PROGRESS AND PROSPECTS OF RESEARCH ON KARST ECOSYSTEM SERVICES

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Abstract. Karst ecosystems, among the world's most fragile, are heavily impacted by human activities, disrupting the ecosystem services they provide. Understanding these dynamics is key to improving karst ecosystem quality. This study reviews current research, highlighting progress, challenges, and future directions. Findings show increasing diversity in assessment targets and improving evaluation methods, with a growing focus on changes in karst ecosystem services across different spatial and temporal scales. Researchers are also examining trade-offs and synergies among services and quantifying supply-demand relationships. Ecological restoration to enhance both ecosystem services and human welfare is a key focus. However, challenges remain, including the need for better evaluation methods and models tailored to karst environments. Current research lacks comprehensiveness and needs to explore the interaction of natural and socio-economic factors more deeply. Future studies should adopt multidisciplinary approaches to better assess trade-offs and synergies among services, refine methods for evaluating human welfare, and investigate how karst ecosystem services impact human well-being under varying human activities.
Keywords: *ecological function, ecological restoration, land use, human welfare, karst region*

Introduction

Ecosystem services refer to the various benefits and products provided by natural ecosystems to humanity, such as water supply, climate regulation, and food production. These services play a crucial role in human survival and the sustainable development of society and the economy (Costanza et al., 1997; Daily, 1997; Lele et al., 2013; Sheergojri et al., 2024). However, since the latter half of the 20th century, rapid global economic growth, population explosion, and excessive human demands have severely damaged ecosystems, leading to a rapid decline in ecosystem services. This degradation poses significant threats to human security, health, and both regional and global ecological stability (MA, 2005; Birhane et al., 2024; Dammag et al., 2024). Consequently, research on ecosystem services has become a prominent and cutting-edge field within international ecology and related disciplines (Birhane et al., 2024; Sokol and Laska, 2024; Vári et al., 2024).

Karst ecosystems are among the world's most fragile ecological systems (Török-Oance and Ardelean, 2012; Tang et al., 2023). Influenced by geological background, hydrological structure, and complex topography, karst regions are characterized by thin soil layers, low fertility, spatial mismatches of soil and water resources, and significant spatiotemporal heterogeneity of water and thermal factors. These conditions result in low environmental carrying capacity, high sensitivity, poor stability, and weak resilience to disturbances (Day, 2010; Liu et al., 2021; Ao et al., 2024; Wen et al., 2024). Nevertheless,

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under these natural conditions, diverse types of ecosystems have formed in karst areas, providing crucial ecosystem services such as water conservation, soil retention, biodiversity maintenance, grain production, water yield, and recreational opportunities (Green et al., 2019; Wang et al., 2019; Mason et al., 2023).

China as the home to the world's most extensive contiguous karst landscapes, faces significant challenges due to the dual impacts of frequent extreme climate events, wildfires, geological disasters, and rapid urbanization, land use changes, and poverty alleviation policies. These challenges create a complex dilemma of increasing resident incomes, accelerating socio-economic development, and protecting the environment (Móga et al., 2013; Chen et al., 2021a). On one hand, prolonged excessive human activities have caused substantial damage to karst ecosystems, with severe rocky desertification (Xu and Zhang, 2014; Zhang et al., 2021). On the other hand, as the karst region, particularly in Southwest China, is a relatively concentrated area of poverty, the processes of poverty alleviation and rapid socio-economic development have led to irrational resource exploitation and ecological degradation (Zhao et al., 2019; Shi et al., 2020; Feng et al., 2022). Changes in natural conditions and these unsustainable human activities have profoundly disrupted the structure and function of karst ecosystems, thereby affecting ecosystem services (*Figure 1*). As a result, research on karst ecosystem services has become a critical focus within the broader field of ecosystem service research (Bai et al., 2023; Xiong et al., 2023a; Zhang et al., 2024a).

