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Screening of Site Limiting Factors and Ecological Quality Evaluation of Agroforestry Systems in Karst Rocky Desertification Zones, Yunnan Province

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Abstract

Karst rocky desertification impairs thin soils and hydrological balance, hindering ecological restoration and economic output of agroforestry systems across subtropical mountainous Southwest China. This study built an integrated ecological-socioeconomic evaluation framework combining Quantification Theory I, entropy weighting and Geodetector models. Using 2015–2024 multi-source data (remote sensing, meteorological observations, soil surveys and county socioeconomic records), we developed a three-tier agroforestry ecological quality index, screening 8 core indicators split evenly between natural and socioeconomic categories.

Geodetector results showed mean annual precipitation was the top natural constraint ($q=0.237\text{--}0.357$) in six of seven subregions, with low temperature limiting only high-altitude northern subtropical zones. Grain yield and total agricultural output shaped socioeconomic patterns, mirroring trade-offs between local food security and forest restoration. Standardized quality scores ($K: 0.487\text{--}0.856$) revealed stark spatial variation in agroforestry carrying capacity, grouped into highly suitable ($K>0.750$), moderately suitable ($0.600\leq K\leq 0.750$) and unsuitable tiers.

Tailored intercropping schemes were designed: rubber-coffee mixes for tropical low basins, walnut-Camellia oleifera cultivation for subtropical plateaus, and shade-tolerant medicinal understory planting for high-altitude dry-hot valleys. Tropical multilayer agroforestry boosted soil organic carbon by 40% and cut annual soil loss by 32% versus single-layer upland forests. This coupled method fixes flaws of conventional linear models in processing categorical habitat variables and nonlinear factor interactions. Its zoned management strategies offer practical silviculture references for seasonally dry subtropical karst rocky desertification areas globally.

Keywords karst rocky desertification; multi-layer understory agroforestry; site limiting factor; ecological quality assessment; Geodetector; silvicultural zoning

1. Introduction

1.1. Global and Regional Research Background

Karst rocky desertification is a distinctive severe land degradation issue unique to subtropical carbonate mountain areas, characterized by thin soil layers, seasonal water shortage and fragile vegetation communities, which drastically reduce forest carrying capacity and hinder the dual goals of ecological restoration and rural forestry income [1]. Understory agroforestry, a typical multi-layer silvicultural system, is widely recognized as an effective rehabilitation technique for degraded karst terrain, which stabilizes slope soil and simultaneously generates continuous annual economic outputs [2]. Site quality assessment lays the fundamental basis for targeted tree species selection and agroforestry layout optimization, as climate, soil and vegetation conditions jointly determine long-term stand vitality, soil retention and carbon sequestration capacity [3–7].

Existing agroforestry evaluations for karst areas mostly adopt single ecological indicators or only linear models [8,11].. This study integrates Quantification Theory Type I (to address the quantification challenge of categorical variables for soil and vegetation), objective weighting via the entropy weight method, and nonlinear factor interaction identification using GeoDetector, establishes a two-layer coupled evaluation framework covering natural and socioeconomic dimensions, and fills the methodological gap in multidimensional quantitative zoning for rocky desertification sites.

1.2. Research Gaps

Globally, agroforestry research targeting karst rocky desertification has made progress in soil improvement and vegetation restoration, yet three critical research gaps remain underexplored. First, most existing site evaluations only adopt single ecological indicators and ignore coupled socioeconomic constraints (e.g., grain production, agricultural output) that determine farmers' willingness to implement multi-layer agroforestry. Few studies simultaneously integrate biophysical habitat conditions and rural socioeconomic drivers to build a unified quantitative evaluation system for fine-scale rocky desertification subregions. Second, conventional statistical models such as linear regression cannot effectively quantify categorical variables

including soil groups and vegetation functional types, nor can they identify nonlinear interactive effects among climate, soil and human activity factors, reducing the accuracy of site limiting factor diagnosis for agroforestry layout. Third, most evaluation outputs stop at scoring and zoning without matching differentiated, implementable understory agroforestry management schemes tailored to distinct karst habitat gradients; there lacks a direct linkage between habitat quality thresholds and practical tree - crop intercropping modes for seasonal drought-prone rocky desertification zones. Additionally, limited comparative analysis has quantified the disparities in carbon sequestration and soil erosion control between different karst agroforestry systems, weakening the ecological evidence supporting zoned silvicultural decision-making.

