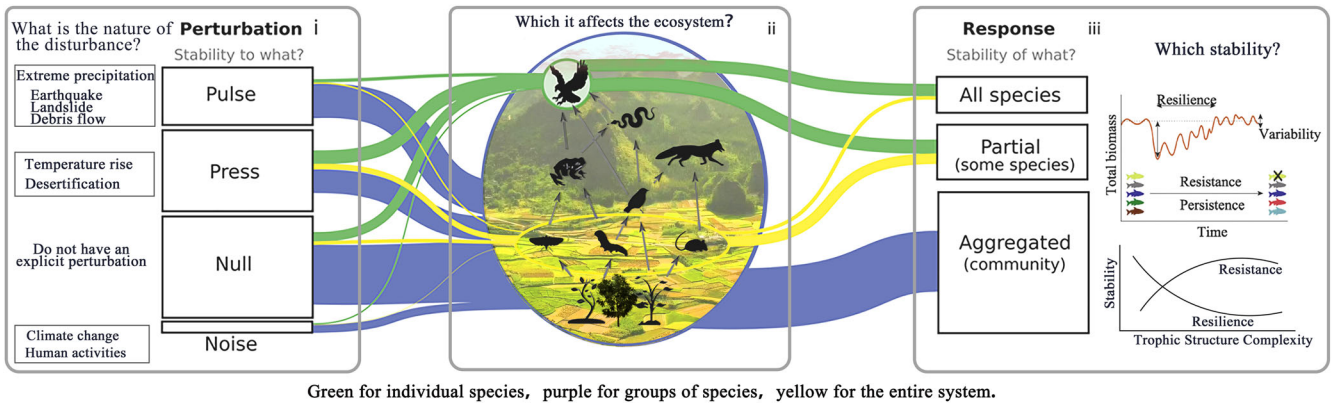

Fig. 7 | Types of Ecosystem Disturbances (Null refers to studies that do not have an explicit perturbation but rather compare treatments (e.g., Biodiversity-Ecosystem Functioning studies or studies comparing persistence of different food web structures).

perturbations in karst environments are often characterized by long-term environmental changes such as climate change, land use changes (such as agricultural expansion, and urbanization), and exploitation of water supplies[68,69]. These disruptions have a slower but more lasting impact, eventually diminishing ecosystem productivity and species diversity. For example, protracted temperature increases and droughts can disrupt the water cycle in karst environments, resulting in groundwater depletion and vegetation damage. Environmental stochasticity in karst environments is mostly manifested as random climate fluctuations (such as irregular shifts in precipitation patterns) and natural variations in species population sizes[70,71]. These disturbances are typically unforeseen, but their cumulative impacts may have an impact on ecological stability in the long run. For example, irregular rainfall patterns in karst locations can impair subsurface river recharge, altering local biodiversity and ecological services[72]. Environmental stochasticity is defined as continuous environmental fluctuations induced by random causes in the biotic and abiotic environment. Because karst ecosystems are complex and multilayered, different sorts of disturbances can have a variety of effects on ecosystem stability. Internal system reactions include species-level changes such as fluctuations in species richness and population sizes, as well as changes in community structure and overall ecosystem performance. The vulnerability to external disturbances underscores the fragility of karst ecosystems, underlining the importance of long-term monitoring and adaptive management measures to alleviate the cumulative consequences of disturbances.

Disturbances in nature are frequently a combination of the three common disturbance patterns, with more diversified traits. Pulse perturbations, press perturbations, and noise are three examples of global climate change disruptions. A substantial chunk of research has focused on assessing ecological stability in the absence of significant disturbances, sometimes known as "Null disturbance"(Fig. 7). Most studies look at the link between diversity and community or ecosystem stability in such situations[73].To summarize, the types of disturbances in karst regions are complex and diverse, necessitating that managers take into account the cumulative effects of many disturbances as well as ecosystems' multiscale responses when developing conservation plans.

Drivers of ecosystem stability. The "generation-flow-use" of ecosystem services is a complicated dynamic process that is time and space-dependent. Any changes in the driving variables for any step of this process might result in changes in ecosystem service functions, affecting human well-being[74,75]. Ecosystem stability is the outcome of interactions between species diversity, environmental circumstances, and external perturbations. The effect of species diversity on stability has been extensively researched[76,77], but the ecological repercussions of biodiversity loss are unknown. A loss of biodiversity, particularly owing to human activities, may result in a fall in ecosystem services and stability, thereby causing extinction cascades[78]. Species contribute to stability in multiple ways, with the ability to produce both stabilizing and destabilizing impacts at the same time[79]. Community structure, through species interactions, is crucial to sustaining environmental stability[80].

