Ten Major Issues and Countermeasures for Karst Ecological Restoration in Southwest China: Postprint

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Abstract

The karst region of Southwest China constitutes a key and challenging area for the Beautiful China Initiative, encompassing issues such as soil erosion, sloping cropland ratio, water resource pollution, karst drought, ecological restoration, synergistic carbon sequestration, ecological effects of urbanization, rocky desertification control indicators, biodiversity, and sustainability assessment. This article synthesizes knowledge accumulated from ecological restoration practices in karst areas into problems and solutions across ten aspects, including soil erosion, sloping cropland ratio, water resource pollution, karst drought, ecological restoration, synergistic carbon sequestration, ecological effects of urbanization, rocky desertification control indicators, biodiversity, and sustainability assessment. These help explain the challenges encountered in achieving sustainability in karst ecological restoration, while the article also proposes solutions. They constitute a set of core principles that can guide scientists, policymakers, and practitioners in addressing sustainability challenges in karst ecological restoration projects.

Full Text

Ten Problems and Solutions for Restoration of Karst Ecosystem in Southwest China

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Abstract

The karst areas in southwest China represent one of the key yet challenging regions for the "Beautiful China"initiative, encompassing issues such as soil erosion, slope farmland proportion, water resource pollution, karst drought, ecological restoration, synergistic carbon sinks, urbanization ecological effects, rocky desertification control indicators, biodiversity, and sustainability assessment. This article synthesizes knowledge accumulated during ecological restoration practice in karst regions into ten major problems and corresponding solutions across these dimensions. These frameworks help explain the challenges of achieving sustainability in karst ecological restoration and point toward viable solutions, constituting a core set of principles to guide scientists, policymakers, and practitioners in addressing sustainability challenges in karst ecological restoration projects.

Keywords: karst, rocky desertification, rock weathering carbon sink, soil erosion, climate change, ecosystem services, ecological restoration

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Background

The karst region in southwest China is the world's largest continuous karst distribution area with the most complete developmental types, covering 450,000 km^2, of which rocky desertified land exceeds 100,000 km^2, accounting for 22.3% of the karst area [1]. Controlled by the dual surface-subsurface three-dimensional structure, coupled with uneven distribution of water and soil resources and rapid hydrological changes, soil formation rates are slow, water conservation capacity is poor, and ecological recoverability is low in karst areas [2,3]. Meanwhile, extensive rocky desertification and complex geological backgrounds create negative feedback that further restricts local economic development, highlighting the urgency of achieving sustainable economic, social, and natural ecosystem development [4]. Located in the upper reaches of the Yangtze and Pearl River systems, ecological construction in this region determines the ecological security of the middle and lower reaches, making it strategically important for the "Beautiful China" initiative and rural revitalization strategy [5].

After years of effort, vegetation coverage in southwest China karst areas has significantly improved [6]. However, the rocky desertification process involves complex multi-sphere interactions, and the systematic balance among economic development, poverty alleviation, and ecosystem protection remains unresolved. According to President Xi Jinping's important instructions for Guizhou Province—the province with China's largest karst distribution area—emphasizing the need to firmly maintain both development and ecological red lines, karst ecological restoration faces both old problems and new challenges that intertwine, creating a reality where ecological construction outpaces basic research. Without changing traditional ecological governance patterns, this may affect karst ecological construction and even the overall strategic goals of "Beautiful China." Advancing karst ecological restoration requires shifting from single-element, one-sided governance to systematic, comprehensive regulation, with precise control over interactions among the lithosphere, pedosphere, hydrosphere, biosphere, and anthroposphere in the region (Figure 1 [Figure 1: see original paper]), focusing efforts on ten aspects to enhance ecological restoration levels.

