Sustainability in Environment
ISSN 2470-637X (Print) ISSN 2470-6388 (Online)
Vol. 11, No. 2, 2026
www.scholink.org/ojs/index.php/se

Original Paper

Research Progress in Ecosystem Carbon Sequestration Function and Implications for Karst Desertification Governance

Shenhui Yu[1] & Kangning Xiong[1*]

[1] Guizhou Normal University, Huaxi University City, Guiyang, Guizhou, China

[*] Corresponding Author

Received: February 01, 2026 Accepted: March 12, 2026 Online Published: March 23, 2026

doi:10.22158/se.v12n1p53 URL: http://dx.doi.org/10.22158/se.v12n1p53

Abstract

Carbon sequestration is a core ecosystem service for mitigating global warming, yet it is highly vulnerable to degradation in karst desertification areas due to geological and anthropogenic factors. By using bibliometric tools such as CiteSpace and VOSviewer, this study conducted a bibliometric analysis of 2247 relevant publications retrieved from the Web of Science database up to 2024, clarifying the global research pattern, research hotspots and three major developmental stages in this field. This study elaborated on the carbon sequestration mechanisms and influencing factors of forest, grassland and soil ecosystems, and meanwhile pointed out the existing research deficiencies such as insufficient exploration of vegetation carbon sequestration potential and inconsistent understanding of soil organic carbon stability. Aiming at the governance of karst desertification, targeted strategies were proposed, including revising remote sensing data combined with field investigations, constructing region-specific assessment systems, and exploring soil carbon fixation pathways at multiple scales, which provides scientific support for carbon sink enhancement, carbon sequestration and ecological restoration in ecologically fragile areas.

Keywords

Ecosystem carbon sequestration, Karst desertification governance, Bibliometric analysis, Ecologically fragile areas

1. Introduction

Carbon sequestration is one of the core ecosystem services. By absorbing atmospheric carbon dioxide (CO_2) and fixing it into organic carbon, it achieves the atmospheric oxygen-carbon balance, and more importantly, serves as a crucial measure for regulating regional climate and mitigating the global greenhouse effect. Driven by human activities, global greenhouse gas emissions have risen sharply, and

CO_2 has become a core factor influencing climate change due to its large emissions and significant contribution to global warming. Enhancing the carbon sequestration capacity of ecosystems has become an important approach to slowing down the increase in atmospheric CO_2 concentration and maintaining the stability of ecosystem structure and function . Meanwhile, carbon sequestration is also a key indicator for evaluating ecosystem health. Healthy forest, grassland and other ecosystems can concurrently achieve the benefits of water conservation, hydrological regulation and biodiversity maintenance while sequestering carbon. The process of carbon sequestration and sink enhancement is essentially the strengthening of ecosystem stability and the comprehensive improvement of ecosystem functions (Zhao, Liu, & Wu, 2020).

To date, fruitful achievements have been made in the research on ecosystem carbon sequestration. As the core carriers of terrestrial carbon sinks, forests, grasslands and soils have been extensively investigated for their carbon sequestration mechanisms and action principles. Forests are among the largest terrestrial carbon pools, accounting for 40% of the carbon storage in terrestrial ecosystems (Pan, Birdsey, Fang et al., 2022). They convert CO_2 into organic carbon through photosynthesis and store it in trunks, branches, leaves, roots and other organs, thus effectively sequestering carbon and mitigating climate warming (Bonan, 2008). Grasslands cover one-third of the global land area and act as a key link in the global carbon cycle . Approximately 90% of their carbon storage is concentrated in roots and soils, which constitutes the core of carbon sequestration in grassland ecosystems (Bai & Cotrufo, 2022). Soil carbon is divided into inorganic carbon and organic carbon: inorganic carbon exists in a stable form, while organic carbon exchanges frequently with atmospheric CO_2, with the surface storage accounting for two-thirds of that in terrestrial ecosystems. The total soil carbon storage is about twice that of the atmosphere and three times that of vegetation, and its minor changes will significantly affect the atmospheric CO_2 concentration (Post & Kwon, 2000). Through their unique carbon sequestration mechanisms, the three have become the main contributors to terrestrial carbon sinks and play an indispensable role in mitigating climate change.

However, in ecologically fragile areas, ecosystem carbon sequestration functions are characterized by high sensitivity, poor stability and weak anti-interference capacity (Zhang, Brandt, Yue et al., 2022). Karst desertification areas are facing more severe challenges of carbon sequestration function degradation due to their unique geological background and human interference. Relying on carbonate rock geology, these areas form a binary three-dimensional hydrological structure, with slow soil formation rate, thin soil cover, soil loss far exceeding soil formation, and extremely poor substrate stability (Jing, Li, Xiong et al., 2025). Despite abundant precipitation, the terrain and hydrological structure result in weak water retention capacity, and soil water shortage severely restricts plant growth (Peng, Dai, Ding et al., 2019). Meanwhile, the population density of the karst area in Southwest China exceeds 200 people per square kilometer. Population growth has intensified the pressure of land development, and the overutilization of cultivated land has further accelerated rocky desertification. The loss of vegetation cover and deforestation directly lead to a decline in photosynthetic capacity and a significant degradation of carbon sequestration capacity, which not only disrupts the regional carbon balance but also affects the carbon cycle and regional climate at a larger scale (Lian, You, Lin et al., 2015).

The ecosystems in karst desertification areas can be restored through human intervention. Forest and grassland restoration as well as soil improvement are the core measures for rocky desertification control, playing a key role in restoring ecological structure and enhancing carbon sequestration capacity. Forest restoration can increase vegetation cover, improve biodiversity, optimize soil structure and reduce soil and water loss. As pioneer plants, grasslands consolidate soil and increase soil fertility through their root systems, laying a foundation for subsequent vegetation succession. Soil improvement specifically ameliorates the physical and chemical properties of soil, creating favorable conditions for plant growth. The three measures jointly strengthen the stability and functions of ecosystems. As the core distribution area of global karst landforms, the karst area in Southwest China is plagued by prominent rocky desertification problems. After more than 20 years of vegetation restoration and control, the area of rocky desertification in this region has been greatly reduced, and the vegetation coverage and carbon sequestration capacity have been significantly improved. The carbon sequestration rate of aboveground biomass has increased from 0.14 Mg $C \cdot hm^{-2} \cdot a^{-1}$ to 0.3 Mg $C \cdot hm^{-2} \cdot a^{-1}$ ($p<0.01$) (He, Wen, Zhu et al., 2017; Tong, Wang, Yue et al., 2017). During the control process, the carbon sequestration potential has been fully released. Forest and grassland restoration have simultaneously improved soil structure, protected biodiversity, promoted the comprehensive improvement of ecosystem services, and driven the dual improvement of regional ecological environment and people's well-being (Liu, Zhang, Wang et al., 2015). It is evident that the improvement of carbon sequestration function is not a single carbon sequestration effect, but can coordinate with other ecosystem services to promote ecological restoration and sustainable development in rocky desertification areas. Exploring its improvement paths and internal mechanisms has become an important urgent issue to be solved in the field of ecological governance.