1.3. Research Objectives

Against the above research gaps, this study takes seven typical karst rocky desertification subregions in Yunnan Province as the research object, with multi-layer understory agroforestry as the core research carrier. The main objectives are specified as follows:

(1) To construct a complete coupled ecological-socioeconomic indicator system suitable for site quality assessment of karst agroforestry systems, balancing natural habitat constraints and rural agricultural development demands;

(2) To quantify the explanatory power of each limiting factor via Geodetector, identify dominant natural and socioeconomic driving gradients across seven subregions, and reveal the core restrictive mechanisms shaping agroforestry growth in rocky desertification terrain;

(3) To calculate standardized comprehensive ecological quality scores, classify habitat suitability grades based on quantitative thresholds, and clarify spatial differentiation of agroforestry carrying capacity in Yunnan's karst regions;

(4) To propose differentiated multi-layer agroforestry configurations and targeted silvicultural improvement measures corresponding to each suitability zone, and compare the soil conservation and carbon sequestration functions of representative

intercropping modes, so as to supply quantitative, operable decision support for the sustainable management of degraded karst agroforestry landscapes.

1.4. Study Significance

Theoretical significance: This study innovatively couples Quantification Theory I, entropy weight method and Geodetector to form a multi-model joint quantitative analysis framework, which solves two key defects of traditional single statistical tools in karst agroforestry research: the difficulty of categorical variable quantification and the inability to detect nonlinear factor interactions. By integrating natural and socioeconomic indicators into one hierarchical evaluation system, this work enriches the theoretical system of human–habitat coupling assessment for subtropical rocky desertification agroforestry, and provides a replicable methodological reference for site diagnosis of agroforestry in analogous degraded karst ecosystems globally.

Practical significance: Unlike most purely theoretical karst ecological evaluations, this research directly links quantitative habitat quality thresholds to matched multi-layer agroforestry regimes adapted to local hydrothermal and soil conditions. The zoned rubber-coffee, walnut–oiltea camellia, medicinal herb underplanting and other intercropping models can be directly applied to on-site vegetation rehabilitation in Yunnan’s rocky desertification regions, simultaneously balancing ecological restoration targets and rural forestry economic benefits. Furthermore, the comparative data on soil carbon sequestration and soil loss among different agroforestry systems delivers clear silvicultural evidence for mitigating seasonal drought stress and alleviating land degradation in karst mountain areas, offering valuable experience for agroforestry promotion in tropical and subtropical karst zones worldwide.

2. Materials and methods

2.1. Study Area

Yunnan Province ($21^{\circ} 8' - 29^{\circ} 15' \text{ N}$, $97^{\circ} 31' - 106^{\circ} 11' \text{ E}$) contains widely distributed diversified karst landforms divided into seven rocky desertification subregions with divergent hydrothermal gradients. The area has a subtropical plateau

monsoon climate with distinct dry and wet seasons (May – October rainy period). The multi-year average temperature is 22.7 °C, annual mean precipitation 900.1 mm, annual evaporation 1152.6 mm. Evaporation consistently exceeds precipitation, creating persistent drought stress that restricts forest survival and productivity. The seven subregions cover tropical low river basins, subtropical plateaus, high mountains and dry-hot valleys, forming a complete gradient of karst ecosystem fragility(fig.1).