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1. Ten Major Problems in Karst Ecological Restoration

1.1 Overlooking the Problem of Excessively High Soil Erosion Standard Moduli Unsuitable for Karst Regions Soil erosion and degradation have been identified as serious geological environmental hazards in karst areas [7,8]. However, current soil erosion risk assessment standards have regional adaptability issues, with standards proposed by local governments and scholars not fully applicable to carbonate rock areas. Currently, China generally uses soil loss tolerance as the discriminant index for soil erosion hazard assessment. According to the existing SL 190—2007 *Standard for Classification and Gradation of Soil Erosion*, the soil loss tolerance in karst areas is 500 $t \cdot km^{-2} \cdot a^{-1}$, with areas below this threshold considered safe from soil erosion. However, previous research found [9] that soil formation rates in China' s karst areas range from 10-134.93 $t \cdot km^{-2} \cdot a^{-1}$, with an average of 18.59 $t \cdot km^{-2} \cdot a^{-1}$—only 3.7% of the 500 $t \cdot km^{-2} \cdot a^{-1}$ standard. According to SL 461—2009 *Technical Standard for Comprehensive Control of Soil and Water Loss in Karst Areas*, the soil loss tolerance in karst areas is 50 $t \cdot km^{-2} \cdot a^{-1}$, which is still nearly 2.5 times higher than the current research average soil formation rate. These standards apply to interbedded carbonate and clastic rock areas but not to pure carbonate rock areas or carbonate rock intercalated with clastic rock areas (forming 4–17 mm of soil per 1,000 years). In continuous carbonate rock areas, the rate is only 1/10 of that required in SL 461—2009, while in carbonate rock intercalated with clastic rock areas, it is 50% of the SL 461—2009 requirement (Table 1). Although previous soil erosion standards have been reduced from 500 $t \cdot km^{-2} \cdot a^{-1}$ to 50 $t \cdot km^{-2} \cdot a^{-1}$, according to current soil formation rate research results [9], the reduced standard remains far greater than soil formation rates in karst areas. This means previously established soil erosion standard moduli are excessively high, leading to long-term neglect of soil erosion risks in karst areas, which may contribute to soil degradation and rocky desertification development [5].

1.2 Overlooking the Problem of Excessively High Slope Farmland Proportion Leading to Heavy Tasks for Cultivated Land Retention and Basic Farmland Protection Karst mountainous areas have fragmented land plots and sharp human-land conflicts, causing agricultural expansion onto slopes and resulting in slope-dominant farmland (54.38%) [10]. Taking Guizhou as an example, the province' s mountainous and hilly areas account for 92.5%, making it the only province without plain support [11]. The Third National Land Survey results show that Guizhou Province has 3.4726 million hectares of cultivated land, with 2.9537 million hectares of slope farmland accounting for 85.06% of the province' s total cultivated land area, of which 19.8% has slopes greater than 25° with an area of 584,700 hectares, representing 14% of the national equivalent slope farmland (4.2 million hectares). Moreover, Guizhou' s land reclamation rate is 25.73%, far higher than Jiangxi (18.5%) and Fujian (10.8%)—both ecological civilization pilot zones—and approximately double the national average. In terms of cultivated land retention, Guizhou's rate is 23.81%, higher than neighboring provinces such as Sichuan (12.95%), Yunnan (14.83%), Guangxi (18.43%), and Hunan (18.74%). This demonstrates that cultivated land retention and basic farmland protection tasks are disproportionately heavy in China's karst areas, inconsistent with actual conditions. With relatively weak production conditions, mismatched agricultural land resources in China' s karst areas generate threats such as soil erosion and mountain disasters [12,13].

1.3 Ignoring the Problem of Frequent Surface Water-Groundwater Conversion Making Water Pollution Control Difficult to Achieve Sustained Effectiveness Karst region groundwater resources total approximately 203.4 billion m^3, accounting for 23% of China' s total groundwater resources [14]. The groundwater environment is extremely sensitive to external disturbances and easily affected by human activities. Due to intense surface water-groundwater interaction in karst areas—far more frequent than in non-karst areas—pollutants easily migrate and diffuse [15]. The *2014 China Environmental Status Bulletin* shows that the proportion of severely polluted groundwater increased from 37% in 2000 to 60% in 2010, showing a growth trend, with 1,012 groundwater pollution points in southwest karst areas alone [16]. Meanwhile, artificial deep "lakes" in karst areas differ from natural shallow lakes in water stratification structure and pollution patterns, with poor self-purification capacity for external pollutants and leakage problems [17]. Therefore, water pollution control is crucial in karst ecological restoration. However, current efforts focus more on preventing external pollution sources while ignoring the problem of frequent surface water-groundwater conversion in karst areas, which leads to unsustained regional water pollution control effectiveness.

