

Article

Study on the Synergy/Trade-Off Relationships Between the Concentrated-Contiguous Conservation and Utilization of Traditional Villages and the Social-Ecological System Based on Network Science

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Abstract

Harmonious interactions among multiple functions form the foundation of sustainable rural development. This study proposes an innovative network-based framework to analyze the relationship between the Concentrated-Contiguous Conservation and Utilization (CCU) of traditional villages and their socio-ecological functions. An empirical analysis of 432 traditional villages in the Wuling Mountain Area of Hunan Province, China, reveals that: (1) The Concentrated-Contiguous Conservation and Utilization Network (CCUN) exhibits low density, local clustering, and limited long-distance connections, with its spatial distribution closely corresponding to forested land. (2) The socio-economic functional system is characterized by unobstructed cultural exchange, a clustered spatial pattern, transportation-dependent development, and a scattered distribution of villages with high attribute values, while the central region serves a significant ecological conservation role. (3) Correlation analysis reveals an overall low level of synergy between the CCUN and the socio-economic system. Through a role matching analysis of core villages across various networks, diverse multifunctional combinations were identified and categorized into four primary types: Coordinated Development, Conflict, Restricted, and Potential. The proposed methodological framework provides a practical tool to guide local governments in steering CCU practices toward multifunctional coordination and sustainability.

Keywords: traditional villages; Concentrated-Contiguous Conservation and Utilization; network science; social-ecological system; synergy / trade-off



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1. Introduction

As the social economy continuously transforms, the functional role of rural areas has evolved from a primary focus on agricultural production and habitation into a multifunctional paradigm integrating production, living, ecology, and culture [1–8]. Favorable economic, social, and ecological conditions, as well as harmonious interactions among these functions, are the basis for achieving sustainable rural development [1,2,4,9]. Driven by initiatives such as the Rural Revitalization Strategy, Beautiful Countryside Construction Plan, and rural tourism development, traditional villages have accelerated their multifunctional transformation [8,10]. Acting as living museums that preserve village culture and history [11–13], traditional villages take cultural inheritance as their core, integrating

production, living, and ecological functions [1,4,6,13–16]. Coordinated development among these functions is key to achieving high-quality sustainable development of traditional villages and balanced regional growth [1,9]. However, due to limited resources, fragile ecological environments, social inequality, and regional development strategies, spatial heterogeneity exists in the combination types, interaction mechanisms, and synergy levels among these multiple functions [1,2,5,7]. Therefore, to advance the sustainable development of traditional villages, it is necessary to examine the relationship between their cultural conservation practices and the social-ecological functions [15].

As a unique geographical unit in rural areas, traditional villages have attracted growing attention to their conservation practices and multifunctionality. From 2020 to 2024, the Chinese government announced 110 demonstration zones for the Concentrated-Contiguous Conservation and Utilization (CCU) of traditional villages [17,18]. Following this advancement in traditional village conservation, the focus of recent research has shifted from isolated preservation to “cluster-based” and “regional” protection [15,16,18–21], such as landscape integration [22], holistic preservation [23], and concentrated-contiguous conservation [15,16,24]. Studies on the CCU of traditional villages have been conducted from various perspectives, including relationships with surrounding resources [12,15], cluster conservation [25], social organisms [26], and regional coordination [27,28]. Topics in this area cover spatial patterns [23,24], risk assessment [16], protection system construction [20,24,28], protection zoning [12], planning methodologies [13,18,25], implementation paths and strategies [15,18,28], village landscape clusters [21], and spatial governance and control systems [19,29]. Methodologically, research has employed approaches such as value assessment [23,25], the MST clustering algorithm [12,24], network science [18], and formation mechanism analysis [21]. As can be seen from the literature above, existing CCU research has largely been confined to group traditional villages for conservation [18,24,25] or to qualitative analyses of their relationships with resources, the economy, and transportation [28]. Very few traditional village studies have focused on the relationship between CCU and the social-ecological functional system from the perspective of multifunctional development.