Temperature, nutrients, CO_2, light, salinity, and rainfall are examples of environmental disturbances that have a substantial impact on ecosystems. Habitat degradation and fragmentation are essential drivers of global change, yet they are frequently underestimated. Climate change affects ecosystem stability and function by introducing new ecological niches and increasing human disruptions[31,81,82]. Climate models forecast rising temperatures, shifting rainfall patterns, and an increase in extreme weather events, all of which have an impact on ecosystems via modifying disturbance mechanisms[83–85]. Warming temperatures and increased nitrogen deposition alter the availability of nitrogen and phosphorus to plants in the soil, influencing ecosystem structure and function[86–88]. This is especially obvious in the fragile agricultural ecosystems of karst regions, where agriculture is more prone to drought and problems like land degradation and water scarcity are more severe[84]. Legume intercropping and improving soil nitrogen-fixing bacterial populations are two strategies that can help minimize nitrogen loss[63,89]. Rocky desertification has a substantial impact on ecological stability in karst regions. Karst landscapes have limited water and nutrient availability due to their distinct geological and hydrological conditions[90,91]. While landscape heterogeneity benefits biodiversity in agricultural environments, excessive spatial fragmentation can limit heterogeneity, resulting in habitat fragmentation and loss[92]. Human activities and extreme weather events have a considerable impact on ecosystem functioning, specifically productivity, stability, and biodiversity. Karst landscapes play a vital part in the global carbon cycle and serve as significant carbon sinks.

The preservation and use of WHSs has long been an issue of concern. Excessive tourism, improper land resource planning, and human production and living activities increase the vulnerability of ecosystems to external disturbances, resulting in the degradation of the ecological environment of heritage sites. The goal of protection efforts is to prevent disruptions from reaching the system's threshold, resulting in realistic succession. Investigating the variables that disrupt the natural environment of WHSs yields data for constructing ecosystem stability models.

Strategies for structural optimization and stability enhancement. Structural optimization methods can effectively alleviate the disruption caused by human activities on ecosystems, impacting species richness and biodiversity, and hence altering the ecosystem's ability to deliver services. In terms of landscape structure optimization, a study on regional ecosystem structure and function is critical. Landscape pattern studies allow for the quantitative examination of internal landscape dynamics, the research of elements impacting landscape patterns, and the evaluation of these patterns, with the ultimate goal of offering optimization strategies. This contributes scientific evidence to regional sustainable

development and builds the groundwork for larger-scale or global change studies[91].

Designing landscape corridors of various scales and hierarchical levels is a main responsibility in landscape building, while promoting the growth of landscape patches in ecologically vulnerable areas is an important measure[93]. The core zone of heritage sites has always been the most important ecological source area in the study region, as well as a critical component of the forest landscape. As a result, it can serve as habitat and movement corridors for forest animals, so contributing significantly to biodiversity conservation and environmental stability[94]. In terms of afforestation models, mixed and natural cluster planting are used, with natural cluster planting along roadsides and shoreline regions to emphasize ecological and natural impacts. The "patch-corridor-matrix" paradigm is part of the overall design of ecological corridors. Various biological units are mixed and interact organically to create appropriate habitat spaces. By improving connectivity between patches, forest belts with ecological restoration functions are developed, boosting environmental benefits[95]. Ecosystem services and landscape connectivity are integrated to identify and optimize ecological resources. Using circuit theory to extract ecological corridors and barriers, the study discovered that three ecosystem services—soil and water conservation, biodiversity maintenance, and soil retention—have large spatial heterogeneities. The designed ecological network structure greatly improves ecological connectedness[96]. As a result, optimizing landscape structure is an essential solution to the unavoidable challenge of reconciling the sustainable development of cultural site environments with tourism development.

Key scientific problems to address

The structure of the karst ecosystem influences its function. The system principle "structure determines function" emphasizes that a well-organized structure is required for ecosystems to constantly execute their activities, making structure adjustment a critical strategy[74]. Research on ecosystem structure will help clarify how structure influences function[97].