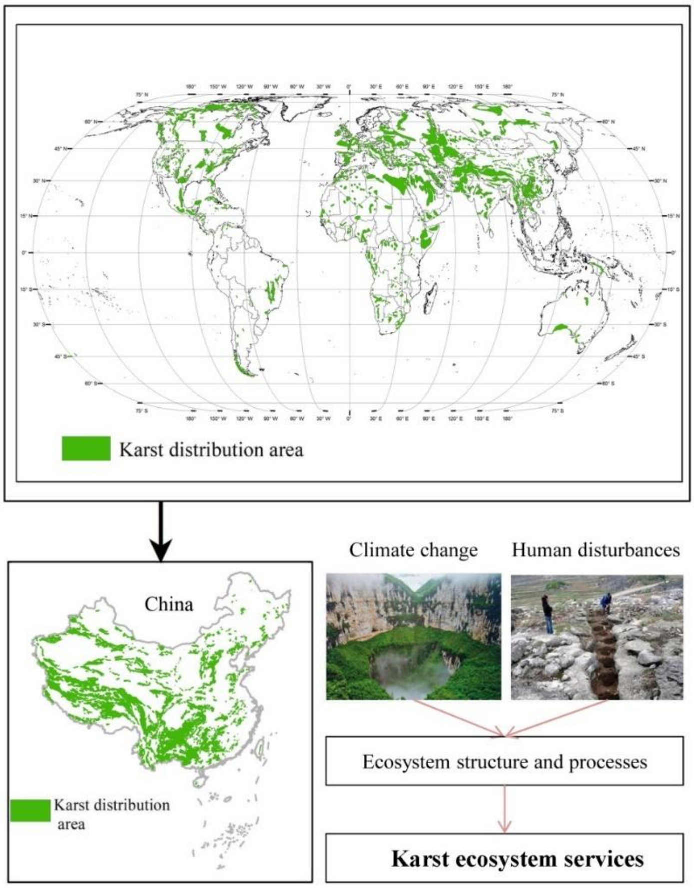

Figure 1. *Karst distribution and strongly disturbed ecosystems (The global and Chinese karst distribution maps are from the Karst Data Center: http://www.karstdata.cn; Photos taken in June 2024, Qiannan and Qianxinan Prefectures, Guizhou Province, China)*

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Building on a comprehensive review of existing literature on karst ecosystem services, this study summarizes the current state of research, identifies the challenges, and outlines future research directions. The goal is to provide a scientific basis for the development, utilization, and protection of karst ecological environments, thereby promoting better environmental management, rational resource use, and sustainable socio-economic development in karst regions.

Evaluation and Methods of Karst Ecosystem Services

Evaluation of Karst Ecosystem Services

The primary types of karst ecosystems currently being evaluated include forest ecosystems, rocky desertification ecosystems, urban ecosystems, and grassland ecosystems. In contrast, there has been relatively less research on other types of karst ecosystems such as cultivated land, lakes, and wetlands. Case studies indicate that water conservation, soil retention, carbon sequestration, and product supply are the most frequently examined services in karst ecosystems. However, significant differences exist in the ecosystem service types evaluated across different ecosystems. For instance, assessments of forest ecosystems focus mainly on carbon sequestration, water conservation, soil retention, and climate regulation. Evaluations of rocky desertification ecosystems primarily consider water conservation, soil retention, and soil fertility. Due to the unique characteristics of urban ecosystems, their ecosystem service evaluations markedly differ from those of other ecosystems (*Table 1*).

Based on the classification of ecosystem services by the Millennium Ecosystem Assessment (2005), evaluations of karst ecosystem services primarily concentrate on provisioning services, regulating services, and supporting services, with relatively less emphasis on cultural services. Research on provisioning services predominantly focuses on the supply of forest products, agricultural products, and freshwater, with limited attention to the supply of genetic resources (Han and Dong, 2017a; Xiong et al., 2023b; Zhou and Wang, 2023). Regulating service studies primarily address climate regulation, water conservation, soil retention, and water purification (Han and Dong, 2017b; Chen et al., 2021b; Xiong et al., 2023c), with fewer studies on disease prevention, pest control, and pollination. Supporting service research largely focuses on carbon sequestration, soil fertility, habitat quality, biomass, and carbon storage (Gao and Xiong, 2015; Song et al., 2016; Li et al., 2024a), with scant attention to biodiversity and water cycling.

Methods for Evaluating Karst Ecosystem Services

Current methods for evaluating karst ecosystem services mainly include physical quantity assessment methods, value assessment methods, and model assessment methods. The value assessment method uses ecosystem service value coefficients or ecological economic calculation methods to evaluate the value of karst ecosystem services. The value coefficients are primarily based on those proposed by Xie et al. (2003) for China's terrestrial ecosystems, adjusted for the specific characteristics of karst regions. For example, Chen et al. (2021c) used the value coefficient method to assess the ecosystem service value in the karst regions of Southwest China. Ecological economic calculation methods include market value methods, shadow engineering methods, production cost methods, and opportunity cost methods.

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***Table 1.** Typical cases of classification, research objectives, and evaluation methods for karst ecosystem services*

Primary Type	Secondary Type	Classification	Research Objectives	Research Methods	References
Forest ecosystem	Artificial economic forests, broadleaf mixed forests, coniferous and broadleaf mixed forests, and coniferous mixed forests	Water retention, carbon sequestration, oxygen release, soil fertility maintenance, and timber supply	Impact of multiple driving factors on ecosystem services of karst forest	PQAM	Xiong et al., 2023b
	Deciduous broadleaf forests, evergreen and deciduous broadleaf forests, mixed forests, and evergreen broadleaf forests	Soil nutrient content, enzyme activity, and microbial biomass	Impact of vegetation restoration on soil ecosystem services in karst forests	PQAM	Lu et al., 2022a
	Mixed forests, deciduous broadleaf forests, evergreen broadleaf forests, evergreen coniferous forests, and shrub	Provisioning, regulating, supporting, and cultural services	Valuation of ecosystem services of karst forest	VAM	Zhou et al., 2023
	Primary forests and secondary forests	Carbon sequestration	Assessment of carbon sequestration services in karst forest during vegetation restoration	PQAM	Guo et al., 2021
	Plantation forests and secondary forests	Soil water holding capacity, species diversity, soil retention, and carbon storage	Optimization of ecosystem services during vegetation restoration in karst forests	PQAM	Xiong et al., 2023c
	Broadleaf forests, coniferous forests, and shrub	Eco-hydrological services (precipitation regulation)	Assessment of eco-hydrological services of litterfall in karst forests	PQAM	Zhang et al., 2022b
	Primary forests and plantation forests	Water conservation, water quality purification, soil conservation, carbon sequestration, oxygen release, environmental purification, forest product production, and recreational activities	Valuation of ecosystem services of karst forest	VAM	Li et al., 2010； Zhou et al., 2010
Grassland ecosystem	Cultivated pastures	Water retention	Impact of drought on water retention capacity of karst grasslands	PQAM	Dong et al., 2020
	Cultivated pastures	Ecological-economic value	Ecological-economic valuation of different agricultural and forestry planting patterns	VAM	Zou et al., 2019
	Natural grasslands	Gas regulation, climate regulation, water conservation, soil formation and protection, waste disposal, biodiversity maintenance, food production, raw materials, and cultural recreation	Valuation of ecosystem services of natural grasslands in karst regions	VAM	Chi et al., 2013