Since the late 1990s, multifunctionality has become a new paradigm of development for both primary industries and rural areas [7,9]. Research on rural multifunctionality focuses on its definition [8,30,31], the assessment of multifunctional levels [7,8,32,33], synergy/trade-off relationships among multiple functions [5], and the spatial pattern and spatio-temporal evolution [2]. The analytical methods adopted include mathematical models such as multi-indicator integrated evaluation [2,5,33,34], social network analysis [2], coupling coordination models [2], production possibility frontiers [2], and spatial autocorrelation analysis [35]. These studies cover scales ranging from counties, cities, and urban agglomerations to provinces, as well as typical regions such as agro-pastoral ecotones and the Loess Plateau [5]. Due to their unique role in cultural heritage preservation, the multifunctional development of traditional villages has begun to attract scholarly attention [1,6,18]. For instance, Li, Wu and Chen [1] employed a multi-indicator integrated approach and a coupling coordination model to scientifically measure the multifunctional development level and synergistic state of traditional villages. Bao and Chen [6] introduce a coupling coordination model to construct a measurable methodology for assessing the synergistic integration between functional-spatial relationships of traditional villages. However, a review of the literature reveals that while existing studies have primarily focused on the typology and formation mechanisms of rural functions at a regional scale, research specifically targeting the multifunctional development of traditional villages remains notably scarce [1,4,6,7]. Additionally, current multifunctionality research has two main limitations: (1) Studies on the interactions within the multifunctionality of tradi-

tional villages should be integrated with the practice of CCU. This is because the cultural heritage function of traditional villages is now largely realized through CCU [16]. It is necessary to align the research better with the practical needs of preserving, inheriting, and revitalizing traditional villages. (2) The multi-indicator evaluation methods designed for individual villages are inconsistent with the cluster-based conservation model for traditional villages [18]. This methodological limitation overlooks the functional interactions among traditional villages.

To fill this gap, this paper makes the following improvements and contributions: (1) It innovatively couples CCU with multifunctionality to investigate the interaction among different functions in traditional villages system; (2) Methodologically, it innovatively applies network analysis to model the complex, multi-dimensional functional interactions within a traditional village system, moving beyond single-village assessments; (3) The Wuling Mountain Area of Hunan Province has a dense distribution of traditional villages (including 6 CCU demonstration zone) and is a priority area for biodiversity conservation. The contradiction between rural tourism brought about by CCU and ecological protection is particularly pronounced in this area. Therefore, the investigation of the relationship between CCU and social-ecological systems in the Wuling Mountain Area is of greater practical urgency.

Therefore, this study aims to explore CCU practices for multifunctional coordinated development through an interaction analysis among different functions. The specific objectives of this paper are as follows: (1) to propose a network-based method framework for analyzing the relationship between the CCU and social-ecological functional systems; (2) to analyze the synergy/trade-off relationships in the Wuling Mountain Area of Hunan Province, and (3) to propose practical strategies for sustainable development of traditional villages based on their relationships. Ultimately, this paper contributes to both theory and CCU practice by offering a replicable, scalable framework for analyzing multi-dimensional functional interactions and by providing targeted guidance for CCU practices to inform multifunctional coordinated development.

2. Materials and Methods

2.1. Study Area

The Wuling Mountain Area of Hunan Province (located at 108°47′–114°15′ E, 24°38′–30°08′ N) is situated in the western part of Hunan and includes seven prefecture-level cities. It covers a total of 86,000 km² with a population of 18.91 million, approximately 34% of whom belong to ethnic minorities, primarily the Miao, Tujia, Dong, and Yao ethnic groups. By the end of 2024, the region's gross domestic product (GDP) reached 761.48 billion yuan, with a per capita GDP of 33,200 yuan. Based on the State Protection List of Traditional Villages, this study selects 432 national-level traditional villages from the first to fifth batches within this region as research objects. Density analysis reveals that Xiangxi Tujia and Miao Autonomous Prefecture have the highest density of traditional villages (Figure 1a). Since 2020, several areas, including Xiangxi Tujia and Miao Autonomous Prefecture, Rucheng County, Xupu County, Yongding District, Tongdao County, and Anhua County, have been successively designated as national CCU demonstration zone. As a key cluster of traditional villages in Hunan Province, the region is also one of the 11 contiguous poverty-stricken regions in China, making economic development and poverty alleviation priority tasks. Furthermore, the forest land area in the Wuling Mountain Area is 65,883.42 km² (Figure 1b), accounting for 76.61% of the region's total area (compared to 20.19% for cultivated land and 0.95% for construction land). This highlights the area's critical role in ecological and biodiversity conservation. Facing the dual challenges of economic development and ecological preservation, research on the relationship between