1.4 Ignoring Soil Drying and Its Impact on Karst Ecosystems Soil water accounts for only 1/100,000 of total hydrosphere water and 0.05% of total freshwater reserves, making it easily overlooked, yet it affects the evolution of all life in karst areas. In recent years, karst engineering water shortage problems have occurred frequently, and the drought stress caused by engineering water shortage will restrict the restoration and stable development of karst ecological environments, but this serious problem lacks sufficient attention. Vegetation cooling effects can serve as an important standard for measuring ecological balance, but the buffering capacity of greening in karst areas is limited, particularly as CO_2 fertilization effects on vegetation photosynthesis are constrained by nitrogen, phosphorus, and water availability [18]. Research based on station measurements and reanalysis data found that soil drying areas in karst regions exceed 64%; the drying rates in southern and northern karst areas are 0.327$×10^{-3}$ $m^3 \cdot m^{-3} \cdot a^{-1}$ and 0.157$×10^{-3}$ $m^3 \cdot m^{-3} \cdot a^{-1}$ respectively, with the fastest drying areas in southern karst being 1.26 times that of the entire karst region [19]. Therefore, low soil water supply and high atmospheric saturation vapor pressure deficit are considered two main driving factors constraining vegetation greening in China' s karst region [20], threatening ecological balance. Engineering water shortage in karst areas restricts vegetation growth, leading to unsustainable cooling effects, energy imbalance, and ultimately extreme climates that further damage already fragile karst ecosystems and threaten human survival.

1.5 Ignoring That Karst Ecological Restoration Is Controlled by Carbonate Rock Background Properties and Climate Change Impacts Karst areas have complex geological backgrounds with huge internal differences, and different regions have significantly different research foundations, key issues, and ecological restoration measures. For example, in tropical and summer-humid temperate karst areas, calcium-rich substrates are more conducive to groundwater storage, making their ecosystem gross primary productivity (GPP) about 32% and 13% higher than silicon-rich areas; conversely, in arid grasslands and winter-dry temperate karst areas, silicon-rich areas' precipitation supply patterns better maintain vegetation water requirements, making their GPP 12% and 7% higher than calcium-rich areas [21]. This demonstrates that vegetation growth is controlled by different lithologies. Additionally, karst trough valley areas are prone to high-altitude water resource leakage and frequent drought [22], while relatively low-lying depressions and basins are water accumulation areas causing waterlogging [23], both inhibiting vegetation growth. Finally, based on net primary productivity and using partial derivative methods, eight different scenarios were designed to analyze climate change and human activity impacts on vegetation productivity changes. Results showed that in southern karst areas with intensive human activities, climate change contributed negatively up to 70.72% due to decreased solar radiation, offsetting 59.07% of the positive effects of ecological engineering and causing greater net primary productivity (NPP) losses [24]. Ecological restoration ignores karst background properties and climate change impacts, fails to consider vegetation growth characteristics, and one-sidedly pursues forest and grassland area expansion, affecting restoration effectiveness and damaging ecosystems, threatening human survival and development.

1.6 Ignoring the Ecological Compensation Problem of Rock Weathering Carbon Sink and Soil Formation Process Supporting Vegetation Photosynthetic Carbon Sink A core issue of karst ecosystem degradation is ignoring the ecological compensation mechanism by which rock weathering carbon sinks and soil formation processes support vegetation photosynthetic carbon sinks. Karst rocks absorb atmospheric CO_2 to form weathering carbon sinks and soil formation, which in turn serve as essential nutrients and the main water carrier for vegetation growth, supporting vegetation photosynthetic carbon sink potential [25]. However, current accounting standards cannot accurately quantify rock weathering carbon sinks and vegetation photosynthetic carbon sink potential, resulting in a lack of ecological compensation mechanisms. China' s karst rock weathering carbon sink (CO_2) totals 57.7937–64.5157 Mt [26,27], while vegetation photosynthetic carbon sink (CO_2) in China's terrestrial ecosystems is 0.70–0.95 $Mt \cdot a^{-1}$ [28]. Rock weathering carbon sinks and soil formation processes supporting vegetation photosynthetic carbon sinks play an irreplaceable role in achieving carbon neutrality for China and globally. However, ignoring the ecological compensation problem means the huge carbon sink capacity of karst areas has not received deserved compensation, making various unreasonable land resource development and utilization the greatest threat to karst ecosystem degradation.