Functional diversity should be thoroughly investigated in order to comprehend ecosystem multifunctionality and uncover the effects of many variables on ecosystem stability. It has been demonstrated that the arrangement of several species in multi-component ecosystems results in a significant degree of heterogeneity in the functional features of plants. The intricacy of functional variety provides fresh perspectives on how functional characteristics of plants impact ecosystem services. Although the functioning of karst ecosystems is somewhat understood, there are currently insufficient in-depth debates regarding the impact of plant functional characteristics on ecosystem services, which restricts the optimization of ecosystem service delivery. This limitation makes it impractical to optimize karst ecosystem functions to improve the delivery of ecosystem services. Thus, one of the most important aspects of biodiversity and a key to comprehending how biodiversity affects ecosystem services in karst ecosystems is functional diversity.

Establishing a stability assessment framework suitable for karst regions. Ecosystem stability evaluation methods can be classified into empirical methods, expert judgment methods, and mathematical models. Because the empirical technique depends on the opinions of experts, the results can vary greatly. Although they are frequently employed, mathematical models like food web models and differential equations frequently concentrate on particular aspects. Additional techniques include ecological models, landscape ecology approaches, the PSR model, emergy analysis, the weighted comprehensive average method, the Delphi method, the AHP, and dynamic evaluation models based on SPA and Markov chains (Table 1).

Currently, there is limited research on evaluating the stability of unique karst landforms. The varying landscape structures, geomorphological characteristics, and different levels of natural and human disturbances mean that research methods for each structure differ. Addressing the key scientific questions regarding the response and adaptation mechanisms of ecosystem service functions to environmental disturbances requires an in-depth exploration of how these disturbances, both environmental and anthropogenic, influence ecosystem functions, based on land use structures and long-term monitoring. According to the structural stability characteristics and mechanisms of karst ecosystems, it is crucial to develop an ecosystem stability evaluation index system that provides theoretical support for strategies aimed at improving the stability of karst ecosystems. To enhance the accuracy and operability of ecosystem stability assessments, it is recommended to reconsider key indicators for ecosystem quality evaluations, such as productivity, soil organic matter, plant diversity, and landscape fragmentation. The development of a new ecosystem quality assessment system based on an "ideal reference frame + key indicators" can meet the need for rapid evaluation of ecosystem quality at regional or national scales in the current era. This system will offer scientific guidance for more rational resource allocation and improved conservation effectiveness.

Table 1 | Common methods for assessing ecosystem stability

Methods	The main content
Fuzzy Comprehensive Evaluation Method:	A comprehensive evaluation method based on fuzzy mathematics theory. This method combines qualitative and quantitative indicators, using fuzzy sets and membership functions to perform fuzzy quantification and processing of uncertain evaluation indicators.
Gray Relational Analysis	A multi-factor statistical analysis method based on gray system theory. It evaluates the state of the object at a certain stage concerning a predetermined target, allowing for an assessment of the object's performance under various factors.
Analytic Hierarchy Process (AHP)	A decision-making method that decomposes elements related to the decision into multiple levels, such as goals, criteria, and alternatives. Based on this hierarchy, it conducts both qualitative and quantitative analysis to assist in decision-making.
Ecological Model	A scientific concept involving computational models used in the field of ecology to analyze and evaluate ecosystem health, stability, and biodiversity.
Pressure-State-Response (PSR) Model	A method used to measure the pressure, state, and response of ecosystems. Pressure refers to the impacts of human economic and social activities on the environment. State refers to the environmental quality and health of the ecosystem at a specific time. The response indicates how humans act to mitigate, halt, restore, and prevent the negative impacts of human activities on the environment.
Emergy Analysis	A method used to assess the energy usage and conversion efficiency in natural and human-made systems. It converts different forms and sources of energy into a unified measurement standard, typically in solar energy units.
Markov Dynamic Evaluation Model	A model uses probabilistic Markov chains to predict future states based on current conditions. It's widely applied in ecological studies for modeling species dynamics, land use changes, and succession, providing insights into long-term stability and trends through stochastic transitions.