the CCU of traditional villages and social-ecological systems in this region is particularly urgent. Such studies hold significant practical value for guiding multidimensional and sustainable development in traditional villages.

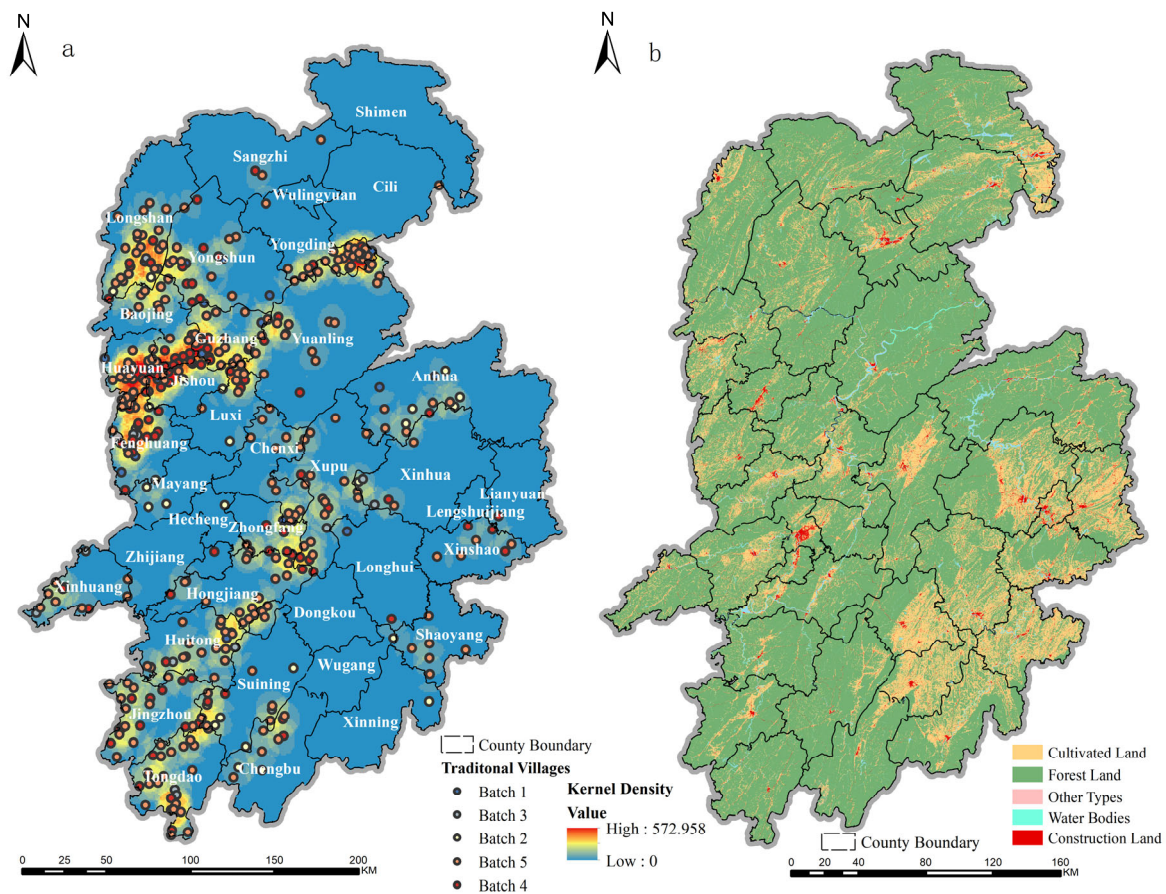


Figure 1. Distribution characteristics of traditional villages (a) and land use types of the Wuling Mountain Area of Hunan Province (b).