1.7 Ignoring That Urbanization Can Accelerate Ecological Environment Improvement Urbanization implies population transfer from rural to urban areas, urban expansion, land use change, and vegetation destruction. However, research shows vegetation growth is generally enhanced in urban environments, increasing 1.8-fold, with vegetation enhancement index approaching 0.22 in highly urbanized areas [29]. Currently, research on urbanization's ecological environment impacts in karst areas lacks quantification. Moreover, as urbanization accelerates, rural population reduction and farmland abandonment have promoted vegetation restoration, becoming key factors affecting human-land conflicts in karst areas and greatly influencing ecological restoration. Chang et al. [30] found that rural population in southern China decreased by 4.8 million, with aboveground biomass (C) highest in rural migration areas (0.015 $Mt \cdot km^{-2} \cdot a^{-1}$). In karst ecological restoration, urbanization and rural population reduction decrease population pressure, effectively promoting ecological improvement in karst areas, affecting ecosystem structure, and generating important ecological carbon sinks. However, existing research fails to recognize the positive role of urbanization and rural population reduction in achieving carbon neutrality goals, hindering ecological governance and rural revitalization and restricting regional economic development, making it difficult for karst ecological restoration to achieve sustained effectiveness.

1.8 Ignoring the One-Sidedness and Short-Sightedness of Using Vegetation Coverage as an Indicator for Rocky Desertification Control Effectiveness Assessment Ecological restoration projects such as rocky desertification control have significantly promoted vegetation coverage improvement, making important contributions to rocky desertification mitigation and control [31,32]. However, the response of ecosystem services to vegetation coverage improvement remains unclear. Research shows that while vegetation coverage increases in karst areas, vegetation communities are degrading, seriously threatening ecosystem sustainability [33]. Previous use of vegetation coverage as a key indicator for evaluating ecological restoration effectiveness [34] ignores karst characteristics such as slow soil formation rates and unique surface-subsurface hydrological structures that adversely affect vegetation restoration. This oversight causes ecosystem service function decline, deteriorates supply-demand relationships, reduces ecosystem stability, and causes biodiversity loss [35]. Therefore, how to synergize ecosystem service improvement while promoting vegetation coverage enhancement and maintain ecosystem health has become a key issue in karst ecological restoration. Without proper attention, this will lead to decreased restoration effectiveness, lagging ecosystem service function improvement, imbalanced supply-demand relationships, and unsustainable ecological services.

1.9 Ignoring the Mismatch Between Biodiversity Hotspot Areas and Ecological Protection Zones and the Incomplete Protection System China’ s southwest karst mountainous area is one of the world’ s 36 biodiversity hotspots, containing 50% of the nation’ s birds and mammals and over 30% of higher plants, making it one of Earth’ s largest biodiversity repositories [36]. Currently, about 10.8% of China’ s threatened plant species and 21.4% of threatened vertebrate species (932 species) exist, with amphibians comprising the highest proportion (43.1%) [37]. These data indicate Chinese species face serious threats, meaning large numbers of species in China’ s karst mountainous areas also face corresponding challenges. Establishing protected areas is an important biodiversity conservation approach [38], yet China’ s nature reserves cover only 15.1% of land area, with threatened mammal habitats comprising 17.9%, birds 6.4%, plants 13.1%, amphibians 10.0%, and reptiles 8.5% of this area [39]. This shows current nature reserve planning only considers single relationships between species and environment, which is one-sided and will lead to ecological health problems such as water resource crises and intensified natural disasters [40].

1.10 Ignoring the Economic Contribution of Ecosystem Service Enhancement to Regional Sustainable Development How to maintain both development and ecological red lines has become a research focus, but current research is scarce, leading to misjudgment in natural asset assessment and ecological compensation. Hu et al. [41] estimated China' s karst ecosystem service value (ESV) using land use data, equivalent value coefficients, and value transfer methods, finding that China' s karst ESV is generally in a beneficial state, with losses in only a few areas. Due to limitations in traditional national accounting systems, both international green economic accounting systems and domestic green GDP accounting systems only reduce resource and environmental costs of economic system growth without considering ecosystem service benefits, potentially causing excessive economic growth pursuit that destroys ecological environments [42]. Wu et al. [43] found that ecosystem service value contributes 20.54% to advancing and stabilizing human well-being according to modified Genuine Progress Indicator (GPI), but environmental and resource consumption significantly reduces GPI. Therefore, ignoring ecosystem services' important role in ecological construction and economic development, separating ecological restoration from ecological industry development, industrial structure adjustment, and livelihood improvement, may cause irreversible loss of ESV as an advantageous resource base due to unreasonable human activities, thereby restricting economic and social development and even causing misjudgment of national economic and social development progress.