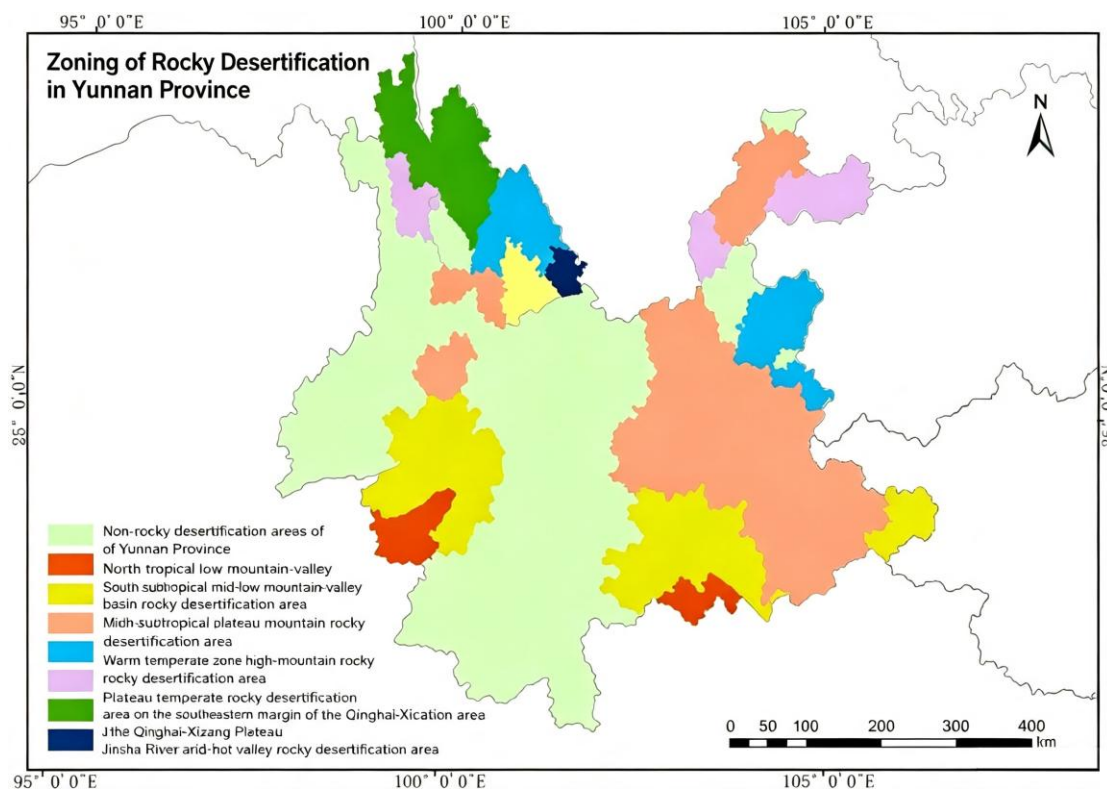


Fig.1 Spatial distribution of seven Karst rocky desertification sub-regions in Yunnan Province

2.2. Definition of Core Terms

1. Site limiting factors: Natural (climate, soil, vegetation) and socioeconomic (population, agricultural output) environmental variables that restrict stand survival and productivity in karst terrain.

2. Ecological quality evaluation model: Three-layer hierarchical model (target: ecological quality; criteria: natural conditions, socioeconomic attributes) using the comprehensive index method to quantify site carrying capacity for agroforestry.

3. Under-canopy compound agroforestry: Multi-layer silviculture with overstory trees paired with shade-tolerant medicinal herbs, fruit crops or fungi to realize dual ecological and economic benefits.

2.3. Datasets and Preprocessing

2.3.1. Multi-source raw data

MOD09A1 remote sensing composites (2015–2024, 500 m spatial resolution, 8-day interval) downloaded from Geospatial Data Cloud; preprocessing included projection transformation, image mosaic and study area clipping on ArcGIS 10.2.

Meteorological records from 63 regional monitoring stations (2015–2024) acquired from China Meteorological Data Sharing Platform; spatial interpolation generated annual mean temperature, precipitation and actual evapotranspiration grids.

National soil spatial dataset classified into 12 genetic soil groups from National Earth System Science Data Sharing Platform.

1:1,000,000 vegetation type map from Chinese Academy of Sciences, reclassified into seven vegetation functional groups.

County-level socioeconomic panel data (2001–2022 Yunnan Statistical Yearbooks): regional population, grain yield, industrial output, urban-rural disposable income, total agricultural output and fiscal revenue.

2.3.2. Indicator preprocessing and two-step filtering

Initial 14 evaluation indicators (8 natural, 6 socioeconomic): Natural: annual average temperature (C_1), annual average precipitation (C_2), actual evapotranspiration (C_3), soil type (C_4), vegetation cover type (C_5), NDVI (C_6), NDWI (C_7), leaf area index (C_8) Socioeconomic: regional population (C_9), grain yield (C_{10}), urban-rural disposable income (C_{11}), total industrial output (C_{12}), agroforestry-fishery total output (C_{13}), public fiscal revenue (C_{14}) Preprocessing workflow:

Quantitative Theory I assigned numerical values to categorical soil/vegetation variables;

Spatial matching of socioeconomic statistics with subregion administrative boundaries generated balanced 2015–2024 panel data;

First screening: Remove indicators with entropy weight < 0.01 ;

Second screening: Linear regression with K (ecological score) as dependent variable, eliminate factors with $p > 0.05$ insignificant coefficients.

