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Quantification of Agroforestry Ecosystem Services in Karst Desertification Control

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Abtract: *This study assesses the ecosystem services of agroforestry in karst regions affected by desertification, highlighting its potential for ecological restoration and sustainable management. Agroforestry systems significantly enhance soil stability, water management, and carbon sequestration, thereby contributing to ecological health and helping mitigate the adverse effects of desertification. The research was conducted across various karst areas in southern China, delineated into zones based on degradation severity. The methodology involved quantifying key ecosystem service indicators such as biomass, net primary productivity, carbon storage, and soil quality through innovative models adapted to local environmental conditions. Results indicate that agroforestry systems not only improve provisioning and regulating services inversely related to degradation levels but also offer substantial cultural benefits by enhancing ecological perception and aesthetics through diverse vegetation and topography. Specifically, areas with intense agroforestry interventions showed higher biomass and carbon storage compared to less managed zones. Furthermore, the cultural services provided by these ecosystems, like enhanced ecological perception through improved landscape aesthetics and increased accessibility, underscore their integral role in local ecological and human communities. By integrating ecological and economic strategies, agroforestry in karst regions fosters a sustainable interaction between human activities and natural habitats, supporting both conservation efforts and local livelihoods. The findings advocate for expanded agroforestry practices as a key component of land management policies aimed at ecological restoration and sustainable development in degraded landscapes.*

Keywords: *Agroforestry, Ecosystem services, Supply, Regulation, Cultural*

1. Introduction

Ecosystems are on the verge of severe degradation (Cardinale, et al. 2012; Fu et al., 2022)[1,2], with significant negative effects on ecosystem services (ES). Despite significant efforts to promote biodiversity conservation and restoration, land use change remains a major driver of biodiversity destruction (Jaureguiberry, et al., 2022)[3]. Here, agroforestry (AF), an ecologically based land use that integrates trees/crops as well as livestock farming (Nair, 1989)[4], creates promising opportunities for ecosystem restoration (Garrity, 2004; Wurz, et al., 2022)[5,6], to a much greater extent than land use systems represented by monocropping traditional agriculture (Notaro, M., et al. 2022)[7]. On the one hand, AF provides a wide range of food, fodder and tree products that can be used for income generation or for consumption by family farmers (Escalante, et al. 2017)[8], and on the other hand, multi-species integration facilitates soil fertility, erosion reduction, carbon and nitrogen sequestration, and climate regulation, among others (Jose, 2009; Aryal, et al. 2023)[9,10], hence the term 'vulnerability healer', which is helping many ecologically fragile areas that require a combination of livelihood security and environmental restoration to slowly heal (Miccolis, et al., 2016)[11], thus ensuring ecosystem sustainability and resilience, and thus the long-term provision of goods and services to humans.

As an important environmental restoration strategy, AF ecosystems have been widely used in the management of karst areas (KD), providing a huge "umbrella" for fragile ecosystems due to their ecologically sustainable production methods (Chen et al., 2019; Jiang et al., 2022; 2022; Xiao et al., 2022)[12,13,14]. However, few studies have quantified the protective effect of the umbrella in KD, and even less is known about its effectiveness under environmentally different conditions. However, we cannot blindly stand under the umbrella without understanding the importance of AF systems in protecting karst habitats. Based on this, this study will take a typical fragile karst desertification region as the research background to quantify the ability of AF systems to provide ES in fragile environments, with a view to revealing the unique roles of AF systems in KD environments.

2. Study area and methodology

2.1 Overview of the study area

The karst region in southern China, covering an area of approximately 1.94 million km², has 28% of its land affected by habitat degradation, including irrational land use and extensive sloping croplands, leading to significant soil erosion (Cao et al., 2004; NFGA, 2018; Xu et al., 2021)[15,16,17]. In response, researchers have developed various AF models tailored to different degradation levels and production needs. These models enhance farmers' incomes and ecological health, incorporating strategies like eco-efficient AF (ASV) and customized multi-purpose woodlands (MWL) and flexible home garden AF (HG) based on environmental, economic, and cultural conditions (Cao et al., 2019; Zou et al., 2019)[18,19]. Conversely, the Karst Non-Desertification (KND) region continues to sustain traditional agriculture due to favorable hydrothermal conditions unaffected by degradation. This study examines both non-desertified and desertified karst areas, categorizing them into zones like Potential-slight and Moderate-severe KD, to investigate habitat degradation gradients (Figure. 1).