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Primary Type	Secondary Type	Classification	Research Objectives	Research Methods	References
Rocky desertification ecosystem	Dominated by cultivated land, grassland, shrubland, and bare rock	Organic matter production	Impact of land use changes on soil organic matter production in rocky desertification areas	PQAM	Zhang et al., 2010
	Dominated by cultivated land, grassland, forest, and bare rock	Gas regulation, climate regulation, water conservation, soil formation and protection, waste disposal, biodiversity maintenance, food production, raw materials, and cultural recreation	Influence of rocky desertification control on ecosystem service values	VAM	He et al., 2022
	Dominated by cultivated land, shrubland, and bare rock	Provision of products, water conservation, soil retention, soil fertility, carbon sequestration, and oxygen release	Impact of ecological restoration projects on ecosystem service values in rocky desertification areas	VAM	Gao and Xiong, 2015
	Dominated by cultivated land, forest, grassland, and bare rock	Water conservation, soil retention, carbon sequestration and oxygen release, organic matter production, and atmospheric purification	Valuation of ecosystem service values in rocky desertification ecosystems	VAM	Wu et al., 2012
Cultivated land ecosystem	Dryland and paddy fields	Gas regulation, climate regulation, water conservation, soil formation and protection, waste management, biodiversity maintenance, food production, raw materials, and cultural recreation	Impact of karst slope land use changes on ecosystem service values	VAM	Luo et al., 2014
	Dryland and paddy fields	Agricultural production, regulating services, and cultural services	Valuation of ecosystem service of karst agricultural land	VAM	Zhou and Wang, 2023
Urban ecosystem	Dominated by forests, built-up land, and grassland	Habitat quality, carbon storage, water yield, and soil conservation	Analysis of trade-offs in urban ecosystem services in karst regions	MAM	Li et al., 2024a
	Urban green spaces	Climate regulation	Assessment of urban cooling services provided by green spaces in karst regions	MAM	Chen et al., 2021b
	Urban green spaces	Leisure and recreation	Assessment of recreational services provided by urban green spaces in karst regions	MAM	Luo et al., 2022
	Urban green spaces and built-up land	Flood regulation	Assessment of flood regulation services provided by urban areas in karst regions	MAM	Crespo et al., 2019

Notes: Physical quantity assessment methods: PQAM, Value assessment methods: VAM, Model assessment methods: MAM

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For instance, Zhou et al. (2010) quantitatively assessed the economic value of ecosystem services provided by artificial forests around karst cities using market value and alternative cost methods. The value assessment method is suitable for comparative studies of different types of ecosystem services in karst regions due to its ability to aggregate and compare different services (Yin et al., 2021).

The physical quantity assessment method evaluates ecosystem services from a physical quantitative perspective, often based on ecosystem processes or functions, thereby objectively reflecting the formation mechanisms of ecosystem services (Fu et al., 2013; Agudelo et al., 2020; Kokinou et al., 2023). Small-scale evaluations of karst ecosystem services often use monitoring data from fixed-point observations combined with ecological models, while large-scale assessments typically use monitoring and remote sensing data to establish models. This method effectively illustrates the relationship between karst ecosystem processes and services, providing an accurate reflection of the state of ecosystem services (Dong et al., 2020; Niu et al., 2022; Chang et al., 2024). For example, Zhang et al. (2015) used remote sensing and climate data to analyze changes in vegetation carbon sequestration services in karst areas.

In recent years, supported by GIS technology and based on remote sensing, socio-economic, and ecological environment data, ecosystem service assessment models (such as InVEST, ARIES, SolVES, etc.) have emerged. These models offer the advantages of speed, convenience, and clear spatial representation. Among these, the InVEST model has been widely applied in karst regions (Tian et al., 2016; Han et al., 2022a). It allows for the input of user-specific regional data, has a broad application range, and possesses strong spatiotemporal representation capabilities. This model can simulate changes in ecosystem services under different scenarios, providing scientific support for management decision-making in karst regions (Lang and Song, 2018; Gu et al., 2022).