Existing reviews mostly focus on the classification, application practice and research methods of ecosystem carbon sequestration functions (Huang, Zhou, Lv et al., 2020). However, most studies concentrate on the basic characteristics, measurement methods and macro benefits, lacking in-depth analysis of the effective paths to enhance carbon sequestration capacity, and the targeted research on ecologically fragile areas is particularly scarce. At the same time, studies on carbon sequestration in forests, grasslands and soils mostly focus on carbon sink potential and carbon absorption capacity, with insufficient research on the optimization and enhancement strategies of carbon sequestration mechanisms in different ecosystems under specific environments. Based on this, this paper systematically combs the relevant global literatures, summarizes the key research achievements of carbon sequestration in forests, grasslands, soils and other ecosystems, and identifies the existing research blind spots and challenges. It aims to provide a new perspective for the research on ecosystem carbon sequestration, and more importantly, offer scientific guidance and practical reference for enhancing the carbon sequestration capacity of ecologically fragile areas such as karst desertification regions and promoting their regional ecological restoration and sustainable development.

2. Materials and Methods

2.1 Data Sources

Literature retrieval was conducted based on the core database of Web of Science (WOS), with the search time scope covering the full span of the database and the deadline set as December 31, 2024. In the WOS database, “theme” was adopted as the retrieval field, with “Ecosystem services” + “carbon sequestration” as the initial search terms. “Forest”, “grassland” and “soil organic carbon” were added as restrictive terms for separate retrieval, respectively. Finally, through screening titles, keywords and abstracts, a total of 2247 publications were identified, including 1952 Articles, 195 Reviews, 27 Book Chapters, 40 Proceedings Papers, 18 Early Access papers, 2 Corrections, 2 Letters and 11 Additional Materials.

2.2 Methods and Data Analysis

Bibliometric cluster analysis was performed in this study using CiteSpace, VOSviewer and Scimago Graphica software. CiteSpace is a scientific literature analysis tool jointly developed by Dr. Chaomei Chen from the College of Information Science and Technology, Drexel University, USA, and the WISE Laboratory of Dalian University of Technology. It is capable of conducting visual analysis on the literature in a specific research field based on time series. VOSviewer is a product developed by the Centre for Science and Technology Studies (CWTS) at Leiden University in the Netherlands, which can be used to visualize the cooperation relationships among different countries and research trends in the field.

2.2.1 Country Analysis

Among the 2247 retrieved publications, the United States had the highest number of publications (N=656, 29.1%), followed by China (N=536, 23.8%), Germany (N=187, 8.3%) and Australia (N=175, 7.7%) (Fig. 1). All these countries have signed the Paris Agreement and committed to achieving net-zero emissions by the mid-21st century. As developed countries, the United States, Germany and Australia boast a sophisticated industrial foundation and are highly reliant on fossil fuels such as coal and natural gas in the course of economic development. As the world's largest developing country, China has generated a large volume of greenhouse gases amid its rapid economic development and industrial expansion. Thus, against the backdrop of enormous carbon emission pressure, all these countries have strengthened research on carbon sequestration functions. Data processing via VOSviewer 1.6.20 enables an intuitive visualization of the cooperation relationships among countries, which provides substantial support for the further analysis of research findings from different countries. In this study, the minimum number of publications per country was set at 10, and a total of 56 countries met this threshold.

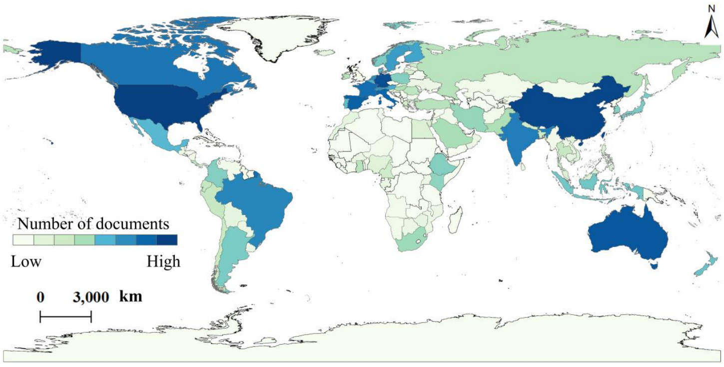
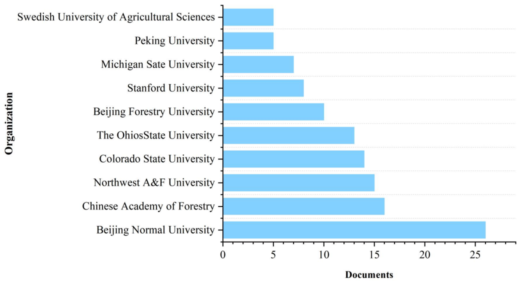


Figure 1. Country Distribution

2.2.2 Institutional and Author Analysis

A statistical analysis of all 2247 publications revealed that the contributing institutions could be categorized into four types: universities, research centers, government departments and enterprise institutions. Among them, universities and research centers accounted for more than 80% of the total publications, indicating that these institutions attach greater importance to research on ecosystem carbon sequestration functions. In addition, statistical analysis of relevant research institutions showed that the top five institutions in terms of publication output were the Beijing Normal University, the Chinese Academy of Forestry, the North A&F University, the Colorado State University, The OhiosState University (Fig. 2). Statistical analysis of the global publication output by authors indicated that scholars including Escobedo Francisco J, Fu Bojie, Baskent Emin Zeki, Bardgett Richard D and Blanco-Canqui Humberto form the core research teams and academic leaders in this field (Figure 3).