2.2. Data Sources and Us

The research data comprises three categories: traditional village attribute data, geospatial data, and inter-village relationship data. The data used in this study were sourced from open sources, with specific acquisition pathways detailed in Table 1. To ensure temporal consistency, all data used in this study are from 2024. Traditional village attribute data include location, ethnic composition, income, population, the list of five batches, and Baidu search volume. These attribute data were used to construct the Ethnic Relationship Network (ERN) and the Socioeconomic Network (SEN). Village location information was obtained from the Amap Open Platform (<https://lbs.amap.com/tools/picker>) (accessed on 8 June 2024). Data on ethnic composition, income, and population were sourced from the Digital Museum of Chinese Traditional Villages (<https://www.dmctv.cn>) (accessed on 15 November 2024). The data on the list of five batches were collected from the Ministry of Housing and Urban-Rural Development of the People's Republic of China (<http://www.mohurd.gov.cn>) (accessed on 8 June 2024). The Baidu search volume data were obtained from the Baidu Search Resource Platform (<https://ziyuan.baidu.com/keywords/index>) (accessed on 11 October 2025). Geospatial data comprise the Digital Elevation Model (DEM), land use data, road data, river systems data, and administrative division data. The Digital Elevation Model (DEM) data was acquired from the Geospatial Data Cloud of the Chinese Academy of Sciences (<https://www.gscloud.cn>) (accessed on 14 October 2025). Land use

data and vector data for roads, river systems, and administrative divisions were all obtained from the Resource and Environment Science and Data Center of the Chinese Academy of Sciences (<https://www.resdc.cn>) (accessed on 14 October 2025). The DEM and land use data are provided as raster layers with a resolution of 30 m. Accessibility, derived from road and land use data, was used to build the Spatial Pattern Network (SPN). Integrating this accessibility measure with the attribute data enabled the construction of the SEN. The Spatial Distribution Data of River Systems in China was used to generate the Water System Network (WSN). Furthermore, the land use data, DEM, and road data were jointly utilized to construct the Ecological Green Space Network (EGSN). The inter-village relationship data were obtained based on whether the names of two villages co-occurred in Baidu search engine results. This data primarily consists of two categories: CCU-based relationships and other co-occurrence relationships. Actual data collection revealed that co-occurrences of two traditional village names are rare, with most instances appearing in records such as those from the CCU (The Department of Housing and Urban-Rural Development of Hunan Province, available at <https://zjt.hunan.gov.cn>) (accessed on 24 October 2024) and the State Protection List of Traditional Villages. The inter-village relationship data were then used to construct the Concentrated-Contiguous Conservation and Utilization Network (CCUN).

2.3. Methods

2.3.1. Method Framework

This paper innovatively couples CCU with the social-ecological system and proposes a network-based methodological framework for analysing the synergy/trade-off relationships within the multifunctionality of traditional villages. It explores a scientific method that can be replicated and popularized to investigate the interaction among different function system of traditional villages system. Firstly, we differentially constructed six separate networks to systematically describe the CCU and social-ecological function system based on the traditional village multifunctional development system theory [1]; Secondly, correlation matrix, network analysis and bivariate spatial autocorrelation were applied to recover the synergy/trade-off relationships between CCU network and social-ecological network. The method framework of this paper is as follows (Figure 2).