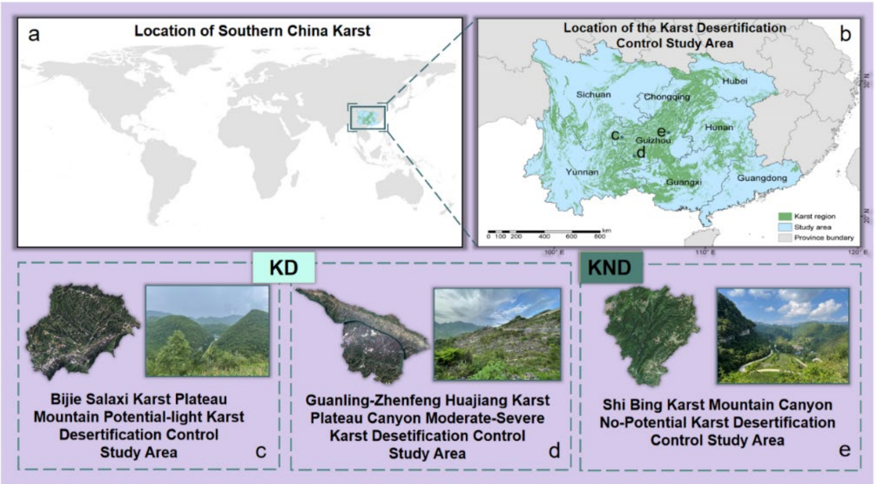

Figure. 1 Study Area Overview (a. Region map showing karst locations in southern China; b. Detailed view of the area spanning eight provinces; c. PKD-BJ zone; d. MKD-HJ zone; e. KND-SB zone)

2.2 Research methodology

This study analyzed six crucial ES indicators: biomass, net primary productivity, carbon storage, soil quality, microclimate regulation, and ecological perception.

2.2.1 Supply services

① Biomass:

a) The biomass of the herbaceous layer was estimated using dry weight data from herbaceous plants and multiple validated relationships between biomass and relative growth (Du et al., 2014)[20]. These relationships were established through regression analysis using the formula

$$W_{evergreen} = 0.0755(D^2 diameterH)0.8941 \tag{1}$$

$$W_{dioecious} = 0.0495(D^2 diameterH)0.0740 \tag{2}$$

b) Below-ground biomass: This study estimates below-ground biomass using dry weight data from plant roots.

② Net primary productivity: Annual average net production was employed as an indicator to estimate productivity (Pang et al., 2014)[21].

$$P = \left(\frac{W_{\text{Aboveground}}}{a}\right) + \left(\frac{W_{\text{Below-ground}}}{a}\right) \tag{3}$$

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P: Average annual net production. W: Biomass (t) of each component above ground. a: Age of each component, measured as follows: For trees and shrubs: Age determined using the Swedish Haglof tree growth cones (CO300-52) via the drilling method, with a weighted average of the measurements. For herbaceous plants: Assumed uniformly to be 2 years.

2.2.2 Supply services

① Carbon Stock Calculation:

Total Carbon Stock (kg/m²): Computed as the sum of soil carbon and plant carbon, where the biomass fraction is assumed to be 0.5 (Salas Macias et al., 2017)[22].

a) Soil Carbon: Estimated using the Walkley-Black method (Bazan, 1996). The formula below was used to calculate the soil carbon stock per unit area:

$$\text{Soil carbon}=\sum_{\text{Soil stratification}=i}^{\text{Soil stratification}=n}\left(\left[\left(\mathrm{BD}_i\times\mathrm{TH}_i\times\left[1-\frac{\mathrm{CR}_i}{100}\right]\right)\times\mathrm{C}_i\right]\times 100\right) \tag{4}$$

BD_i: Bulk density of stratum i (g/cm³). TH_i: Soil thickness of stratum i (m). CR_i: Percentage volume of coarse grains in stratum i (m), used to adjust the bulk density for potential biases caused by soil clustering. C_i: Percentage of organic carbon in stratum i.

b) Plant Carbon: Total biomass was converted into plant carbon by multiplying it by the carbon fraction of 0.5, as recommended by the IPCC (International Panel on Climate Change).

② Microclimate Regulation:

Differences in light, atmospheric temperature, soil temperature, and bare rock temperature across sample plots were analyzed to develop a comprehensive index reflecting the microclimate regulation capabilities of the mixed AF ecosystem (Duan et al., 2014)[23].