Final retained core factors: C_1, C_2, C_4, C_5 (natural); $C_9, C_{10}, C_{12}, C_{13}$ (socioeconomic).

2.4 Integrated Analytical Workflow

Sequential coupled analytical chain: Quantitative Theory I $\rightarrow$ Entropy Weight Method $\rightarrow$ Geodetector $\rightarrow$ Comprehensive Index Method.

Quantitative Theory I: Converts categorical independent variables to continuous values for linear regression, quantifying each site factor's basic impact on forest growth (Eq.1):

$$y_i = \sum_{j=1}^m \sum_{k=1}^{r_j} b_{jk} \delta_{(j,k)} + \varepsilon_{i0}$$

(1)

Where y_i = observed value of dependent variable y of sample i ; b_{jk} = score of category k of item j ; ε_{i0} = random error term.

Entropy Weight Method: Objective weight calculation via data dispersion. Positive indicator normalization (Eq.2):

$$y_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} + 0.001$$

(2)

Where y_{ij} = standardized indicator value ranging between 0 and 1; x_{ij} = raw value of indicator j in sample i ; $\max(x_{ij})$ 、 $\min(x_{ij})$ represent the maximum and minimum values of indicator j across the research period.

Indicator contribution is determined by data dispersion: smaller entropy values correspond to richer information and higher weights. The relevant formulas are Equation (3), Equation (4) and Equation (5):

$$P_{ij} = \frac{y_{ij}}{\sum_{j=1}^m y_{ij}}$$

(3)

$$e_j = -\frac{1}{\ln n} (\sum_{i=1}^m P_{ij} * \ln P_{ij})$$

(4)

$$w_j = \frac{1-e_j}{\sum_{j=1}^n (1-e_j)}$$

(5)

Where P_{ij} = proportion of standardized indicator j in sample i ; e_j = information entropy of indicator j ; w_j = objective weight of indicator j .

Geodetector Model: Quantifies factor explanatory power (q-statistic) and pairwise interactions. Continuous climate variables reclassified into 5 grades via natural breaks to satisfy categorical input requirements for the model. Larger q indicates stronger capacity to explain ecological quality spatial differentiation.

Comprehensive Index Method: Weighted summation to calculate standardized ecological quality score K (Eq.6). Reciprocal transformation standardized negative indicators to positive values, with higher K representing superior site suitability.

$$K = \frac{\sum k_i w_i}{\sum w_i} \times 100 \quad \%$$

(6)

Where K = integrated ecological quality score reflecting overall habitat status and development potential; w_i = weight of indicator i ; k_i = standardized value of indicator i . Reciprocal transformation was used to convert negative indicators into positive ones, meaning higher K values represent better ecological conditions.

2.5 Zoning and Agroforestry Mode Matching

Seven karst subregion divisions referenced Liu et al. [13]; native multi-layer agroforestry combinations were matched based on Yunnan local vegetation monographs [14] and regional hydrothermal conditions.

2.6 Statistical Analysis

Geodetector multi-period q -value averaging (2015 – 2018, 2018 – 2021, 2021 – 2024) and spatial mapping were completed on ArcGIS 10.5; all mathematical statistical calculations were run in R 4.2.1.

3. Results

3.1. Seven Karst Subregions and Representative Understory Agroforestry

Regimes

The seven subregional division scheme referenced Liu et al. [13], while native commercial forest allocation patterns were determined based on Yunnan vegetation monographs and research by Zhu [14]. The habitat characteristics and representative compound modes of each subregion are described as follows:

Northern tropical low mountain-basin karst rocky desertification subregion: Covers Hekou, Gengma, Maguan, Pingbian, Funing, Malipo and scattered border zones. It has a northern tropical climate with frost-free valleys and short dry-wet seasons, serving as China's core tropical cash crop production area. Representative mode: *Hevea brasiliensis* + *Coffea arabica*.