Changes and Driving Mechanisms of Ecosystem Services in Karst Regions

Changes in Ecosystem Services in Karst Regions

The characteristic changes in ecosystem services in karst regions are a core focus of research on the dynamics and driving mechanisms of ecosystem service changes. Relevant studies often concentrate on the spatiotemporal characteristics and scales of ecosystem service changes. There is significant emphasis on analyzing spatiotemporal change characteristics. For instance, Ci et al. (2023), using ecological models, analyzed changes in soil retention, water conservation, and carbon sequestration services in the southwestern Chinese karst region from 2000 to 2020, revealing heterogeneity in spatial patterns of ecosystem service changes across different historical stages. Lu et al. (2022b), employing a value coefficient method, analyzed the spatiotemporal changes in ecosystem service values over the past 35 years in a typical karst area (Guizhou Province, China), highlighting variations across different karst landforms and terrain gradients. Much of the existing research has focused on the characteristics of ecosystem service changes in historical periods, particularly emphasizing spatiotemporal changes since 1990 (Jiao et al., 2022; Zeng et al., 2024). This is directly related to ecological engineering projects such as rocky desertification control, reforestation, and rapid economic development (Lang and Song, 2019; Han et al., 2022b; He et al., 2022).

Karst ecosystem services depend on ecological and geographical processes at different spatial scales, imparting spatial scale effects (Gao et al., 2022). Therefore, emphasizing spatial scale is a crucial perspective in current research on changes in karst ecosystem

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services. Numerous scholars have studied changes in karst ecosystem services across multiple spatial scales, including global, national, provincial, regional, and watershed scales (Wang et al., 2020; Yuan and Huang, 2022; Chi et al., 2023; Li et al., 2024b). Regional-scale studies are predominant, with research on southwestern China dominating (Miao et al., 2022; Du et al., 2023). It is noteworthy that research on changes in karst ecosystem services at different spatial scales focuses differently: larger scales often concentrate on regulating and supporting services (e.g., carbon sequestration, water conservation, soil erosion control), while smaller scales tend to emphasize provisioning and cultural services (e.g., recreational activities, agricultural supply) (Tian et al., 2016; Han et al., 2022c; Kokinou et al., 2023).

Driving Mechanisms of Changes in Karst Ecosystem Services

Changes in karst ecosystem services result from the coupling of various driving factors (*Figure 2*).

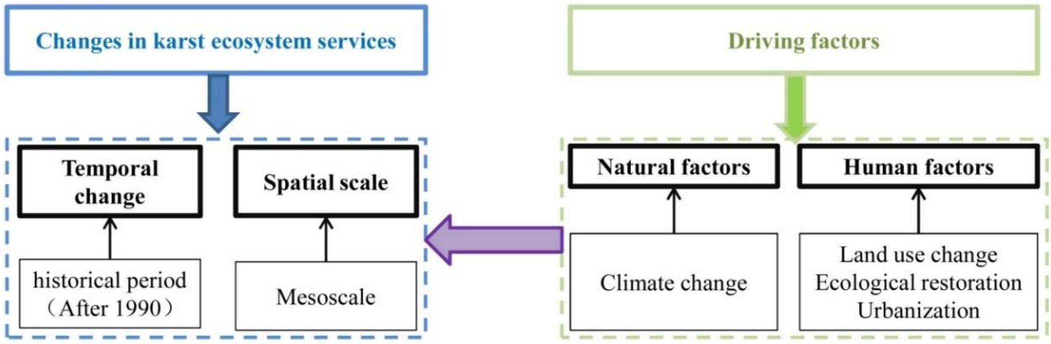

Figure 2. *Research focus on changes and driving mechanisms of ecosystem services in karst regions*

Impact of Natural Factors on Karst Ecosystem Services

Climate change directly or indirectly affects karst ecosystem services. Direct impacts include water supply, water quality purification, net primary productivity, vegetation cover, and soil erosion control, while indirect impacts affect soil formation and habitat quality (Brandt et al., 2018; Han et al., 2021; Siegel et al., 2023). For example, Han et al. (2020a) analyzed the effects of climate change and land use change on soil erosion control and water quality purification services in karst regions, finding that climate change has a more pronounced impact on these services compared to land use change. Huang et al. (2013) analyzed the spatiotemporal characteristics of net primary productivity of vegetation in southern Chinese karst regions under climate change, revealing an increasing then decreasing trend from 2000 to 2010, with significantly greater fluctuations in net primary productivity in karst areas compared to non-karst areas under climate change.

Impact of Human Factors on Karst Ecosystem Services

Land use changes affect the structure, processes, and functions of karst ecosystems and subsequently influence the supply of ecosystem services. The impact of land use changes on changes in karst ecosystem services has both positive and negative aspects

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(Chen et al., 2021c; Xiong and Li, 2024). Studies have confirmed that urbanization directly alters land cover, thereby affecting the structure, function, and services of karst ecosystems. Rapid urbanization leading to extensive use of built-up land has a significantly negative impact on habitat quality, carbon storage, and soil erosion control services in karst urban green spaces (Li et al., 2024a). Increased bare rock areas due to rocky desertification result in substantial losses in ecosystem service values such as organic matter production, carbon sequestration, soil erosion control, nutrient accumulation, biodiversity conservation, and landscape recreation in karst regions (Wang et al., 2013). It is noteworthy that the conversion of a large amount of slope farmland to forests and shrub is highly beneficial for increasing ecosystem services in karst regions (Luo et al., 2014; Wang et al., 2020; Yuan and Huang, 2022).