③ Soil Quality Index:

Soil quality was assessed using seven indicators: bulk density, porosity, pH, organic matter, total nitrogen, total phosphorus, and total potassium. These factors were weighted and their standardized values converted into affiliation values ranging from 0 to 1, indicating each sample's contribution to overall soil quality. Calculation formula:

$$SQI=\sum_{i=1}^{n} w_i\cdot Q(x_i) \tag{5}$$

w_i: Weight of the ith soil factor. $Q(x_i)$: Affiliation of the ith soil factor. n: Total number of soil factors.

2.2.3 Cultural services

① Ecological Perception:

To assess the restoration impact at the sample sites, a comprehensive index was developed using the rock exposure rate, vegetation cover, and slope. This index indirectly quantifies the local perception of rejuvenation attributed to mixed AF ecosystems.

a) Bare Rock Rate (BBR) Measurement: BBR was determined in 20x20m sample plots using both the mechanical pointing method and photography. The formula used is $\mathrm{BBR}=\frac{clicks\ on\ the\ rock\ sample}{total\ sample\ points}$. Additionally, overhead digital photographs of exposed rocks were analyzed using ImageJ software to calculate the area and size of surface exposure (Liu et al., 2018)[24].

b) Vegetation Cover and Slope:

Vegetation analysis was conducted in five 1m×1m diagonal sample squares per plot using the five-point method to inventory plant species. Coverage for all species and the geographic coordinates of each plot were recorded using a handheld GPS, while the direction and slope measurements were taken using a slope meter.

The formula for calculating the composite index is as follows:

$$CI=\sum_{i=1}^{n}(w_i\cdot x'_i) \tag{6}$$

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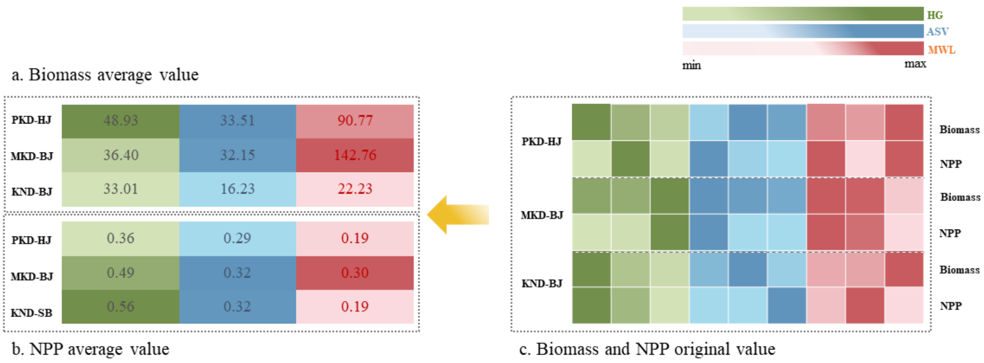
CI: Composite Index. w_i: Weight of indicator x'_i: Standardized value of indicator i. n: Total number of indicators.

3. Results

The unique advantage of mixed AF ecosystems is their ability to provide a variety of ES, such as improved soil stability, water management, soil erosion control, enhanced carbon storage, and increased production capacity (Jose et al., 2009)[9]. These services are vital in areas affected by rocky desertification, as they mitigate its adverse effects and support sustainable development. In areas without rocky desertification, these ecosystems similarly contribute to maintaining ecosystem stability. This study evaluates the representativeness and practicality of these services by selecting indicators of provisioning, regulating, and cultural services. The aim is to assess their functional roles in different ecological contexts, thereby laying a groundwork for future research and application.

3.1 Supply services



(Biomass: biomass kg/m2; NPP: net primary productivity kg/m^2)

Figure. 2 Biomass and Net Primary Productivity (NPP)

As depicted in Figure. 2 the biomass of the HG system was significantly higher than that of the ASV system in the PKD-BJ study area, whereas the MWL system exhibited the highest biomass, nearly doubling that of ASV. This indicates MWL's superior biomass accumulation and diverse planting strategies. Although the net primary productivity (NPP) of HG and ASV were similar, both were significantly higher than MWL's, likely due to the large biomass of woody plants in MWL reducing its NPP. In the MKD-HJ area, MWL's biomass far exceeded that of HG and ASV, reflecting the effective management practices enhancing plant growth and biomass in MWL. Conversely, HG had the highest NPP, suggesting greater ecological efficiency. In KND-SB, HG had more biomass than ASV, yet a lower NPP, implying denser plant populations with slower individual growth. MWL showed lower biomass and NPP, indicating adaptive strategies like drought tolerance or alternative survival tactics. Summarizing across the three zones: In PKD-BJ, different management practices in mixed AF led to high biomass in MWL. In MKD-HJ, environmental adaptability was demonstrated with MWL boosting biomass and HG optimizing NPP. In KND-SB, the data reveal complex interactions between biomass and NPP in mixed AF ecosystems, highlighting varied growth strategies.