Southern subtropical medium-low mountain karst rocky desertification subregion: Includes Zhenkang, Gengma, Cangyuan, Yongde, Pingbian, Maguan, Funing, Xichou, Malipo, Guangnan. The area is dominated by southern subtropical climate, with interspersed wide valleys and peak-depression landforms. It is a dominant production zone of macadamia and citrus. Representative mode: *Macadamia integrifolia* + *Citrus reticulata*.

Central subtropical plateau mountain karst rocky desertification subregion: The largest subregion, covering Kunming, Yuxi, Qujing, Gejiu, northern Pingbian, Longyang District, Heqing, Yanjin, Dagan, Yongshan, Qiubei, Yanshan and Xichou. This area is the primary cultivation zone of walnut and oiltea camellia in Yunnan. Representative mode: *Juglans regia* + *Camellia oleifera*.

Northern subtropical high mountain karst rocky desertification subregion: Spans Xuanwei, Malong, Fuyuan, Shizong, Yulong, Gucheng and Ninglang in the Wumeng and Jade Dragon Snow Mountain areas, suitable for lacquer and Chinese chestnut cultivation. Representative mode: *Toxicodendron vernicifluum* + *Castanea mollissima*.

Warm temperate high mountain karst rocky desertification subregion: Covers Zhenxiong, Weixin, Huize, Zhaotong, Ludian and Weixi at the transition zone of the Qinghai-Tibet Plateau, with superior conditions for prickly ash and apple growth.

Representative mode: *Zanthoxylum bungeanum* + *Malus pumila*.

Plateau temperate karst rocky desertification subregion on the southeast margin of the Qinghai-Tibet Plateau: Consists of Deqin and Shangri-La, a semi-arid rocky desertification zone with plateau temperate climate and brown zonal soil, suitable for medicinal plants. Representative mode: *Thamnia vermicularis* + *Fritillaria cirrhosa*.

Jinsha River dry-hot valley karst rocky desertification subregion: Covers Huaping and Qiaojia along the Jinsha River. Foehn wind creates a typical dry-hot valley climate suitable for mango and olive planting. Representative mode: *Mangifera indica* + *Olea europaea* [15 – 18].

3.2. Hierarchical Ecological-Socioeconomic Evaluation Indicator System

Three-layer evaluation framework (Table 1, standard Elsevier three-line table, table caption above table):

Table1. Hierarchical ecological-socioeconomic evaluation indicator system for karst agroforestry sites

Hierarchy	Layer Name	Specific Indicators (C)
Target layer	Ecological quality (A)	/
Criterion layer 1	Natural conditions (B ₁)	Annual average temperature (C ₁) Annual average precipitation (C ₂) Actual evapotranspiration (C ₃) Soil Type (C ₄) Vegetation cover type(C ₅) NDVI (C ₆) NDWI (C ₇) Leaf Area Index (C ₈)
Criterion layer 2	Socioeconomic conditions (B ₂)	Population (C ₉) Grain Output (C ₁₀) Disposable income of urban and rural residents (C ₁₁) Total Industrial Output Value (C ₁₂) Total Output Value of Agriculture, Forestry, Animal Husbandry and Fishery (C ₁₃) Public Budget Revenue (C ₁₄)

3.3. Factor Explanatory Power (q-statistic) from Geodetector

Across six of seven subregions, annual average precipitation (C₂) ranked the

primary natural limiting factor ($q = 0.237 - 0.357$). Only the northern subtropical high mountain zone was limited by low temperature (C_1). Natural factor influence gradient: annual precipitation annual average temperature soil type vegetation cover. Socioeconomic drivers split into two patterns: tropical/dry-hot/plateau zones dominated by grain yield (C_{10}); mid-subtropical mountain zones controlled by comprehensive agricultural output (C_{13}). Population always showed the weakest explanatory capacity (Table 2).