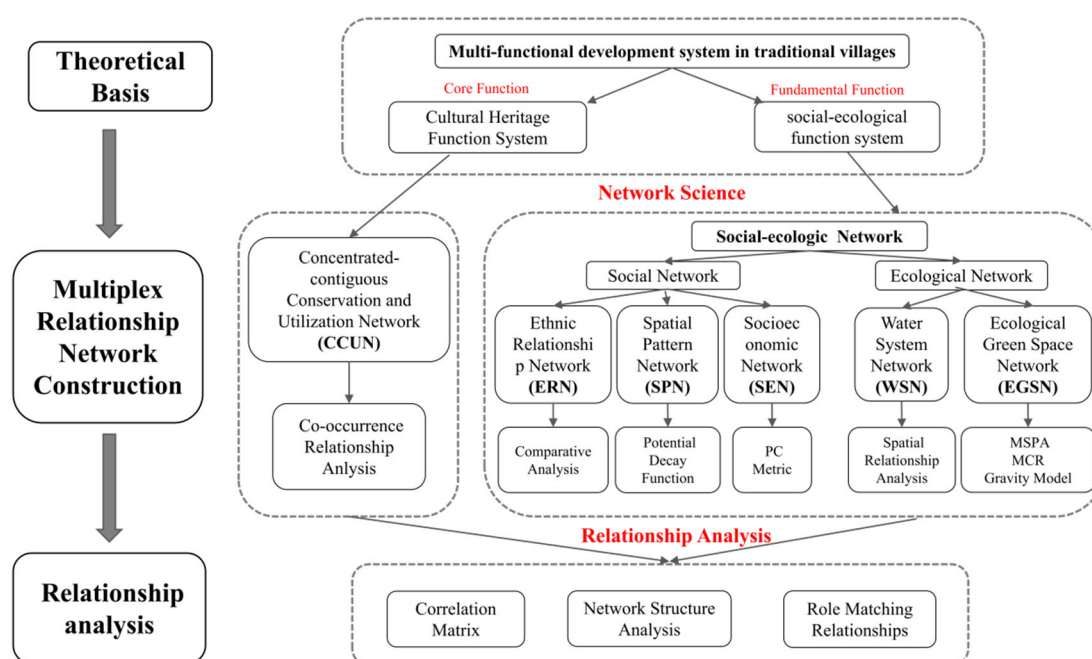


Figure 2. The network-based method framework for relationship analysis.

Table 1. Specifications of multiplex relationship networks.