Figre 2. Top 10 literature - publishing Organization

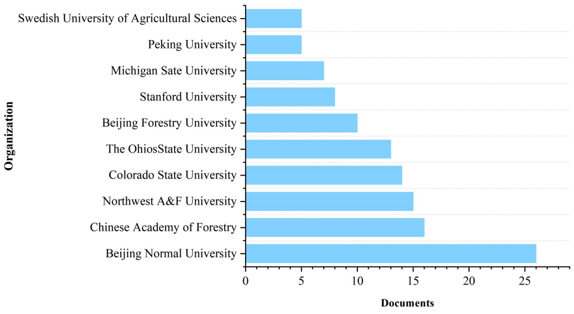


Figure 3. Top 10 literature - publishing Author

2.2.3 Research Hotspots and Trends

Carbon sequestration as a component of ecosystem services is of great significance for mitigating global climate change and maintaining ecological balance. A total of 8961 keywords were extracted from the 2247 retrieved publications; thus, the threshold was set at 50 in this study, with 72 keywords meeting the preset criteria. Keyword frequency analysis was conducted on the publications related to carbon sequestration functions from the Web of Science (WOS) core database using VOSviewer 1.6.20, which could intuitively reflect the research hotspots in the relevant field in recent years (Fig. 4). The more distinct the color in the figure, the higher the occurrence frequency of the corresponding keyword. As shown in Fig. 5, ecosystem services, carbon sequestration, biodiversity, climate change and conservation are the research hotspots in the field of carbon sequestration function research. As a key ecosystem service, carbon sequestration can regulate atmospheric carbon dioxide concentration and mitigate climate change, and research on this service is of great global strategic significance for evaluating and optimizing ecosystem services as well as addressing climate change. Carbon sequestration is the core of mitigating climate change and achieving carbon neutrality. Against the backdrop of global warming, improving carbon sequestration efficiency and carbon fixation capacity has become a research priority. Biodiversity is the foundation of ecosystem health and functionality, and it is closely associated with carbon sequestration; protecting biodiversity can enhance the carbon absorption and sequestration capacity of ecosystems. Meanwhile, climate change has heightened attention to carbon sequestration research, and the carbon sequestration capacity of ecosystems is conducive to regulating the climate system. In addition, ecological conservation is closely linked to carbon sequestration: protecting carbon-rich ecosystems such as forests and wetlands can strengthen carbon sequestration functions, and the integration of ecological conservation with carbon market mechanisms in recent years has also promoted the application of carbon sequestration research at the policy and management levels.

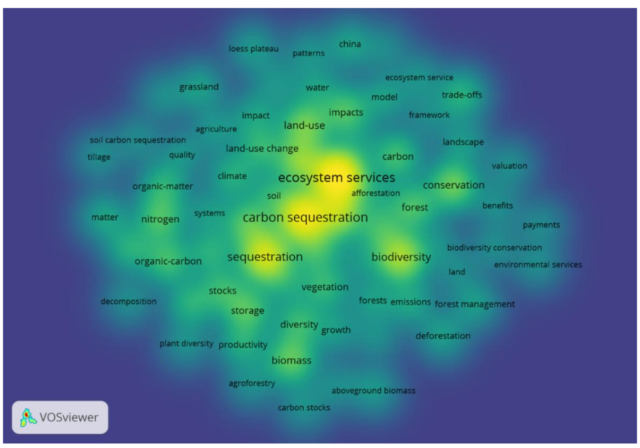


Figure 4. Keywords Frequencies

Ecosystem carbon sequestration services have garnered widespread attention against the backdrop of global warming. A burst keyword refers to a keyword that suddenly emerges as a research hotspot or a focal point in a specific period, which can reflect the research trends in different fields . A total of 25 burst keywords were identified from the 8961 keywords in this study, which are representative of the research trends in the field of ecosystem carbon sequestration from 2000 to 2024 (Fig. 5). As shown in Fig. 5, keywords including biomass, biodiversity, conservation, environmental services and biodiversity conservation exhibited an early emergence and a long burst duration, indicating that the early research focus was concentrated on exploring the relationship between biological factors and carbon sequestration functions. With the evolution of keywords, the research directions have been continuously expanded. The prominence of keywords such as deforestation, payments, policy and greenhouse gas emissions reveals that against the backdrop of ecological deterioration, research has begun to explore multiple dimensions including the correlations between ecosystem carbon sequestration functions and ecological restoration as well as its ecological benefits. With the development of the global carbon trading market, the relationship between carbon sequestration and the carbon market has become increasingly close. The carbon trading market provides economic incentives for carbon sequestration, prompting more research to focus on how to promote the realization of carbon sequestration services through market mechanisms. Since 2021, the emergence of keywords such as soil carbon sequestration, degradation, patterns, plant diversity, microbial biomass and InVEST model has indicated the shift of research resources toward new research fields. Ecological restoration remains a research hotspot in this field, while the importance of soil carbon pools has become increasingly prominent. The research focus has shifted from the measurement of total soil organic carbon content to the investigation of soil carbon fractions, stability and transformation processes. With the in-depth research on ecosystem carbon sequestration mechanisms, the research focus has gradually moved from single ecosystem carbon sequestration to comprehensive research at multi-levels and multi-scales. Research not only focuses on the carbon sequestration potential at the global scale but also has been gradually refined to the exploration of carbon sequestration mechanisms at the regional, national and even micro-ecological unit scales. In general, the research trends of carbon sequestration services present interdisciplinary and cross-field comprehensive characteristics, emphasizing the interactions among factors such as ecosystems, climate change, land use and economic incentives. In the future, with the advancement of technology and the promotion of policies, carbon sequestration services will become an important means to address climate change and achieve sustainable development.