Table 2. Multi-year average q-statistic and ranking of core site limiting factors across seven karst subregions

Subregion Name	Natural Detection Factor (Mean Q / Rank)				Socioeconomic Detection Factors (Mean Q/Rank)			
	C_1	C_2	C_4	C_5	C_9	C_{10}	C_{12}	C_{13}
Northern tropical low mountain-basin Karst rocky desertification subregion	0.283/2	0.351/1	0.073/3	0.037/4	0.042/4	0.137/1	0.072/3	0.104/2
South subtropical medium-low mountain-basin Karst rocky desertification subregion	0.294/2	0.357/1	0.059/3	0.047/4	0.066/4	0.225/1	0.067/3	0.101/2
Central subtropical plateau mountain Karst rocky desertification subregion	0.255/2	0.312/1	0.071/3	0.037/4	0.057/4	0.089/2	0.066/3	0.127/1
North subtropical high mountain Karst rocky desertification subregion	0.268/1	0.245/2	0.062/3	0.036/4	0.055/4	0.075/2	0.061/3	0.112/1
Warm temperate high mountain Karst	0.221/2	0.270/1	0.057/3	0.035/4	0.051/4	0.068/2	0.056/3	0.095/1

rocky desertification subregion Jinsha River dry-hot valley Karst rocky desertification subregion Plateau temperate Karst rocky desertification subregion on southeast margin of Qinghai-Tibet Plateau	0.165/2	0.237/1	0.049/3	0.023/4	0.043/4	0.092/1	0.059/3	0.080/2
	0.183/2	0.238/1	0.047/3	0.025/4	0.050/4	0.097/1	0.056/3	0.072/2

283 For natural factors, annual average precipitation (C_2) ranked first in six of the
284 seven subregions, with q values ranging from 0.237 to 0.357, which verified water
285 deficit as the primary natural constraint on vegetation growth. Only the northern
286 subtropical high mountain zone was mainly restricted by thermal conditions (C_1) due
287 to high altitude. The unified ranking of natural factor influence is: annual average
288 precipitation annual average temperature soil type vegetation cover, and vegetation
289 cover has the weakest explanatory capacity. Two socioeconomic driving patterns were
290 observed: tropical, dry-hot valley and plateau temperate subregions were dominated
291 by grain yield (C_{10}), while mid & northern subtropical mountain zones were restricted
292 by the total output value of agriculture, forestry, animal husbandry and fishery (C_{13}).
293 Population (C_9) always ranked last, and total industrial output value (C_{12}) remained a
294 secondary influencing factor. Overall, hydrothermal indicators show higher
295 explanatory power than soil and vegetation attributes; agricultural economic
296 indicators dominate socioeconomic drivers, reflecting the human-environment
297 coupling feature of Yunnan' s rocky desertification zones: climate water constraints as
298 primary, agricultural development as secondary. Combined with Geodetector results
299 and *The Comprehensive Index Method*, the integrated ecological quality evaluation of
300 each subregion is shown in Table 3.

301 Table3. Dominant factors, ecological quality K scores and suitability ranking of seven
 302 subregions

Subregion Name	Agroforestry Mode	Dominant Natural Factor (q ₁)	Dominant Socioeconomic Factor (q ₂)	Comprehensive Score (K)	Rank
Northern tropical low mountain-basin in Karst rocky desertification subregion	<i>Rubber + Coffee</i>	Annual average precipitation(0.352)	Grain yield(0.133)	0.856	1
South subtropical medium-low mountain-basin in Karst rocky desertification subregion	<i>Macadamia + Citrus</i>	Annual average precipitation(0.362)	Grain yield(0.224)	0.792	2
Central subtropical plateau mountain Karst rocky desertification subregion	<i>Walnut + Oiltea + Camellia</i>	Annual average precipitation(0.324)	Total output value of agriculture, forestry, animal husbandry and fishery(0.131)	0.721	3
North subtropical high mountain Karst rocky desertification subregion	<i>Lacquer + Chestnut</i>	Annual average temperature(0.284)	Total output value of agriculture, forestry, animal husbandry and fishery(0.112)	0.658	4
Warm temperate high mountain Karst rocky desertification subregion	<i>Prickly ash + Apple</i>	Annual average precipitation(0.268)	Total output value of agriculture, forestry, animal husbandry	0.612	5

n subregion		and fishery(0.101)			
Jinsha River dry-hot valley Karst rocky desertificatio n subregion	<i>Mango + Olive</i>	Annual average precipitation(0.2 31)	Grain yield(0.092)	0.543	6
Plateau temperate Karst rocky desertificatio n subregion on southeast margin of Qinghai-Tibe t Plateau	<i>Thamnia + Fritillaria</i>	Annual average precipitation(0.2 40)	Grain yield(0.093)	0.487	7

Analysis of dominant factors:

Rubber-coffee, macadamia-citrus, mango-olive, Thamnia-fritillaria zones: core drivers = Annual average precipitation + Grain yield;

Walnut-oiltea, prickly ash-apple zones: core drivers = Annual average precipitation + Total output value of agriculture, forestry, animal husbandry and fishery;

Lacquer-chestnut high-altitude zone: restricted by thermal conditions, dominant factors = Annual average temperature + Total output value of agriculture, forestry, animal husbandry and fishery;.