Network Name	Definitions	Data Sources	Network Construction Method	Roles of Core Villages
Concentrated-Contiguous Conservation and Utilization Network (CCUN)	An undirected network with traditional villages as nodes, where an edge connects two traditional villages if their names co-occur in at least one Baidu search result.	(1) CCU-based relationship data: Department of Housing and Urban-Rural Development of Hunan Province (https://zjt.hunan.gov.cn) (accessed on 24 October 2024); (2) Other co-occurrence relationship data: Identified through co-occurrence analysis of village names in Baidu search results (http://baidu.com) (accessed on 3 December 2024).	The CCUN is constructed based on co-occurrence relationships among traditional villages through a four-step process. First, all possible pairwise combinations are generated from the 432 traditional village names through a combination tool (https://gongju.chuanxiang.net/cizu/) (accessed on 24 October 2024). A total of 432×432 combinations are ultimately obtained. Second, each pair is queried on Baidu; co-occurrence is recorded as 1, and non-co-occurrence as 0. The search revealed that co-occurrence was sparse and mainly indicated CCU relationships. Subsequently, graded scores are assigned to these CCU relationships based on the implementation progress of their respective CCU demonstration zone. The data comes from the official websites of the county governments. Finally, the network is built in two scenarios: using binary co-occurrence edges L_{ij}^1 , and using edges L_{ij}^2 weighted by implementation progress scores. $L_{ij}^1 = (1, 0)$ $L_{ij}^2 = (1, 0.8, 0.5, 0.3, 0.1, 0)$ If villages i and j co-occur in relevant documents and have been approved as part of a CCU demonstration zone with tendering for implementation, then $L_{ij}^2 = 1$. If they have only been approved but no tendering has taken place, then $L_{ij}^2 = 0.8$. If there is only project filing, then $L_{ij}^2 = 0.5$. If a demonstration zone application is planned, then $L_{ij}^2 = 0.3$. For other passive connections, such as shared conservation list inclusion, joint village surveys, or adjacency, $L_{ij}^2 = 0.1$. If the two villages do not co-occur in any relevant context, then $L_{ij}^2 = 0$.	Demonstrate active engagement and a collaborative foundation with other traditional villages.
			$L_{ij} = (1, 0)$ L_{ij} represents the probability of connection in the ERN If villages i and j belong to the same ethnic minority group, then $L_{ij} = 1$, indicating that they are likely to share language and customs, which conversely suggests a high degree of homogeneity between them. If they belong to different ethnic groups, then $L_{ij} = 0$.	Are characterized by multi-ethnic integration and serve as bridges for cultural exchange.
Social Network (SN)	Spatial Pattern Network (SPN)	Land use and road data: Resource and Environment Science and Data Centre of the Chinese Academy of Sciences (https://www.resdc.cn) (accessed on 14 October 2025).	To effectively reflect the spatial diffusion decay effect, probability connection models are commonly adopted in spatial or ecological network research [36]. In the probability connection model, the direct diffusion probability p_{ij} between traditional villages represents the likelihood or probability of direct diffusion between two villages across landscapes with different land use types [36,37], generally calculated using a potential decay function [38]. $p_{ij} = e^{\beta d_{ij}}$ P_{ij} represents the edge value in SPN, characterizing the spatial proximity relationship between villages. d_{ij} refers to the distance between traditional villages i and j , while β is a constant determined by a set of parameters p_{ij} and d_{ij} .	Exhibit high accessibility to other villages through spatial agglomeration and proximity.
	Socioeconomic Network (SEN)	Income and population data: Digital Museum of Chinese Traditional Villages (https://www.dmctv.cn) (accessed on 15 November 2024); List of Five Batches data: Ministry of Housing and Urban-Rural Development of the People's Republic of China (http://www.mohurd.gov.cn) (accessed on 8 June 2024); Baidu search volume data: Baidu Search Resource Platform (https://ziyuan.baidu.com/keywords/index) (accessed on 11 October 2025).	Considering both the attributes and accessibility of traditional villages, the Probability of Connectivity (PC) index from ecology is introduced to assess their potential for socioeconomic connectivity [34]. The attributes of a traditional village include: its designation batch (assigned a weight of 0.5), annual Baidu search volume (0.2), population (0.15), and per capita income (0.15). The attribute data were standardized using min-max normalization, and the attribute weights were determined using the Entropy Weight Method. The comprehensive attribute value for each village was then obtained through weighted synthesis. For accessibility, we employed the direct diffusion probability (P_{ij}) from the SPN framework. Furthermore, the index was modified from an overall network metric to a link-specific indicator (PC_{ij}) for constructing the socioeconomic network between villages: $PC_{ij} = \frac{a_i a_j}{a_{max}} p_{ij}$ PC_{ij} represents the strength of socioeconomic connections between traditional villages i and j ; where a_i and a_j denote comprehensive attribute values of the villages i and j . a_{max} is the maximum attribute value, and P_{ij} indicates the accessibility between villages.	Are defined by their locational advantages and high development potential.

Table 1. Cont.

Network Name		Definitions	Data Sources	Network Construction Method	Roles of Core Villages
Ecological Network (EN)	Water System Network (WSN)	An undirected binary network in which traditional villages serve as nodes. An edge exists between two villages if they are connected by a shared river.	River system spatial distribution data: Resource and Environment Science and Data Centre of the Chinese Academy of Sciences (https://www.resdc.cn) (accessed on 14 October 2025).	A water system network was established for traditional villages according to their spatial association with rivers. In this binary network, a connection (value = 1) is created between two villages if they are both proximate to and linked by a common river stretch; if not, no connection is made (value = 0). As villages do not physically occupy river channels, a 1500 m buffer search was implemented to define proximity to a river.	Are often situated near water bodies, acting as connectors for communication via the water network.
	Ecological Green Space Network (EGSN)	An ecological network, consisting of ecological sources, corridors, and nodes, alleviates spatial ecological fragmentation by effectively linking habitat patches through its corridors [39,40].	Digital Elevation Model (DEM) data: Geospatial Data Cloud of the Chinese Academy of Sciences (https://www.gscloud.cn) (accessed on 14 October 2025); Land use and road data: Resource and Environment Science and Data Centre of the Chinese Academy of Sciences (https://www.resdc.cn) (accessed on 14 October 2025).	Following the ecological network analysis framework of “source identification–resistance surface construction–corridor extraction–gravity model–two-mode matrix”, the ecological green space network of traditional villages is constructed [40]. This will be explained in detail below.	Are located within significant ecological source areas and corridors.