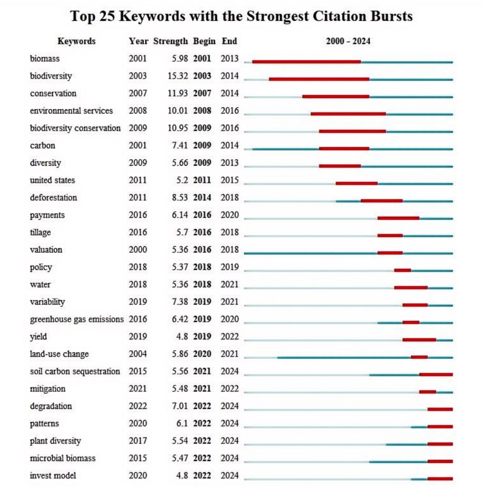


Figure 5. Evolution of top 25keywords during 2000-2024

2.2.4 Division of Research Stages

As indicated by the publication distribution map, research on carbon sequestration functions commenced in 1998 and reached its peak in 2024, and the research period can be roughly divided into three stages. The first stage was from 1998 to 2010, during which research on the mechanisms of ecosystem carbon sequestration was limited, with the total number of publications no more than 100; this stage is referred to as the Germination Stage. The second stage spanned 2011 to 2020, characterized by a fluctuating growth trend in the number of publications, and this stage is defined as the Development Stage. The third stage covers 2021 to 2024, in which the annual number of publications has exceeded 200 with a rapid development trend, and this stage is named the Prosperity Stage. From the perspective of the overall development trend, the publication output on this topic will continue to rise in the future (Fig. 6). In the Germination Stage, relevant research was scarce, with fewer than 100 publications published. This stage focused primarily on the quantitative assessment of ecosystem carbon sequestration functions and their correlations with climate change . In the Development Stage, the volume of research increased substantially, with research becoming more in-depth and diversified. Scholars began to investigate the various relationships between ecosystem services and carbon sequestration functions , and research methods were continuously improved and innovated. Meanwhile, against the backdrop of threats to ecosystems and human livelihoods, the research focus shifted to ecosystem restoration, carbon sink enhancement technologies (e.g., afforestation, land use planning) and their impacts on carbon sequestration . In the Prosperity Stage, with the deepened understanding of ecosystem multifunctionality, research has paid greater attention to the ecological benefits of ecosystem carbon sequestration and their relationships with human well-being (Table. 1).

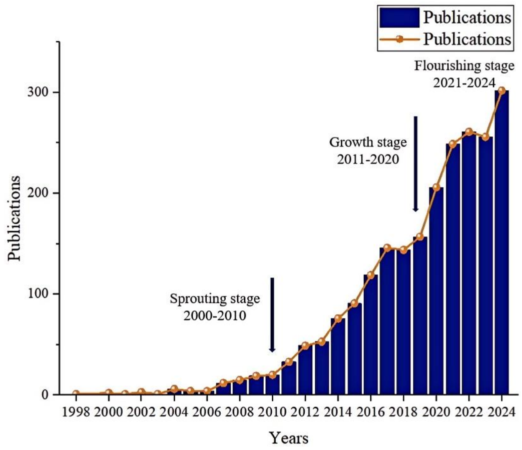


Figure 6. Distribution of Publication Years of Publications

Table. 1 Study Phases

Research Phases	Development Background	Research Content	Key Characteristics
Sprouting Stage 1998-2010	Kyoto Protocol: Adopted in 1997, it promoted global attention to greenhouse gas emission reduction efforts, including ecosystem carbon sequestration, in the subsequent years	The relationships between ecosystem carbon sequestration functions and global warming, land-use change, ecosystem degradation, etc.	Focus on the research of ecosystem carbon sequestration mechanisms
Growth Stage 2011-2020	Against the backdrop of recognizing threats to ecosystem carbon sequestration capacity, research focus shifted to ecosystem restoration, carbon sink enhancement technologies and	Research on the relationship between ecological restoration technologies and carbon sequestration capacity, as well as prediction of changes in carbon sequestration	Centered on ecological restoration and the improvement of ecosystem carbon sequestration capacity

	their impacts on carbon sequestration. Meanwhile, the adoption of the Paris Agreement further promoted global attention to this field	functions	
Flourishing Stage 2021-2024	After 2020, countries around the world have issued relevant acts on climate change and ecological restoration, increased financial support, and spurred the vigorous development of research on ecosystem carbon sequestration mechanisms	Comprehensive evaluation of ecosystem carbon sequestration and multiple goals including ecological security and socio-economic benefits	Involves complex interdisciplinary cooperation including ecology, climatology, economics, etc., promoting the comprehensive quantification of ecosystem services and policy formulation

3. Results

3.1 Vegetation Carbon Sequestration Mechanisms

3.1.1 Forest Carbon Sequestration Mechanisms

As one of the most active carbon pools in nature, terrestrial ecosystems play a vital role in the global gas cycle through the processes of carbon dioxide fixation and oxygen release. Meanwhile, they provide irreplaceable ecosystem services for humans and maintain the stability of the natural world. In terms of terrestrial ecosystems, forest carbon storage is nearly twice that of other terrestrial vegetation ecosystems, making the forest carbon sequestration function irreplaceable for maintaining ecological stability. At present, the calculation methods for forest carbon storage are mainly divided into two categories. One is the traditional method based on field survey data, which mainly includes the biomass continuous function method, biomass expansion factor method and volume expansion method, and is applicable to the calculation of forest carbon storage at the plot scale. With the improvement of forestry information systems and the development of remote sensing technology, the model simulation method and remote sensing estimation method based on the forest biomass method are suitable for large-scale applications. The model simulation methods for forest carbon storage include three types: first, empirical models such as the MIAMI model; second, process-based models such as the CENTURY model and BIOME-BGC model; third, empirical process-based models such as the TRIP-LEX model and CASTANEA model. The remote sensing estimation method is based on satellite image data, and it estimates forest net primary productivity and carbon storage by establishing the correlation between vegetation indices and biomass. The other method is the carbon flux method, which mainly includes the eddy covariance method and closed chamber method. Based on micrometeorological principles, the eddy covariance method directly measures the net CO_2 exchange between terrestrial ecosystems and the atmosphere to calculate net primary productivity. This method can accurately reflect temporal variations but has high operational requirements and is subject to calculation errors (Baldocchi, 2003; Castellví, Snyder, & Baldocchi, 2008). The closed chamber method is suitable for measuring sources with low emission rates by detecting changes in gas concentrations within a sealed chamber, yet it is not applicable for large-area measurements (Table 2).