Human intervention through ecological restoration measures (policies) actively changes land cover types, enhances biodiversity, and thereby positively impacts ecosystem services. Measures such as rocky desertification control projects and grain for green projects are crucial for ecological restoration in karst regions, playing significant positive roles in increasing karst ecosystem services (Deng et al., 2023). Research has shown that grain for green project in karst regions can effectively mitigate the negative impacts of drought on water yield, soil erosion control, and water quality purification services (Han et al., 2022b). Rocky desertification control increases the area of ecological land (such as forests, grasslands, shrublands), thereby increasing the value of ecosystem services (He et al., 2022). However, in karst regions, the impact of ecological restoration models, based on various planting methods integrated with economic development, on ecosystem services exhibits significant heterogeneity. Studies have found notable differences in regulating services, supporting services, and provisioning services across ecological restoration models based on different planting methods in rocky desertification areas. It is recommended to select different models according to regional differences and the needs of local farmers to enhance the level of ecosystem services in areas undergoing rocky desertification restoration (Zou et al., 2020).

Trade-offs, Synergies, and Supply-Demand Relationships of Karst Ecosystem Services

Due to the diversity of ecosystem service types, uneven spatial distribution, and selective human usage, dynamic changes occur in the relationships among karst ecosystem services, manifesting as trade-offs and mutual synergies (*Figure 3*). Current research on trade-offs and synergies of karst ecosystem services primarily focuses on provisioning, regulating, and supporting services. Scholars have found trade-off relationships between water yield and habitat quality, and between water yield and soil erosion control in karst regions, while synergistic relationships exist between water yield and carbon storage, and between carbon storage and habitat quality (Li et al., 2024a). Methods for studying trade-offs and synergies of karst ecosystem services mainly involve mathematical modeling and model simulation methods such as the InVEST model simulation, spearman's correlation analysis, production possibility frontier analysis, and Bayesian belief network model (Lang and Song, 2018; Peng et al., 2022; Zhang et al., 2024a). It is important to note that multiple factors contribute differently to the trade-offs and synergies of ecosystem services, primarily depending on the main influencing factors of changes in different ecosystem service types (Tian et al., 2016; Han et al., 2020b; Niu et al., 2022; Yuan and Huang, 2022; Li et al., 2024a).

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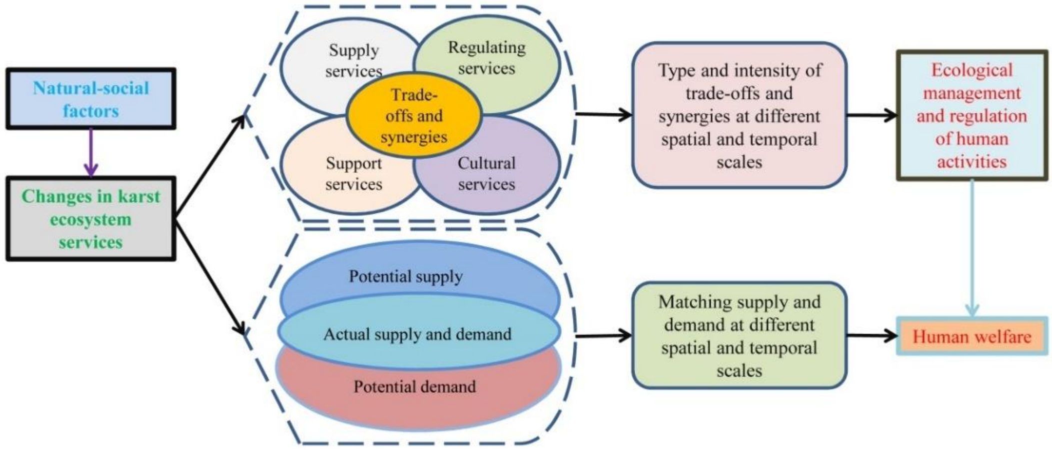

Figure 3. *Trade-offs/Coordination and Supply-Demand Relationships of Karst Ecosystem Services and Cascade Relationships with Human Well-being*

Due to the ecological fragility of karst regions, excessive human activities can easily lead to imbalances in ecosystem service supply and demand (Fang et al., 2022). Therefore, research on the supply-demand relationships of karst ecosystem services is increasingly emphasized (Jiang et al., 2022). Currently, quantitative analyses of the supply-demand relationships of four ecosystem services–carbon storage, water yield, agricultural products, and recreational activities–in karst regions have been conducted (Zhang et al., 2019; Luo et al., 2022). Studies have found that in southern Chinese karst regions, the overall supply-demand relationships of carbon storage, water yield, and agricultural products show a surplus state but exhibit significant spatial heterogeneity, primarily due to mismatches between natural environments and human activities (Tan et al., 2023). Similarly, influenced by uneven human activity intensity and urban green space distribution, there are spatial differences in the supply-demand of recreational services in karst urban areas (Luo et al., 2022).