Urgent need to explore the drivers of structure and stability for optimization strategies. Various climax communities, including evergreen broadleaf forests, evergreen-deciduous broadleaf forests, and evergreen sclerophyllous forests, are formed by the geological features, varied topography, and subtropical climate of karst regions. These communities serve as a testament to the subtropical karst ecosystems' abundant biodiversity and ecological succession processes. By studying indicators such as species richness, evenness, and diversity, researchers can gain insights into these dynamics. Biodiversity loss, changes in trophic structures, community disruption, and the impact of invasive species all negatively affect ecosystem stability. Land use changes, such as the conversion of farmland to forestland, have significant effects on ecosystem stability. Understanding how these driving factors act individually and in combination with system stability can aid in developing effective management and conservation strategies to optimize ecosystem resilience.

Human activity and natural forces are the two main obstacles to the management and preservation of the SCK World Natural Heritage Sites. Natural elements, such as geological disasters like earthquakes, collapses, and landslides brought on by the release of internal earth forces and natural climate change disturbances, are mostly associated with non-anthropogenic processes during the formation of karst landforms. Problems caused by human activity include urbanization, water pollution, rocky desertification, pressures on tourism development, and pressures on community development. The degree to which tourism impacts ecosystem stability is one of the anthropogenic elements that is still unknown.

Enhancing the stability of Karst World Heritage ecosystems

The SCK region, with its unique geological and climatic history, has evolved a diverse range of landforms and supports distinctive ecosystems and biodiversity. Large tracts of distinctive, widely dispersed primary forests are preserved in the Karst WHSs. However, these karst forest ecosystems are characterized by the difficulties in restoring the environment, the sluggish recovery and succession of plant groups, their low resilience to perturbations, and their vulnerability to degradation when injured[98]. In order to preserve the karst forest ecosystem's overall environmental balance and water equilibrium, it is imperative to create vegetation ecosystems with great stability and robust ecological functions.

Enhancing ecosystem stability is a crucial guarantee for improving the ecosystem service functions of karst ecosystems. Natural disasters and human activities, especially tourism, which has a major impact on ecosystem stability, are threatening the biological value of Karst WHSs. The vulnerability of these sites necessitates careful attention to ecological protection during tourism activities. Construction of tourist amenities and projects that potentially detract from the heritage sites' visual value should be strictly restricted or prohibited. Ecological restoration methods and suitable biological control measures must be used to preserve these areas when their value is threatened. Natural landscape World Heritage sites typically represent a combination of geological and ecological features, making them vulnerable to both natural and human-induced threats[99]. In response, specific protection measures and restoration techniques for natural landscape heritage sites have been proposed. When natural factors such as wind erosion, water erosion, and landslides threaten the value of these sites, engineering solutions such as vegetation restoration and reconstruction, slope reinforcement, and river channel modification can be implemented. In cases where human activities pose a threat to heritage sites, removing sources of disturbance is the primary condition for vegetation restoration. By adopting appropriate landscape designs, vegetation and soil can be effectively restored under natural conditions.

Discussion

This paper conducted a literature search on ecosystem structure and stability using the WOS and CNKI databases, analyzing and reviewing 145 selected papers. The following conclusions were drawn: (i) We observed an overall upward trend in related publications, with research on karst ecosystem structure and function being the most common topic (accounting for 41.38% of publications), followed by research on karst stability and service capacity, representing 25.52% of the publications; (ii) We summarized the major advancements and milestone achievements in karst ecosystem structure and stability research, and explored related key scientific issues; (iii) The findings highlight key areas for improving the control of ecosystems in Karst WHSs, revealing the relationship between humans and the environment from the perspectives of structure and stability.

In conclusion, this paper summarizes the current research progress in five areas: structural characteristics of ecosystems, stability research, types of disturbances, driving factors, and sustainable development improvements. It discusses the key scientific questions that need to be addressed within the scope of this study and points out future research directions for optimizing ecosystem structure and enhancing stability in WHSs. These insights provide important guidance for enhancing ecosystem service provision and sustainable development in karst regions.

Data availability

No datasets were generated or analysed during thecurrent study.

Abbreviations

WHSs	World Heritage Sites
SCK	South China Karst
SLR	Systematic Literature Review
AHP	Analytic Hierarchy Process
PSR	Pressure-State-Response
WOS	Web of Science
CNKI	China National Knowledge Infrastructure

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Author contributions

Conceptualization: K.X., X.B.; methodology: X.B.; data collection and analysis: X.B.; writing—original draft: X.B.; writing—review and editing: K.X., X.B.; supervision: Y.C., Z.Q., Y.Q., Q.Q.; funding acquisition: K.X., Z.Q. All authors read and approved the final manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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