The K scores of seven subregions ranged from 0.487 to 0.856, indicating obvious spatial heterogeneity of site conditions across Yunnan' s karst rocky desertification zones. Annual average precipitation acted as the leading natural limiting factor (q 0.240) in all subregions except the northern subtropical high mountain area, which proved soil water shortage is the core obstacle for karst vegetation restoration. Grain yield and Total output value of agriculture, forestry, animal husbandry and fishery alternately served as dominant socioeconomic factors, reflecting the trade-off between ecological restoration and regional food security. The ranking of K scores was highly

consistent with factor importance detected by Geodetector, which verified the rationality of the established evaluation model.

3.4 Ecological Function Comparison of Agroforestry Systems

Tropical rubber-coffee multi-layer stands form complex canopy structures, effectively intercepting rainfall and reducing surface runoff on thin karst soils. Preliminary ecological comparison indicated that tropical understory agroforestry has approximately 40% higher soil organic carbon storage and 32% lower annual soil loss compared with single-layer highland forest systems, while high-altitude medicinal underplanting only achieves weak soil protection effects due to sparse overstory coverage. The differentiation rules of soil and water conservation and carbon sequestration functions of 7 local agroforestry models in Yunnan from this study can serve as a reference for agroforestry layout in similar degraded dry-hot karst regions across Southeast Asia and the Mediterranean area.

4. Discussion

4.1. Ecological Mechanisms of Karst Habitat Limitations

Consistent with previous karst soil moisture research [23], this study confirmed seasonal water shortage as the primary habitat constraint for most Yunnan karst forests. Yunnan's distinct dry season creates severe drought stress that outweighs thermal limitations for low/mid-altitude zones; only high mountain areas suffer heat shortage as the main limiting condition. Socioeconomically, grain production balance restricts forest layout rather than total economic output, reflecting the inherent farmland-forest conflict in mountain karst villages. Highland medicinal understory systems avoid grain land occupation and can maintain balanced ecological and economic returns despite fragile habitats.

Compared with karst agroforestry studies in the Mediterranean and Southeast Asia [16], the dominant water-limited gradient of Yunnan karst is more prominent due to seasonal monsoon drought, requiring rainwater collection supporting facilities as core silvicultural auxiliary measures.

4.2. Advantages of the Coupled Multi-Model Evaluation Framework

The integrated four-step workflow overcomes two critical defects of traditional regression tools in karst research: it quantifies categorical soil/vegetation variables and detects nonlinear factor interactions that linear models ignore. This system provides a more complete interpretation of human-karst-forest coupling than single statistical methods, consistent with international progress in agroforestry habitat evaluation.

4.3. Silvicultural Implications of Habitat Suitability Zoning

Most existing karst evaluation research only constructs indicator systems without field-applicable forest management plans. This study directly links quantitative K thresholds to targeted silvicultural regimes. For dry-hot valleys with $K < 0.55$, simple single-layer afforestation results in low survival rates, which must be matched with rainwater harvesting cellars to alleviate seasonal drought stress. Multi-layer tropical agroforestry maximizes canopy shading and reduces karst soil erosion simultaneously, which can be widely promoted in high-suitability basins. The three-grade zoning standard provides quantitative spatial control thresholds for local forest administration to design rocky desertification restoration plans.

Three differentiated silvicultural pathways:

Highly suitable zones ($K \geq 0.750$): Rubber-coffee intercropping, multi-layer canopy reduces soil erosion and raises unit-area ecological and economic outputs;

Moderately suitable zones ($0.600 \leq K \leq 0.750$): Walnut-Camellia oleifera three-dimensional planting, supplemented by organic fertilizer to improve thin karst soil physicochemical properties;

Unsuitable zones ($K < 0.600$): Sparse overstory matched with shade-resistant medicinal plants, avoiding grain land competition while realizing long-term forest restoration.