Karst Ecosystem Services and Human Welfare

Karst ecosystem services can affect components of human welfare, exhibiting a nonlinear relationship between the two. Conversely, human welfare also directly or indirectly affects karst ecosystem services (*Figure 3*). On one hand, improving the supply level of karst ecosystem services can meet the increasing demand for ecosystem products and services, alleviating supply-demand imbalances. Existing research has demonstrated that enhancing urban flood regulation services in karst regions can reduce the incidence of gastrointestinal diseases (Crespo et al., 2019). However, pursuing a high supply capability of a particular karst ecosystem service may have negative consequences for humans, such as increased water and nitrogen outputs due to increased food production, leading to higher environmental and production costs (Gu et al., 2022). On the other hand, humans can influence ecological processes through various proactive measures, thereby enhancing the supply capability of ecosystem services and enhancing human welfare provided by ecosystems. For example, improving water-fertilizer coupling technologies can effectively increase water resource utilization in rocky desertification areas, reduce carbon and nitrogen losses, and thus provide more forest ecosystem services (such as

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timber production and soil conservation) to humans (Xiong et al., 2023d). Developing ecological animal husbandry in karst regions can improve grassland ecological carrying capacity and provide new approaches for rural revitalization and ecological civilization construction, thereby enhancing rural residents' income levels (Song et al., 2022). However, various measures taken by humans do not necessarily increase the supply capability of karst ecosystem services, contributing to improved human welfare. Studies have found that although grain for green projects in karst mountainous areas can enhance supporting and regulating services of forest ecosystems, ensuring food supply and freshwater supply remains challenging, threatening human food and drinking water security (Yue et al., 2020; Liu et al., 2022; Zeng et al., 2024).

Currently, research on the relationship between karst ecosystem services and human welfare mostly explores the impact of management policies or measures on karst ecosystem services and related human welfare studies (Zhou et al., 2022; Li et al., 2023; Yang et al., 2023; Maragkaki et al., 2024). For instance, some scholars have proposed that karst ecological protection zones can promote the realization of ecological value through territorial spatial planning and regulation, thereby promoting the development of ecological industries and improving local income levels (Zhang et al., 2024c). Scientific agricultural and forestry landscape management can consolidate the effectiveness of rocky desertification control in ecosystem services, thereby enhancing the welfare of local residents (Wu et al., 2023).

Challenges and Research Prospects

Improvement of Classification System and Assessment Methods for Karst Ecosystem Services

Based on research objectives, current classifications of karst ecosystem services primarily focus on aspects such as service value assessment, land use changes, and ecological governance impacts on ecosystem services. These classifications lack standardization, making it difficult to compare evaluation results horizontally. Furthermore, current classifications often transplant findings from studies like Millennium Ecosystem Assessment (2005), Xie et al. (2003), and Costanza et al. (1997), neglecting the specific characteristics of karst ecosystems. Future efforts should develop a classification system for karst ecosystem services based on the direction of decision-making from research results and the structural and functional characteristics of karst ecosystems.

Although both physical quantity assessment methods and economic value assessment methods are widely applied in karst ecosystem service assessments, the uncertainty of assessment results has drawn scholarly attention. Given the complexity and heterogeneity of karst ecosystems, and the dependencies or antagonistic relationships among various karst ecosystem services, the accuracy of assessment results needs improvement (Johnson et al., 2012; Gunton et al., 2017; Hamel and Bryant, 2017; Bryant et al., 2018; Liu et al., 2020; Zhang et al., 2024b). Therefore, future assessments of karst ecosystem services should carefully select assessment methods to avoid redundant calculations and enhance accuracy. Additionally, while ecosystem service assessment models have been applied, the predominant use of the InVEST model for assessing karst ecosystem services overlooks models like ARIES, SolVES, MIMES, EPM, InFOREST, and EcoMetrix. Given the uncertainties in model calculations due to ecosystem characteristics, structural features of models, and simplification of input data, parameters' suitability and model

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applicability during localization should be considered. Hence, future developments should focus on assessment models tailored to the structural and functional characteristics of karst regions.

Research Scale, Objects, and Perspectives of Karst Ecosystem Services

Karst ecosystem services rely on natural ecological and socio-cultural processes across different spatial and temporal scales. Consequently, Karst ecosystem services exhibit scale effects (Gao et al., 2022). Current assessments of karst ecosystem services predominantly focus on small to medium scales (Goldscheider, 2019; Yuan and Huang, 2022), with relatively limited studies at global and national scales. This limitation hinders the understanding of overall characteristics of large-scale karst ecosystem services, thereby complicating the formulation and implementation of public management policies. Moreover, research on karst ecosystem services primarily targets forests, rocky desertification, and urban ecosystems (Pan et al., 2021; Xiong et al., 2023b), with weaker studies on wetlands, lakes, and farmland ecosystems. Supply services, regulatory services, and support services are current focal points in karst ecosystem research (Lang and Song, 2018; Qiu et al., 2021; Han et al., 2022b; Li et al., 2024a). However, research on cultural services remains limited. Therefore, future research should emphasize large-scale studies and diversify the research scope of karst ecosystem services.

Research perspectives on karst ecosystem services predominantly focus on the positive services ecosystems provide to humans (Wang et al., 2023; Xiong and Li, 2024), with relatively fewer studies on negative services (service losses). Future efforts should establish evaluation indicator systems and assessment methods for negative services in karst ecosystems, focusing on aspects like greenhouse gas emissions and heavy metal pollution. Furthermore, current research paradigms often follow a "land use–ecosystem service response or ecological restoration–ecosystem service" framework (Huang et al., 2023; Li and Geng, 2023; Li and Xu, 2023; Zhang et al., 2023), which oversimplifies the complexity and diversity of ecosystems. Future research should adopt a cascading framework of "ecosystem structure, processes–functions–services" to elucidate the relationships between karst ecosystems and ecosystem functions and services.