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2. Countermeasures and Suggestions for Promoting Karst Ecological Restoration

Addressing the above problems and challenges requires shifting karst ecological restoration from single-element, one-sided governance to systematic, comprehensive regulation. We propose feasible countermeasures and suggestions across ten aspects—soil erosion, slope farmland proportion, water resource pollution, karst drought, ecological restoration, synergistic carbon sinks, urbanization ecological effects, rocky desertification control indicators, biodiversity, and sustainability assessment—to continuously promote ecological security and construction in karst areas and provide important theoretical support for "Beautiful China" and rural revitalization strategies.

2.1 Promptly Revise Karst Soil Erosion Risk Assessment Standards Based on Carbonate Rock Weathering Soil Formation Rates The evaluation basis that low soil erosion amounts mean low soil erosion risk has led to increasingly serious soil erosion risks in karst areas, urgently requiring the development of soil erosion classification and gradation standards and risk assessment methods suitable for the region. Theoretically, soil formation rate is the upper limit of soil loss tolerance in karst areas, and different lithology background soil formation rates can serve as the minimum threshold for soil erosion risk [9] (Table 2). If theoretical erosion amount exceeds soil formation rate, the area is dangerous; conversely, it is safe; if equal, it is in a critical state.

2.2 Orderly Promote Ecological Restoration Projects and Appropriately Reduce Slope Farmland Proportion in Karst Areas First, under the premise of ensuring no reduction in China' s basic farmland protection area, orderly reduce the proportion of slope farmland above 25° through overall coordination and adjustment. Second, organically combine farmland structure adjustment with ecological migration and land consolidation, increasing support to consolidate China' s ecological restoration achievements [44]. Finally, improve the guarantee system through policy formulation, strengthened publicity and education, scientific planning, and enhanced supervision and management [45].

2.3 Establish Suitable Surface-Subsurface Water Pollution Coordinated Prevention and Control Technology Systems for Karst Areas A major difficulty in karst groundwater resource protection lies in unclear understanding of pollutant multi-scale migration and transformation mechanisms in karst surface-subsurface dual structures. Therefore, urgent research is needed on karst surface-subsurface water compound pollution mechanisms to establish suitable coordinated prevention and control technology systems [46]. Further optimize karst watershed water quality monitoring and early warning systems, develop anti-seepage technologies for karst artificial lakes, and regularly conduct quantitative leakage prediction and leakage evaluation for karst reservoirs to ensure water source safety.

2.4 Emphasize Monitoring and Early Warning of Unsustainable Cooling Effects Caused by Karst Engineering Water Shortage and Risk Prevention for Ecological Restoration Engineering water shortage will intensify ecological limitations in karst vulnerable areas, where ecological balance is closely related to cooling effects, urgently requiring strengthened drought stress monitoring, early warning, and risk prevention for ecosystem restoration. Construct soil water databases at different temporal and spatial scales to accurately grasp karst soil water dynamics for enhanced risk control of ecosystem restoration. Reveal the impact of surface rock-soil ratios on karst hydrological processes and soil water changes, and predict the sustainability of karst vegetation cooling effects under climate warming and extreme drought events in the context of global warming to further strengthen risk prevention for karst ecological balance.

2.5 Select Vegetation Types and Varieties Adapted to Lithology Background and Climate Change for Ecological Restoration Ecological restoration should follow local conditions. Karst regions have large internal differences, so zoning is significant for guiding spatial layout and restoration methods. We recommend further developing ecological plans based on environmental characteristics for peak-cluster depression, trough valley, plateau, and canyon karst landform types. Karst ecological restoration should consider lithology characteristics and corresponding weathering layer water storage capacity for further zoning [47], thereby selecting vegetation adapted to lithology background and climate change. According to the above zoning, stop implementing some ecological projects, reduce large-scale blind artificial afforestation, while protecting existing natural forest land and cultivated land resources to better provide human well-being, balancing ecological, economic, and social benefits rather than short-term green expansion.