2.3.2. Differentiated Construction of Multiplex Relationship Networks for Traditional Villages

The traditional village system involves multiple functional relationships, including cultural heritage, socio-economic development, ecological conservation services, among others [1,18]. Currently, the cultural heritage function is systematically protected and dynamically revitalized through the CCU [24]. The network analysis method, based on graph theory and complex network theory, abstracts functional systems into a graph structure composed of nodes and connected edges, revealing the complex structure of systems [18,22]. It provides a potential tool to describe and decipher such multiple and complex functional system [17,18]. Based on graph theory, this study treats traditional villages as nodes and various functional interactions as links to construct six multiplex relationship networks. These networks focus on two crucial function systems of traditional villages: CCU relationship and social-ecological functions. The definition, data sources, construction methods, and roles of each network are detailed as follows (Table 1). For SPN, both Euclidean distance (ED) and cost distance (CD) were employed. Due to the large distances between traditional villages, automobile travel was selected as the mode of transportation. The cost-distance resistance surface was constructed in accordance with the Technical Standards for Highway Engineering and relevant literature [41,42]. The assigned resistance values for land use types under this mode are as follows: expressways offer the lowest resistance (0.75), functioning as the most efficient corridors. National, provincial, and county roads exhibit progressively higher resistance values (0.80, 1.20, and 2.00, respectively), while country roads present a significantly higher value (3.00). In contrast, construction areas (e.g., towns, settlements) permit passage with moderate resistance (4.00). Agriculture and open water act as near-absolute barriers, assigned the maximum resistance value (10,000), which effectively blocks automobile movement. Based on this resistance surface, the cumulative minimum cost distance between each village pair was calculated. Regarding the parameter β based on existing research [43], this study sets p_{ij} to 0.05 when d_{ij} equals 15, 60, and 120 min, respectively.

In detail, the construction of EGSN consists of five steps: (1) Selection of ecological sources based on morphology and landscape connectivity [40]. Ecological sources were selected using the Morphological Spatial Pattern Analysis (MSPA) method with the Guidos Toolbox 3.3 software [40]. Green spaces with an edge width of 10 m, an area $> 50 \text{ km}^2$, and a connectivity importance index (dpc) > 1 were selected as ecological sources; (2) Construction of resistance surface using five key factors, namely land use type, slope, elevation, distance to road, and MSPA landscape type (Table 2). Ecological resistance surface represents obstacles during dispersal from source areas [40]. Expert Scoring Method was used to determine the weight of each factor and calculate the comprehensive resistance value; (3) Extraction of ecologic corridors based on the Minimum Cumulative Resistance (MCR) model utilizing Linkage Mapper tool [18]. The MCR model, a fundamental method in ecological network construction, was used to select paths with smaller cumulative resistance values between ecological sources as candidate ecological corridors [40]. (4) The gravity model was introduced to perform a hierarchical importance assessment of ecological sources and corridors; (5) In the EGSN, with traditional villages as nodes, link values are defined by spatial affiliation: villages within the same ecological source are linked with a weight equal to that source's centrality. Villages in different sources are connected with a weight based on the importance of the intervening corridor. Villages situated directly on a corridor serve as "stepping stones" for the source areas at its ends. Villages with no spatial relation to any source or corridor receive a link value of 0.

Table 2. Resistance value and weight of resistance factors.