Complex Driving Mechanisms of Karst Ecosystem Service Changes by Various Factors

The effects of multiple factors on karst ecosystem services are highly complex, exhibiting characteristics such as non-linearity, spatiotemporal scale heterogeneity, heterogeneous intensity and direction of action (Zhang et al., 2022a; Ci et al., 2023; Kong et al., 2023). Therefore, understanding the complex interaction mechanisms, processes, and characteristics of various factors affecting changes in karst ecosystem services remains a current research challenge, with a lack of systematic and in-depth studies. For example, the interaction processes between land use change and climate change and their combined impact on karst aquatic ecosystem services warrant investigation. Additionally, while studies on the mechanisms of land use change and ecological engineering on karst ecosystem services are prominent (Wang et al., 2020; Wang et al., 2022), analyses of the impact mechanisms on climate change remain scarce. Furthermore, as an important aspect of climate change research, there is limited analysis of the mechanisms by which extreme climates affect karst ecosystem services.

Scenario simulation methods, sensitivity analysis methods, regression analysis methods, and geographic detectors have been widely used in studies on the driving mechanisms of karst ecosystem service changes (Lang and Song, 2019; Hu et al., 2020;

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Li and Luo, 2023; Zhang et al., 2024d). For instance, Han et al. (2020a) used scenario simulation methods to reveal that changes in soil conservation in karst areas are primarily influenced by climate change, while water quality purification is mainly affected by land use change. While these research methods straightforwardly demonstrate the magnitude and direction of various factors' impacts on karst ecosystem service changes, they do not comprehensively elucidate the underlying mechanisms (Jiao et al., 2022; Ci et al., 2023). Future research should integrate computer technology, mathematical methods, and geographic information technology to differentiate the impacts of multiple complex factors on karst ecosystem services.

Quantification and Scientific Management of Nonlinear Relationships in Trade-offs/Synergies

The study of trade-offs and synergies in karst ecosystem services can provide a scientific basis for policy formulation regarding the ecological environment and socio-economic development in karst regions, playing a crucial role in the rational use of natural resources (Deng et al., 2023). However, current research on trade-offs and synergies in karst ecosystem services is in its nascent stage, often employing traditional correlation analysis and indicator quantification methods to broadly identify types of trade-offs and synergies (Ran et al., 2020; Yuan et al., 2022). These methods do not reveal the spatial heterogeneity of these relationships, making it difficult to clarify the nonlinear dynamic relationships between karst ecosystem services. Key focus areas include the trade-offs and synergies among soil and water conservation, water production, carbon storage, grain production, habitat quality, net primary productivity, and water purification (Tian et al., 2016; Lang and Song, 2018; Han et al., 2019; Jiang et al., 2023). Conversely, there is limited research on the relationships between other types of karst ecosystem services, such as cultural services, timber production, and climate regulation. Future studies should employ graphical comparison methods, scenario analysis, and model simulation combined with mathematical approaches to enhance the quantification of trade-offs and synergies in karst ecosystem services. Emphasis should be placed on the spatial expression of these relationships and on studying the relationships among a wider range of ecosystem services, such as between cultural services and supporting services.

Research indicates that the driving factors of relationships between different karst ecosystem services vary, with differing intensities of natural and social factors (Zuo et al., 2021; Huang et al., 2023; Li et al., 2024a; Qu et al., 2024; Zhang et al., 2024a). To better mitigate trade-offs in karst ecosystem services, the formulation of policies to optimize these relationships has garnered increasing attention from scholars (Peng et al., 2022; Tan et al., 2023; Qu et al., 2024). For example, urban green space planning, which comprehensively considers land use policies, soil conditions, and transportation layout, can help alleviate trade-offs in karst urban ecosystem services (Li et al., 2024a). The grain for green project in karst regions should consider regional characteristics and project implementation intensity to reduce the intensity of trade-offs (Wang et al., 2022). Optimizing forest community structure and function can improve trade-offs in karst forest ecosystem services (Xiong et al., 2023c). However, these policy measures are primarily qualitative and lack accurate quantitative evaluation, making it difficult to assess their reliability. Future efforts should focus on innovating methods to optimize trade-offs in karst ecosystem services and evaluating the effectiveness of policy measures based on these innovations.

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Quantification of Supply-Demand Relationships of Karst Ecosystem Services at Different Temporal and Spatial Scales

Most current studies focus heavily on quantifying the supply of various ecosystem services in karst regions, and related quantification methods are well-established (Zhou et al., 2022; Yang et al., 2023; Zhang et al., 2024d). However, research on demand quantification remains limited, with only a few service types quantified such as recreation, freshwater demand, and food demand (Fang et al., 2022; Luo et al., 2022). Studies have confirmed prominent spatiotemporal heterogeneity in both supply and demand of karst ecosystem services (Wu et al., 2013; Jiang et al., 2022; Tan et al., 2023). While extensive research has been conducted on quantifying supply at different temporal and spatial scales, understanding of demand characteristics of various karst ecosystem services and supply-demand relationships across scales remains relatively underdeveloped. Future research should expand quantification of demand for various service types, enhance understanding of demand characteristics of karst ecosystem services at different temporal and spatial scales, compare differences in types and intensities of supply-demand relationships, and gradually establish governance mechanisms for karst ecosystem service supply-demand zoning to mitigate uneven supply and demand issues (Shen et al., 2021).