Table 2. Calculation Methodology of Forest Carbon Stocks

Application Scope	Method / Model	Principle
Plot Scale	Biomass Continuous Function Method	Improves the accuracy of biomass estimation by establishing a mathematical relationship between biomass and volume.
	Biomass Expansion Factor Method	Calculates the total biomass of a given forest type by multiplying the total stand volume by the ratio of stand biomass to timber volume, i.e., the Biomass Expansion Factor (BEF).
	Volume Expansion Method	Estimates forest biomass based on known forest growing stock volume.
Regional Scale	MIAMI Model	Established using the least

		squares method based on natural ecosystem temperature and precipitation, it links Net Primary Production (NPP) to mean annual temperature (T, °C) and annual precipitation (P, mm).
	CENTURY Model	A process-based biogeochemical cycle model for terrestrial ecosystems, mainly used to simulate long-term dynamics of carbon (C), nitrogen (N), phosphorus (P), and sulfur (S) in different soil-vegetation systems.
	BIOME-BGC Model	Simulates fluxes and storage of energy, water, carbon, and nitrogen in vegetation and soil components of terrestrial ecosystems..
	TRIP-LEX Model	Calculates forest carbon storage by simulating forest growth and carbon dynamics.
	CASTANEA Model	A process-based multilayer model designed to predict carbon balance in even-aged, single-species deciduous forest stands.
	Remote Sensing Estimation Method	Estimates net production of forest ecosystems based on satellite imagery by establishing relationships between vegetation indices and biomass.
Small Scale	Eddy Covariance Method	A micrometeorology-based method that measures fluxes of

		CO_2, heat, and water vapor by observing 3D wind speed, gas concentration, and water vapor fluctuations.
	Chamber Method / Enclosure Method	Calculates surface exchange fluxes of target gases by placing a closed chamber over soil or vegetation and measuring changes in gas concentration over time within the chamber.

Forest carbon sequestration function is influenced by a variety of factors, including natural factors such as stand factors, topographic factors and climatic factors, as well as anthropogenic factors such as forest management and land use. Stand structure is an important component for describing stand characteristics, serving as a key basis for understanding past forest management practices and formulating future forest management measures (Ali, 2019). It is also one of the important factors affecting the carbon sequestration efficiency of forest ecosystems, mainly including indicators such as tree species composition, stand age, diameter at breast height (DBH), tree height and canopy density. Topographic factors include altitude, slope gradient and aspect. These factors affect the distribution and growth of plants by influencing temperature, light, runoff, precipitation intensity, soil properties and other factors, thereby impacting the carbon sequestration function of plants. Climatic factors largely affect the physiological characteristics, geographical distribution, forest growth and development, as well as the forest carbon sequestration function of vegetation. Soil factors such as clay content ratio, soil pH value, soil humus and sand-gravel ratio affect the ability of vegetation roots to absorb nutrients, water and oxygen, thereby influencing biomass and carbon storage (Baraloto, Rabaud, Molto et al., 2011; Bengough, 2003). Anthropogenic disturbances on forest growth and development play a positive role in the forest carbon sequestration function to a certain extent. Reasonable artificial management activities such as regular pruning, appropriate logging and periodic monitoring ensure the growth of forest vegetation and consolidate the carbon sequestration capacity of forests. However, under the condition of excessive anthropogenic disturbances, forest biodiversity gradually decreases. Therefore, reasonable anthropogenic disturbance activities are an effective approach to enhance the forest carbon sequestration function.

3.1.2 Grassland Carbon Sequestration Mechanisms

Grassland ecosystems account for approximately 45% of the global land area (excluding Greenland and Antarctica) and store 35% of the terrestrial carbon storage, among which 90% of the grassland carbon storage is contained in grassland soils. The grassland carbon sequestration mechanism is interactively influenced by numerous natural factors such as climate and human activities, as well as anthropogenic factors. Natural factors mainly include air temperature, precipitation, CO_2 concentration and nitrogen deposition, which affect the grassland carbon sequestration capacity by regulating plant growth and the decomposition rate of soil organic matter. Moderate warming over a short period can increase grassland carbon storage by affecting the rates of vegetation photosynthesis, growth and soil respiration in some regions; however, long-term warming may promote soil respiration and accelerate organic matter decomposition, thereby offsetting the accumulation of net primary productivity (NPP) (Cao & Woodward, 1998; Weih & Karlsson, 2001)[19-20]. Precipitation affects soil microbial activity and soil respiration by altering soil moisture content, inorganic nitrogen content, soil temperature and humidity conditions, which in turn influences grassland growth and the decomposition of grassland soil carbon. Under conditions of elevated CO_2 concentration, grassland ecosystems exhibit increased vegetation root biomass, thereby enhancing grassland carbon storage (Jones & Donnelly, 2004). Grassland vegetation is generally limited by nitrogen; nitrogen deposition can alleviate nitrogen limitation in grassland ecosystems, improve the net primary productivity of grassland ecosystems, and thus enhance grassland carbon sequestration capacity (LeBauer & Treseder, 2008). Anthropogenic factors affecting grassland carbon sequestration capacity mainly include grazing, enclosure and grazing prohibition, seeding and fertilization. Moderate grazing can increase soil organic carbon content because animals move during foraging, which increases grassland vegetation diversity and coverage while promoting litter input into the soil. However, overgrazing reduces vegetation coverage and decreases soil organic matter input, thereby reducing carbon sequestration capacity . Enclosure and grazing prohibition can reduce anthropogenic disturbances and livestock trampling, facilitating vegetation restoration and soil organic matter accumulation, thus increasing carbon sequestration capacity. Reasonable fertilization can promote plant growth and enhance the ability of photosynthesis to fix CO_2, but excessive fertilization may accelerate the decomposition rate of soil organic matter and reduce carbon sequestration capacity.