2.6 Establish Technical Method Systems for Accurate Accounting and Capacity Enhancement of Rock Weathering Carbon Sinks and Vegetation Photosynthetic Carbon Sinks Addressing the lack of ecological compensation mechanisms for rock weathering carbon sinks and soil formation processes supporting vegetation photosynthetic carbon sinks urgently requires optimizing and constructing accounting models from large-scale carbon sink information system simulation, improved spatial sampling methods, and precision. Based on clarifying karst carbon sink change response mechanisms, formulate industry standards for carbon sink investigation and effect evaluation. Second, use soil improvement methods to increase soil CO_2 concentration and optimize soil water-fertilizer conditions [48,49], and screen and cultivate high-efficiency carbon-fixing tree species or aquatic photosynthetic plants to accelerate rock weathering rates while improving regional vegetation and herbaceous community carbon sequestration potential. This establishes technical method systems for accurate accounting and capacity enhancement of rock weathering carbon sinks and vegetation photosynthetic carbon sinks, providing digital intelligence support for ecological compensation of rock weathering carbon sinks and soil formation processes supporting vegetation photosynthetic carbon sinks in karst areas.

2.7 Orderly Promote Rural-Urban Migration and Strengthen Ecological Space Restoration and Management Rural population reduction reduces ecosystem pressure and improves rural ecological environments, which is significant for ecological restoration [50]. Therefore, government departments should improve green space network systems, legally manage green spaces, strengthen ecological space restoration and management, increase investment in regional education resources, attract external labor or retain highly educated labor, create more non-agricultural employment opportunities, attract more agricultural labor to cities, and thereby promote vegetation improvement, ecosystem service enhancement, and sustainable ecological environment development in ecologically vulnerable areas.

2.8 Establish New Indicators for Karst Rocky Desertification Control Effectiveness Assessment Successful rocky desertification control should be marked by recovery and improvement of biodiversity, ecological processes, soil quality, water cycles, economy, and society—not just vegetation coverage improvement. Therefore, we cannot one-sidedly pursue forest area expansion nor excessively reduce rocky desertification area. We should base efforts on ecosystem integrity and systematicity, adhere to systematic concepts for integrated "mountains, rivers, forests, farmlands, lakes, grasslands, and deserts" management, comprehensively consider the balance between ecological protection and economic development, and conduct multi-dimensional comprehensive evaluation of rocky desertification control effectiveness [51] to avoid potential problems from one-sided vegetation coverage pursuit and excessive rocky desertification reduction.

2.9 Establish Priority Ecological Protection Zone Precise Identification and Protection Systems Effective biodiversity protection urgently requires solving the mismatch problem. Precisely identify priority ecological protection zones, establish reasonable and effective protected areas, protect wildlife habitats, and restore their living environments. Delineate plant protection zones to reduce climate change and human activity impacts on plants, protect the integrity of wild plant habitats, and expand existing nature reserve domains to cover more ecosystem service priority areas. Apply organic fertilizers, implement crop rotation and diversified agricultural models, improve soil environments, and coordinate soil water, air, and heat to create better living spaces for soil organisms to reduce disturbance [52]. Combine aboveground and underground approaches with systematic perspectives for biodiversity protection to achieve harmonious coexistence between humans and nature.

2.10 Achieve Coordinated Improvement of Ecology, Economy, and People' s Well-being Achieving coordinated improvement of ecology, economy, and people' s well-being is important in ecological civilization construction [53]. Future efforts must maintain development and ecological red lines, combine ecological restoration with industrial development, industrial structure adjustment, and livelihood improvement, and rationally allocate agriculture-industry-services (tourism) within ecological environment carrying capacity. Improve primary industry planting production, deepen secondary industry processing production, develop tertiary industry cultural-tourism integration, achieve "connecting secondary and tertiary industries" regulation, and establish a new paradigm for coordinated karst industry development to enhance ecological development sustainability. Simultaneously, conduct ecosystem service process research, construct a comprehensive ecological-economic total value accounting framework, replace "single-wheel traction" with "dual-wheel drive" of ecology and economy, incorporate green GDP and ecosystem service value indicators into government assessment alongside ecological environment planning and evaluation, and increase assessment of ecological resources.

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Note: Figure translations are in progress. See original paper for figures.