4.4. Research Limitations and Future Perspectives

This study adopts static multi-year average panel data and cannot capture annual dynamic fluctuations of habitat quality caused by interannual precipitation variation.

Additionally, the current framework does not monetize carbon sequestration and soil retention ecosystem services of each agroforestry system. Follow-up research can integrate long time-series remote sensing data to track yearly habitat evolution, and couple ecosystem service valuation to further optimize karst forest silvicultural decision-making.

5. Conclusions

The development of sustainable multi-layer understory agroforestry on karst rocky desertification land is jointly constrained by interacting biophysical habitat conditions and rural socioeconomic demands. Across most karst subregions of Yunnan Province, seasonal precipitation deficit constitutes the overriding natural bottleneck limiting stand survival, soil retention and carbon sequestration capacity of tree – crop intercropping systems, while grain – forest land competition represents the dominant human-induced restriction unique to mountainous karst rural landscapes. The hierarchical influence gradient of limiting factors clarified in this study follows a clear order: natural habitat variables exert stronger control over agroforestry site quality than socioeconomic drivers, with annual precipitation ranking first, succeeded by annual mean temperature, soil type and vegetation cover. Socioeconomic constraints are sorted as grain yield, comprehensive agricultural output value, industrial production and resident population scale, which highlights that water availability and regional food security jointly shape the spatial layout potential of agroforestry under rocky desertification backgrounds.

Obvious spatial differentiation of habitat suitability exists among the seven classified agroforestry zones. Low-altitude tropical and subtropical multi-layer intercropping systems (rubber – coffee, macadamia – citrus, walnut – *Camellia oleifera*) exhibit far superior soil conservation and organic carbon sequestration performance compared with sparse single-layer forests and high-altitude medicinal underplanting modes. Tropical compound agroforestry achieves 40% higher soil carbon storage and cuts annual soil erosion by 32%, confirming that complex vertical canopy structures effectively mitigate the inherent thin-soil and seasonal drought

disadvantages of karst terrain. Such functional disparities provide quantitative support for graded, targeted vegetation restoration and agroforestry configuration across degraded karst landscapes.

This research constructs an integrated evaluation framework coupling Quantification Theory I, entropy weight method and Geodetector, which overcomes two prominent limitations of traditional karst site assessment: the failure to quantify categorical soil and vegetation attributes, and the incapacity to capture nonlinear interactions between climate and human activity factors. By combining natural ecological indicators and agricultural socioeconomic metrics into a unified three-layer evaluation system, this work enriches human – land coupling assessment theories for seasonal drought-prone subtropical karst agroforestry, and offers a replicable quantitative diagnostic workflow for analogous limestone mountain regions globally.

Although regional thermal and precipitation patterns cannot be artificially altered, targeted agroforestry silvicultural interventions can substantially relieve habitat limitations. Classified management strategies matched to three habitat suitability grades deliver actionable solutions: high-suitability tropical basins prioritize dense multi-layer intercropping to maximize dual ecological and economic gains; moderately suitable subtropical plateaus adopt walnut – oiltea camellia three-dimensional cultivation combined with organic fertilization to improve degraded karst soil properties; unsuitable high-altitude and dry-hot valley zones deploy sparse overstory trees paired with shade-tolerant medicinal plants to avoid conflicts with grain production while realizing long-term ecosystem recovery.

The zoning standards and matched site-specific agroforestry regimes generated from this work are not only applicable to vegetation rehabilitation in Yunnan’ s rocky desertification areas, but also provide transferable silvicultural references for other subtropical karst regions suffering seasonal water scarcity, including Southeast Asian limestone basins and Mediterranean dry karst mountains. Future research can integrate continuous long-term remote sensing time series to track annual dynamics of agroforestry habitat quality, and couple ecosystem service valuation modules into the existing multi-model framework to further optimize cost-effective decision-making

for sustainable karst agroforestry management.

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Conflicts of Interest

The author declares no competing financial or personal interests that could influence the work reported in this article.

Data Availability Statement

The multi-source spatial and statistical datasets supporting the results of this study can be provided by the corresponding author upon reasonable formal request.

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