3.2 Soil Carbon Sequestration Mechanisms

Soils can store large amounts of organic carbon, which mainly exists in the form of soil organic matter and constitutes one of the largest carbon pools in terrestrial ecosystems. The storage of soil organic carbon is approximately twice that of atmospheric carbon and three times that of vegetation carbon, with organic carbon accounting for more than 50% of the total carbon content. Minor changes in soil organic carbon can significantly affect atmospheric carbon dioxide concentrations (Hu, Liu, Ye et al., 2018; Lal, 2004). Therefore, the soil carbon sequestration function is one of the important approaches to maintaining ecosystem carbon cycles and mitigating temperature changes. Soil organic carbon is mainly composed of soil animal and plant residues, soil humus, and soil microbial biomass carbon. Organic carbon enters the soil in various forms, which can provide nutrients for soil animals and microorganisms, promote the formation of soil biodiversity and humus, enhance soil water-holding capacity and permeability, and improve soil fertility. Since the end of the 20th century, researchers have begun to fractionate soil organic carbon based on its transformation characteristics in soils. There are numerous fractionation methods for soil organic carbon, with significant differences among different methods. According to the differences in principles and properties of various fractionation methods, these methods can be roughly divided into three categories: physical fractionation, chemical fractionation, and biological fractionation (Table. 3). In-depth research on soil organic carbon fractions enhances the understanding of soil carbon cycles and is of great significance for land management and global carbon cycle research.

Table 3. Composition of Soil Organic Carbon

Fractionation		Component	Characteristics
Physical Fractionation	Density Fractionation	Light Fraction Organic Carbon (LFOC)	Newly formed organic matter that is partially decomposed but not yet humified. It is mainly composed of plant and animal residues, microbial debris, mycelia, spores, and other components.
		Heavy Fraction Organic Carbon (HFOC)	Mainly composed of mineral-adsorbed humified organic matter, dominated by humus with a high degree of decomposition and a low C/N ratio.
		Aggregate Fractionation	Macroaggregates (>250 μm) and Microaggregates (<250 μm), Macroaggregates have a fast turnover rate, whereas microaggregates favor long-term carbon

			preservation.
	Particle Size Fractionation	Mineral-Associated Organic Carbon (MAOC)	Chemically bonded or physically protected by clay minerals and Fe/Al oxides (<53 μm), mainly consisting of fragments of cellulose, hemicellulose, and lignin.
		Particulate Organic Carbon (POC)	Incompletely decomposed plant residue fragments (>53 μm) distributed loosely in soil, mainly comprising complexes of humic acids, microbial metabolites, and mineral surfaces.
Chemical Fractionation	Substance Composition Fractionation	Humin	Fulvic acid and humic acid are the main components of humus, collectively referred to as humic acids. Humin binds most tightly to soil minerals, mainly existing as organo-mineral complexes and belonging to recalcitrant humus. These fractions are insensitive to climate change, vegetation type, and agricultural practices, and their application has
		Fulvic Acid (FA)	
		Humic Acid (HA)	

			gradually declined since the 1980s.
	Chemical Solvent Fractionation	Readily Oxidizable Carbon (ROC)	Easily decomposed, oxidized, and mineralized in soil with a short turnover time and involvement in extensive carbon cycling.
		Dissolved Organic Carbon (DOC)	A heterogeneous mixture of organic molecules that can pass through a 0.45 μm filter membrane, mainly including proteins, amino acids, macromolecular humus, and carbohydrates.
		Acid Hydrolyzable Carbon	Organic carbon fractionated via hydrolysis, usually acid hydrolysis (HCl or H_2SO_4). Hydrolyzed organic carbon can be divided into labile and recalcitrant organic carbon.
Biological Fractionation		Microbial Biomass Carbon (MBC)	Refers to bacteria, fungi, algae, and other microbial organisms (5–10 μm) in soil, representing the most active fraction of soil organic carbon.
		Potential Mineralizable	The fraction of soil

	Carbon (PMC)	organic carbon that can be decomposed by microorganisms and converted into CO_2 or CH_4 under given environmental conditions (e.g., temperature, moisture, microbial activity).

The stability of soil carbon pools exerts a significant impact on global climate change and soil quality. Factors such as air temperature, precipitation and vegetation types affect carbon input into the soil, thereby influencing the stability of soil carbon pools. Vegetation changes caused by warming and precipitation variations alter the quality and structure of plant-derived carbon in the soil, which in turn affects the stability of carbon pools (Zhang, Feng, Wang et al., 2023). Different vegetation types determine different types of litter, and litter type is the main factor affecting soil organic carbon content. Various litters indirectly affect the turnover rate of soil organic carbon by regulating the types and community structures of microorganisms. The stronger the litter decomposition capacity, the higher the soil carbon sequestration rate. Soil aggregates and microorganisms are also key factors influencing the stability of soil carbon pools. Soil aggregates adsorb organic carbon, isolate it from microorganisms and enzymes, and reduce the mineralization of organic carbon. Meanwhile, the encapsulation effect of aggregates reduces oxygen input, inhibits the activity of aerobic microorganisms, and enhances the stability of soil organic carbon (McNally et al., 2017; Tang, 2010). Soil microbial activity is the main driving force for the formation, transformation and stabilization of soil organic carbon. Through their metabolic activities, soil microorganisms synthesize relatively stable organic carbon from exogenous carbon and store it in the soil, while promoting the decomposition of organic carbon and releasing CO2 into the atmosphere. These processes are of great significance for maintaining soil organic carbon storage and atmospheric stability (Kleber et al., 2011). Additionally, microorganisms themselves serve as “carbon pools” in the soil: they absorb small-molecule organic matter, form microbial biomass (i.e., microbial biomass carbon) through assimilation, and then accumulate microbial residue carbon through processes such as metabolism and death. From the perspective of chemical properties, soil organic carbon is divided into labile organic carbon and recalcitrant organic carbon. Recalcitrant organic carbon is relatively stable and insensitive to environmental changes (Kleber et al., 2011). In contrast, labile organic carbon is prone to oxidative decomposition and mineralization, with a short carbon turnover period (Six et al., 2002).

4. Discussion

4.1 Vegetation Carbon Sequestration Mechanisms

The potential for enhancing vegetation carbon sequestration capacity is of great significance for assessing regional carbon sequestration capacity. It can evaluate the saturation level of regional carbon storage and serves as a key indicator for regional planning. However, most current studies focus on the current level of vegetation carbon sequestration capacity, while research on the potential for improving existing vegetation carbon sequestration capacity is relatively scarce. Assessing vegetation carbon sequestration potential is crucial for guiding the sustainable development of vegetation and formulating management strategies. This assessment can provide a scientific basis for the rational development of vegetation resources, conservation management, and the optimization and adjustment of ecosystem structures. Additionally, it can offer solid data support for formulating national policies and measures to reduce greenhouse gas emissions and increase carbon sinks. Through in-depth understanding of forest carbon sequestration capacity, forest management activities can be more effectively planned and implemented, ensuring the sustainable utilization of vegetation resources while making positive contributions to addressing climate change. Currently, the main models used to assess vegetation carbon sequestration potential include growth models, remote sensing models, and prediction models. Each type of model has significantly different data sources, leading to doubts about the reliability and accuracy of the model structures. In the future, different field survey data should be organically integrated, and the impacts of different regions, tree species, and climates should be considered in the model construction process. Based on field survey data, model errors can be reduced, providing an important reference for formulating local forest management measures.