3.2 Regulation services

3.2.1 Carbon stocks

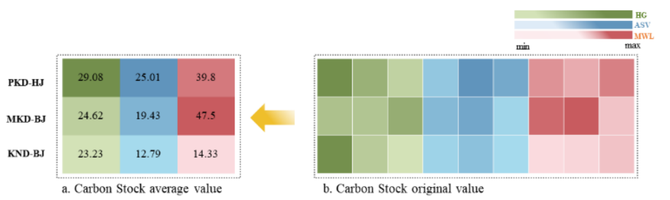


Figure. 3 Carbon Stocks (kg/m^2)

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AF systems play a crucial role in the global carbon cycle by enhancing climate regulation services through significant carbon sequestration in vegetation and soil. This helps reduce atmospheric carbon dioxide levels and mitigate climate change (Pandey et al., 2002)[25]. Figure. 3 illustrates that in the PKD-BJ area, the MWL system showed the highest carbon storage, significantly surpassing HG and ASV systems. This superior capacity is attributed to its effective land management and diverse plant species, indicating a stronger contribution to carbon fixation. In the MKD-HJ area, the MWL system also led in carbon storage, suggesting that even under harsh desertification conditions, its diverse management strategies ensure substantial carbon retention through its biomass. Conversely, in the KND-SB area, the HG system stored more carbon than both ASV and MWL, demonstrating that even simpler plant communities and traditional practices can effectively sequester carbon.

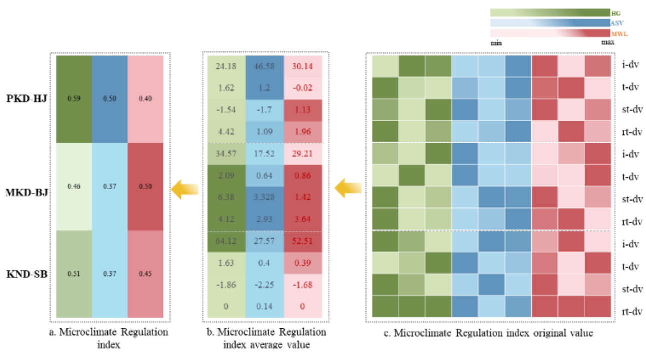
Overall, the PKD-HJ region displayed the greatest total carbon storage, with the MWL system particularly potent in the KND zone and the HG system more effective in high carbon storage in the same zone.

3.2.2 Soil quality index

Figure. 4 SQI (kg/m^2)

This index demonstrates the capability of soil conservation and fertility maintenance, serving as a crucial indicator of mixed AF systems' effectiveness in soil protection and improvement. Healthy, fertile soils underpin sustained ES, including water regulation, pollutant filtration, and biodiversity support (Schwab et al., 2015; Shi et al., 2024)[26,27]. As depicted in Figure. 4, the MWL system showcased the highest soil quality in the PKD-BJ area with an SQI of 0.54, suggesting that its land management practices significantly enhance soil health and functionality. The ASV system also displayed high soil quality (SQI: 0.508), whereas the HG system's lower score (SQI: 0.391) indicates a need for improved soil management strategies.In the MKD-HJ area, the HG system recorded the top SQI score of 0.59, reflecting its effective soil health strategies under challenging conditions. Meanwhile, the MWL and ASV systems achieved SQI scores of 0.531 and 0.469, respectively, highlighting their moderate soil quality maintenance capabilities.In the KND-SB region, the ASV system led with the highest SQI of 0.44, underscoring the effectiveness of its land management in enhancing soil quality. Conversely, the MWL and HG systems, with SQI values of 0.44 and 0.39 respectively, appear to require further optimization of their soil management practices within this ecological setting.