Primary obstacles to demand quantification include reliability of calculation methods and service type characteristics related to human needs (Jiang et al., 2022). Many service types in karst regions (such as biodiversity, water purification, recreation, and pollination) face obstacles in quantification due to challenges in estimating measurement units, data gaps, methodological deficiencies, etc., thereby hindering efforts to quantify relationships between karst ecosystem services and human demand. Future efforts should improve the indicator system for quantifying demand for karst ecosystem services, utilize multi-source data including experimental, monitoring, spatial, and statistical data, develop integrated models for karst ecosystem services, and develop targeted models for specific service types to improve accuracy of demand quantification (Guo et al., 2020).

Evaluation of Human Welfare and Response Mechanisms of Ecosystem Services in Karst Regions

Karst regions are often economically underdeveloped and ecologically fragile, making the provision of various welfare benefits by karst ecosystems crucial for sustainable socio-economic development and rational resource utilization (Telbisz et al., 2020; Bai et al., 2023). Research indicates that enhancing ecosystem service levels through ecological restoration and protection can improve human welfare in karst regions (Qi and Xiong, 2021; Posavec et al., 2023). Initiatives such as ecological compensation, product trading, and ecological security system construction based on karst ecosystem services can effectively promote industrial development, increase local residents' income, and enhance local welfare (Gou et al., 2022; Xiong et al., 2023d). However, difficulty in acquiring human welfare data and spatial representation challenges have led to the predominance of economic indicators in karst region welfare indices (Li et al., 2023; Zhang et al., 2024c), neglecting social, educational, cultural, and psychological health aspects. Future efforts should establish a comprehensive human welfare indicator system encompassing both material and subjective welfare to accurately assess the impact of karst ecosystem services on human welfare. Moreover, due to differences in welfare

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indicator systems across scales, attention should be given to multi-scale effects in constructing indicator systems.

Although scholars have investigated the impact of ecological restoration on enhancing the provision of karst ecosystem services and local residents' welfare, these studies have primarily focused on simple correlation analyses (Yue et al., 2020; Jiang et al., 2022; Tan et al., 2023). The mechanisms by which karst ecosystem services influence residents' welfare remain unclear. It is not well understood which aspects of welfare are affected by karst ecosystem services, the extent of these contributions, the degree to which local residents benefit from these services, or how the flow of karst ecosystem services contributes to residents' welfare (Li et al., 2022). Therefore, future research should aim to further elucidate the complex coupling relationship between the two, clarifying the response mechanisms of residents' welfare to karst ecosystem services, and providing a scientific basis for the formulation of management strategies for karst ecosystem services.

Conclusions

By systematically reviewing the current status of karst ecosystem services research, we identify existing challenges and future prospects. The following conclusions are drawn:

Provisioning services, regulating services, and supporting services are currently the primary focus in the assessment of karst ecosystem services. However, there is less attention given to services such as recreation, biodiversity, plant pollination, and pest control. The assessment methods are gradually shifting from quantity and value methods to model-based approaches. Analysis of changes in ecosystem services at small and medium scales and exploration of the impact mechanisms of human activities on karst system services are significant areas of focus. Quantification of trade-offs and synergies mainly concentrates on services such as soil and water conservation, water production, carbon storage, grain production, habitat quality, net primary productivity, and water purification. Increasing attention is being paid to scientific management to reduce the intensity of trade-offs, but quantitative research on the demand for karst ecosystem services and human welfare is still in the exploratory stage.

Current research on karst ecosystem services faces several challenges, notably the lag in development of assessment models, neglect of karst ecosystem services from lakes, wetlands, and cultivated lands, and insufficient emphasis on large-scale studies. Research perspectives are often singular, disproportionately focusing on land use (or ecological restoration) and cascading impacts on karst ecosystem services. Studies on the effects of climate change (including extreme weather events) on karst ecosystem services remain underexplored, particularly lacking in-depth exploration of coupled impacts of human activities and natural environments. Methods for quantifying trade-offs and synergies, supply-demand relationships, and human welfare related to karst ecosystem services are relatively simplistic. There is a deficiency in revealing complex nonlinear characteristics among karst ecosystem services and exploring driving mechanisms of these services on human welfare.

Future efforts will focus on developing ecosystem service assessment models suitable for the karst region, prioritizing large-scale studies and expanding research into diverse types of karst ecosystem service dynamics. A research perspective based on "karst ecosystem structure, process-function-service" will be explored to highlight the intricate factors influencing karst ecosystem services. Emphasis will be placed on enhancing

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research on non-linear trade-offs and synergies relationships and scientific management of karst ecosystem services. Improvement of methods for assessing ecosystem service supply-demand and human welfare will aim to elucidate the mechanisms through which karst ecosystem services affect human welfare.

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