Karst regions still exhibit strong carbon sequestration potential when facing extreme conditions such as rocky desertification, mainly benefiting from the region's unique hydrothermal conditions, which are highly conducive to vegetation growth. Under positive vegetation restoration measures, the ecosystems in Karst regions have been improved, which not only promotes the increase in biodiversity but also significantly enhances regional carbon sequestration capacity. However, due to the special geological structure of this region, vegetation carbon sinks present significant geological constraints. For example, there are significant differences in the distribution of soil organic carbon (SOC) among different landforms (slopes, depressions, sinkholes) within Karst small watersheds (Li, 2022). Therefore, based on field survey data, remote sensing monitoring data should be corrected to reduce the reduction in the scientificity of research results caused by spatial heterogeneity. Meanwhile, process model parameters should be revised based on relevant datasets of rocky desertification control areas, and an evaluation system suitable for the carbon sequestration benefits of rocky desertification control areas should be constructed. This provides a theoretical paradigm for carbon sink enhancement in fragile ecosystems and further supplements the key carbon sink parameter module of rocky desertification control areas for global carbon budget accounting.

4.2 Soil Carbon Sequestration Mechanisms

The stability of soil organic carbon directly affects the stability of the global atmosphere. Therefore, its stabilization mechanism is a research hotspot nowadays, but there is no unified understanding so far. Researchers such as Lützow et al.(2006) have summarized the stabilization process of soil organic carbon into three main mechanisms: selective preservation, spatial isolation, and the interaction between organic carbon and minerals or metal ions. In contrast, Mayer (2004) proposed a more simplified classification, reducing the stabilization mechanisms to two core elements: resistance to decomposition and biological inaccessibility. In recent years, numerous studies have begun to emphasize the importance of mineral-associated organic carbon in enhancing soil organic carbon stability, responding to climate change, achieving soil carbon saturation, and constructing ecosystem models. In view of this, researchers such as Angst et al. (2021) proposed an updated classification in their latest studies, redefining the stabilization mechanisms of organic carbon into three key components: biochemical stability, formation of mineral-associated organic carbon, and formation of soil aggregates . It can be seen that the stability of soil organic carbon is the result of the combined action of multi-dimensional mechanisms. In the future, strengthening the application of multi-omics technologies (e.g., metabolomics, isotope tracing) and high-resolution imaging (e.g., synchrotron radiation microscopy) will deepen the understanding of the mineral-microbe-plant interaction network, providing theoretical support for the assessment of soil carbon sink functions.

Soils in Karst regions are an integral part of the core ecosystems in these areas and play a crucial role in vegetation restoration and the production and living activities of local residents. Due to the complex terrain, thin and infertile soil layers in Karst regions, the accumulation of soil organic carbon is easily affected by natural factors such as soil and water loss and rock exposure. These factors not only lead to the loss of soil carbon but also affect soil fertility and vegetation growth, thereby restricting the restoration capacity of ecosystems. Therefore, it is particularly important to study the fixation pathways of soil organic carbon in Karst regions. From a micro-scale perspective, technologies such as isotope labeling and X-ray are used to characterize the chemical bonding types of mineral-organic matter complexes; from a macro-scale perspective, combining UAV hyperspectral technology with ground sensor networks to reveal the regulatory laws of soil carbon spatial heterogeneity. Studying soil carbon fixation pathways not only helps improve soil carbon sequestration capacity but also contributes to enhancing soil quality and ecological functions. This is of great significance for improving the ecological restoration capacity of Karst regions, increasing soil retention, reducing soil and water loss, and providing support for achieving the "carbon neutrality" goal.

Conclusion

Ecosystem carbon sequestration is a core measure to mitigate global warming and a key support for ecological restoration in karst desertification areas, a typical ecologically fragile region. Based on bibliometric analysis of 2247 global publications up to 2024, this study clarifies that the research has gone through germination, growth and prosperity stages, with ecosystem services, biodiversity and climate change as core hotspots. The US, China and other countries lead the research, and universities and research institutions are the main research forces. This study systematically elaborates the carbon sequestration mechanisms and influencing factors of forest, grassland and soil ecosystems, and identifies the key constraints of carbon sequestration in karst desertification areas: the fragile geological background leads to high sensitivity of vegetation carbon sequestration, soil organic carbon accumulation is restricted by soil erosion and rock exposure, and the understanding of soil organic carbon stability is inconsistent. Targeted strategies are proposed for karst desertification governance, including revising remote sensing data with field investigations, constructing regional carbon sequestration assessment systems, and exploring multi-scale soil carbon fixation pathways. Under the global carbon neutrality goal, future research on ecological fragile areas should focus on deepening vegetation carbon sequestration potential exploration, revealing soil organic carbon stability mechanisms via advanced technologies, and building a comprehensive governance system integrating ecology, technology and policy. The research results provide scientific support for carbon sink enhancement and ecological restoration in ecologically fragile areas, and lay a theoretical foundation for integrating regional carbon sequestration governance into the global carbon budget, which is of great significance for global climate change response and ecological security construction.

References

Ali, A. (2019). Forest stand structure and functioning: Current knowledge and future challenges. *Ecological Indicators*, *98*, 665-677.

Angst, G., Mueller, K. E., Nierop, K. G. J. et al. (2021). Plant-or microbial-derived? A review on the molecular composition of stabilized soil organic matter. *Soil Biology and Biochemistry*, *156*, 108189.

Bai, Y., & Cotrufo, M. F. (2022). Grassland soil carbon sequestration: Current understanding, challenges, and solutions. *Science*, 377(6606), 603-608.

Baldocchi, D. D. (2003). Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future. *Global change biology*, *9*(4), 479-492.