3.2.3 Microclimate regulation



(i-dv: difference in light; t-dv: difference in atmospheric temperature; st-dv: difference in soil temperature; rt-dv: difference in bare rock temperature)

Figure. 5 Microclimate regulation

Figure. 5 shows that in the PKD-BJ area, the ASV system had a significantly higher light differential between the forest interior and exterior compared to other systems, peaking at 46.58, which underscores its excellent light regulation capability. This indicates that ASV's vegetation might enhance light

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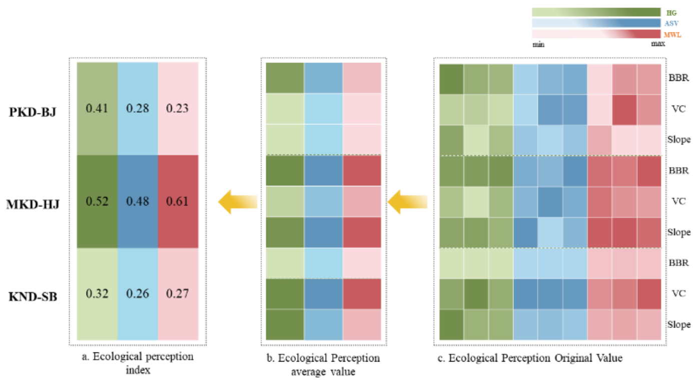
absorption and scattering through denser cover or more effective shading structures. Additionally, the HG system showed significant thermal insulation, maintaining more stable soil temperatures with a negative soil layer temperature difference of -1.54, compared to MWL's -1.13. HG also demonstrated a notable cooling effect on rock surfaces with the highest temperature difference of 4.42. In the MKD-HJ area, HG led in light regulation and soil temperature control, suggesting that its vegetation structure effectively reduces direct sunlight exposure and cools the soil. This robust temperature management implies that HG might need a tailored soil insulation strategy for the area's specific conditions. The MWL system's performance in regulating rock temperatures also suggests its potential to alleviate thermal stress. In the KND-SB non-rocky desertification zone, HG systems displayed exceptionally high light differentials, emphasizing their critical role in light filtration. All systems showed negative soil temperature differences, indicating successful thermal insulation, with HG being the most effective. Lower or negligible bare rock temperature differences suggest that reducing rock temperatures might be a lesser priority in this environment, or that bare rock areas are minimally impactful on the microclimate compared to vegetated areas.

Overall, each system exhibited distinct capabilities and responses to microclimatic challenges across varying desertification levels. ASV was particularly effective in shading and cooling in areas with mild rocky desertification, while HG consistently lowered soil temperatures across all zones. MWL showed promise in mitigating high thermal stress in moderately rocky areas (Figure. 5).

3.3 Cultural services

In karst landscapes, the interaction between humans and nature not only shapes the ecological patterns but also significantly impacts the ecological perceptions of locals and visitors. This subsection evaluates the role of mixed AF ecosystems in enhancing ecological perception within karst rocky desertification areas—a complex ecosystem influenced by both natural elements and human interventions. The cultural services index (CSI), composed of rock exposure rate, vegetation cover, and slope, correlates directly with landscape perception and evaluation. These metrics collectively gauge ecological aesthetics and accessibility: Rock Exposure Rate: Indicates ecological degradation and surface barrenness. Vegetation Cover: Reflects progress in ecological restoration and enhances landscape aesthetics. Slope: Measures the terrain's navigability and influences perceptions of nature's challenges and grandeur.

The integration of these cultural service indicators elucidates the effects of ecological perceptions shaped by AF management in desertified areas, highlighting the balance between nature and human activity, and prompting deeper reflections on natural environments (Du et al., 2008)[28].



(BBR: rock exposure rate; VC: vegetation cover; Slope: gradient)

Figure. 6 Ecological Perception

Figure. 6 illustrates that in the PKD-BJ area, the HG system's high cultural services. CSI underscores its robust ecological perception capabilities. Although high rock exposure often signals ecological degradation, HG's extensive vegetation and moderate slopes improve accessibility and enhance ecological experiences. In contrast, the lower CSI scores of the ASV and MWL systems indicate their more limited roles in ecological restoration and aesthetic improvement despite better accessibility. In the MKD-HJ area, the MWL system boasted the highest CSI, suggesting its dramatic visual impact and strong sense of ecological renewal, supported by dense vegetation and steep slopes. The HG system, with a CSI of 0.52, and the ASV system also demonstrated potential for significant cultural contributions, with their balanced rock exposures and vegetation enhancing the regional cultural services. In the KND-SB area, the low BBR implies minimal rock desertification, positioning the CSI as a gauge of ecological

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perception rather than regeneration. The HG system, with its lush vegetation and gentle slopes, offered substantial ecological experiences and aesthetic value. ASV and MWL also contributed to ecological experiences but to a lesser extent compared to HG.