Baraloto, C., Rabaud, S., Molto, Q. et al. (2011). Disentangling stand and environmental correlates of aboveground biomass in Amazonian forests. *Global Change Biology*, *17*(8), 2677-2688.

Bengough, A. G. (2003). Root growth and function in relation to soil structure, composition, and strength[M]//Root ecology (pp. 151-171). Berlin, Heidelberg: Springer Berlin Heidelberg.

Bonan, G. B. (2008). Forests and climate change: Forcings, feedbacks, and the climate benefits of forests. *science*, *320*(5882), 1444-1449.

Cao, M., & Woodward, F. I. (1998). Net primary and ecosystem production and carbon stocks of terrestrial ecosystems and their responses to climate change. *Global Change Biology*, *4*(2), 185-198.

Castellví, F., Snyder, R. L., & Baldocchi, D. D. (2008). Surface energy-balance closure over rangeland grass using the eddy covariance method and surface renewal analysis. *agricultural and forest meteorology*, *148*(6-7), 1147-1160.

Deng, L., Liu, G., & Shangguan, Z. (2014). Land-use conversion and changing soil carbon stocks in C hina's 'Grain-for-Green'Program: A synthesis. *Global change biology*, *20*(11), 3544-3556.

He N, Wen, D., Zhu, J. et al. (2017). Vegetation carbon sequestration in Chinese forests from 2010 to 2050. *Global Change Biology*, *23*(4), 1575-1584.

Hu, P. L., Liu, S. J., Ye, Y. Y. et al. (2018). Effects of environmental factors on soil organic carbon under natural or managed vegetation restoration. *Land Degradation & Development*, *29*(3), 387-397.

Huang, L., Zhou, M., Lv, J. et al. (2020). Trends in global research in forest carbon sequestration: A bibliometric analysis. *Journal of Cleaner Production*, *252*, 119908.

Jing, J., Li, R., Xiong, L et al. (2025). Binary response of runoff generation and erosion processes to karst vegetation-soil-rock structure and its hydrodynamic mechanisms. *Journal of Hydrology*, *647*, 132319.

Jones, M. B., & Donnelly, A. (2004). Carbon sequestration in temperate grassland ecosystems and the influence of management, climate and elevated CO2. *New Phytologist*, *164*(3), 423-439.

Kleber, M., Nico, P. S, Plante, A. et al. (2011). Old and stable soil organic matter is not necessarily chemically recalcitrant: Implications for modeling concepts and temperature sensitivity. *Global change biology*, *17*(2), 1097-1107.

Lal, R. (2004). Carbon emission from farm operations. *Environment international*, *30*(7), 981-990.

LeBauer, D. S., & Treseder, K. K. (2008). Nitrogen limitation of net primary productivity in terrestrial ecosystems is globally distributed. *Ecology*, *89*(2), 371-379.

Li, H. P., Li, D., & Li, H. (2022). Evaluation of potential carbon sink benefits of Grain for Green Project in Guizhou Province. *Acta Ecologica Sinica*, *42*(23), 9499.

Lian, Y., You G J Y, Lin K, et al. Characteristics of climate change in southwest China karst region and their potential environmental impacts[J]. Environmental Earth Sciences, 2015, 74(2): 937-944.

Liu, S., Zhang, W., Wang, K. et al. (2015). Factors controlling accumulation of soil organic carbon along vegetation succession in a typical karst region in Southwest China. *Science of the Total Environment*, *521*, 52-58.

Lützow, M., Kögel-Knabner, I., Ekschmitt, K. et al. (2006). Stabilization of organic matter in temperate soils: Mechanisms and their relevance under different soil conditions–a review. *European journal of soil science*, 57(4), 426-445.

Mayer, L. M. (2004). The inertness of being organic. *Marine Chemistry*, *92*(1-4), 135-140.

McNally, S. R., Beare, M. H., Curtin, D. et al. (2017). Soil carbon sequestration potential of permanent pasture and continuous cropping soils in New Zealand. *Global Change Biology*, *23*(11), 4544-4555.

Pan, Y., Birdsey, R. A., Fang et al. (2011). A large and persistent carbon sink in the world's forests. *science*, *333*(6045), 988-993.

Peng, X., Dai, Q., Ding, G. et al. (2019). The role of soil water retention functions of near-surface fissures with different vegetation types in a rocky desertification area. *Plant and Soil*, *441*(1), 587-599.

Post, W. M., & Kwon, K. C. (2000). Soil carbon sequestration and land-use change: processes and potential. *Global change biology*, *6*(3), 317-327.

Sinsabaugh, R. L., Manzoni, S., Moorhead, D. L. et al. (2013). Carbon use efficiency of microbial communities: Stoichiometry, methodology and modelling. *Ecology letters*, *16*(7), 930-939.

Six, J., Conant, R. T., Paul, E. A. et al. (2002). Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. *Plant and soil*, *241*(2), 155-176.

Tang, X., Liu, S., Liu, J. et al. (2010). Effects of vegetation restoration and slope positions on soil aggregation and soil carbon accumulation on heavily eroded tropical land of Southern China. *Journal of Soils and Sediments*, *10*(3), 505-513.

Tong, X., Wang, K., Yue, Y. et al. (2017). Quantifying the effectiveness of ecological restoration projects on long-term vegetation dynamics in the karst regions of Southwest China. *International Journal of Applied Earth Observation and Geoinformation*, *54*, 105-113.

Weih, M., & Karlsson, P. S. (2001). Growth response of Mountain birch to air and soil temperature: Is increasing leaf-nitrogen content an acclimation to lower air temperature?. *New Phytologist*, *150*(1), 147-155.

Zhang, X. M., Brandt, M., Yue, Y, M. et al. (2022). The carbon sink potential of southern China after two decades of afforestation. *Earth's Future*, *10*(12), e2022EF002674.

Zhang, Y., Feng, T., Wang, L. et al. (2023). Effects of long-term vegetation restoration on soil physicochemical properties mainly achieved by the coupling contributions of biological synusiae to the Loess Plateau. *Ecological Indicators*, *152*, 110353.

Zhao, Y., Liu, Z., & Wu, J. (2020). Grassland ecosystem services: A systematic review of research advances and future directions. *Landscape Ecology*, *35*(4), 793-814.