Overall, the CSI highlights the varying abilities of AF systems to foster ecological perception and aesthetic appreciation across different regions. In PKD-BJ and MKD-HJ, HG and MWL excelled in conveying a sense of ecological renewal. In the non-desertified KND-SB region, cultural services focused on appreciating ecological diversity and natural beauty, with HG providing superior services due to its optimal vegetation cover and slope (Figure. 6).

4. Discussion

In terms of provisioning services, the biomass and NPP of mixed AF ecosystems demonstrated an inverse relationship with the degradation gradient, observed as MKD-HJ > PKD-BJ > KND-SB. This trend could be due to earlier ecological restoration efforts in MKD-HJ, spurred by severe degradation. Additionally, the maturity of trees and shrubs, indicated by a positive correlation between their age and both diameter at breast height (Dbh) and height, contributed to the disparities in biomass between regions. In PKD-BJ and MKD-HJ, AF management strategies were tailored to local environmental limits. For example, PKD-BJ extensively adopted a mixed system of deep-rooted and drought-tolerant pecan and prickly pear, both significant cash crops well-suited to the arid conditions and proving impactful on the ecological landscape. Conversely, in MKD-HJ, the predominant AF model included measuring tape and pepper, selected for their profitability and ability to thrive under water-scarce conditions, thereby enhancing biomass and NPP even in rocky desertified environments. Although the KND-SB region's mixed AF systems might not reach the productivity levels of more degraded areas, its more favorable ecological and hydrothermal conditions could allow alternative systems like woodlands and agriculture to excel. This suggests that by choosing appropriate crops and employing effective management, biomass and NPP can still be enhanced in less arid settings.

In terms of regulating services, the PKD-BJ region exhibited the highest carbon stock, followed by MKD-HJ, while KND-SB recorded the lowest. This pattern underscores the impact of karst geology and ecology on carbon storage capabilities. In PKD-BJ, reduced soil erosion and less ecological degradation helped maintain fertile soil and adequate water conditions, fostering robust plant growth and significant biomass accumulation. Additionally, taller plants in this region enhanced photosynthesis efficiency, capturing more atmospheric CO^2 and converting it into biomass carbon. Although the MKD-HJ region experienced more severe degradation, which diminished soil fertility and water retention, its unique dry and hot river valley climate—particularly the warm and moist conditions—sped up nutrient conversion in plants. This partially offset the reduced carbon storage capacity, placing MKD-HJ's carbon stock above KND-SB but below PKD-BJ. In contrast, KND-SB's karstic environment facilitated substantial underground carbon storage in cavities and groundwater, detracting from surface carbon stock. Furthermore, MKD-HJ boasted a higher SQI than PKD-BJ, attributed to targeted climatic and ecological management strategies that improved soil attributes. Regarding microclimate regulation, both PKD-BJ and MKD-HJ outperformed KND-SB. The complex structure and extensive canopy of mixed-AF systems in these regions moderated atmospheric and soil temperatures and minimized heat reflection from exposed rocks, thereby enhancing microclimatic conditions.

In the cultural services assessment, the MKD-HJ area showcased significant value, attributed to its high rock exposure and diverse topographic features that offer a unique experience for tourists. Observations of ecological degradation prompted deep reflections on the interplay between natural forces and human activities (Pihkala et al., 2017)[29]. Furthermore, witnessing the rehabilitation and development of mixed AF in these environments provided visitors with insightful perspectives on ecological restoration, delivering a more profound emotional and cognitive impact than that experienced in ecologically stable environments. This pattern illustrates an ecological perceptual U-curve, where initial exposure to degradation followed by recognition of restoration efforts enhances the overall cultural service value (Zoogah et al., 2016)[30].

5. Conclusion

AF ecosystems exert a significant positive impact in areas affected by karst desertification. This study quantified the ES provided by AF, highlighted variations across different degradation gradients and AF types, explored how these services adapt to environmental changes, and offered a scientific foundation

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for sustainable management and strategic responses. The main conclusions are as follows:

Provisioning Services: Trends in MKD-HJ, PKD-BJ, and KND-SB inversely correlate with degradation levels, suggesting that effective AF management can sustain high provisioning services due to its adaptive capabilities.

Regulating Services: The sequence PKD-BJ, MKD-HJ, KND-SB underscores the impact of karst's unique geology and ecology on ecosystems' carbon storage capacities.

Cultural Services: Demonstrated that even in intensely desertified regions, AF can transform ecological restoration efforts into substantial cultural value.

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