Resistance Factors	Resistance Value					Weight
	1	2	3	4	5	
Land Use Type	Cultivated land, Forest land	Grassland	Shrubland	Wetland Water, body	Construction land, Bare land	0.26
Slope (°)	<8	8–15	15–25	25–35	>35	0.21
Elevation (m)	<300	300–500	500–1000	1000–1500	>1500	0.13
Distance to Road (m)	<800	800–2000	2000–3000	3000–5000	>5000	0.20
MSPA Landscape Type	Core Area	Bridge, Loop	Branch Islet	Edge	Perforation Background	0.20

2.3.3. Analysis of Synergy/Trade-Off Relationships Between CCUN and Social-Ecological Networks

Correlation Matrix

Correlation analysis has been widely applied to measure synergy/trade-off interactions between functions [44,45]. First, correlations between each pair of networks were quantified, employing the Quadratic Assignment Procedure (QAP) Test [37]. The QAP Test is used to compare the similarity of each lattice value in two square matrices or networks [18]. Specifically, it compares each lattice value of the matrices, computes correlation coefficients between them, and performs non-parametric tests on these coefficients [41]. A positive correlation coefficient indicates a synergistic relationship, whereas a negative one suggests a trade-off. Second, to characterize the overall relationship between the CCU network and the social-ecological networks, the average of their correlation coefficients was computed.

$$\mathbf{R} = \begin{bmatrix} r_{cc} & r_{cer} & r_{csp} & r_{cse} & r_{cw} & r_{ceg} \\ r_{erc} & r_{ever} & r_{ersp} & r_{erse} & r_{erw} & r_{ereg} \\ r_{spc} & r_{sper} & r_{spsp} & r_{spse} & r_{spw} & r_{speg} \\ r_{sec} & r_{seer} & r_{sesp} & r_{sese} & r_{sew} & r_{seeg} \\ r_{wc} & r_{wer} & r_{wsp} & r_{wse} & r_{ww} & r_{weg} \\ r_{egc} & r_{eger} & r_{egsp} & r_{egse} & r_{egw} & r_{egeg} \end{bmatrix}$$

where r_{ij} represents the correlation coefficient between network i and j . Here, i and j can, respectively, represent different types of traditional village networks (e.g., CCUN, ERN, SPN, SEN, WSN, EGSN).

Network Structure Analysis

This study employs six network-level structural metrics to characterize the features of different networks. Through comparative analysis of these metrics, potential synergistic or trade-off relationships between CCUN and the social-ecological network are explored. Density is the proportion of actual edges to the maximum possible number of edges in a network [45]. A high density value indicates a dense network, whereas a low value suggests a sparse network. Clustering Coefficient is defined as the probability that two neighbors of a node are also directly connected to each other [17]. A high global clustering coefficient indicates a strong tendency for transitivity among nodes [46]. Average Shortest Path Length is used to measure the efficiency of information flow within a network [46]. Component refers to a subgraph in which all nodes are connected internally, with no connections to nodes in other components [47]. The metric (number of components) serves to identify how many subgroups of traditional villages exist [18]. The degree and betweenness

centralization measure the extent to which a network's structure revolves around one or a few central nodes, quantifying the overall centralization level of the network.

Role Matching Relationships

This analysis evaluates the spatial matching between core traditional villages across functional networks. Core-periphery analysis first identifies core villages in each network, followed by bivariate spatial autocorrelation to examine the spatial matching between CCUN and socio-ecological network cores, thereby revealing synergy / trade-off between CCU and the social-ecological system.

(1) Core-Periphery Structure

The core-periphery structure, a model in social network analysis, describes actor positions by distinguishing between two main types: core and peripheral actors [40]. Applying this structural analysis to traditional villages reveals their relative position and importance within a specific network, which in turn indicates the significance of their role in the corresponding functional system.

(2) Bivariate Spatial Autocorrelation

Bivariate spatial autocorrelation, which measures the correlation between two variables across neighboring spatial units, is highly effective for characterizing spatial interdependencies [44]. Accordingly, this study applies this method via GeoDa 1.22 software to analyze the spatial matching of core traditional villages across various functional networks. The analysis delineates five patterns of spatial association: High-High areas, Low-Low areas, High-Low areas, Low-High areas, and non-significant areas.

3. Results

3.1. Result of CCUN Construction

Since search results for "Village A Village B" and "Village B Village A" are identical, a total of 93,096 Baidu searches were conducted, resulting in 2310 co-occurrence records (accounting for 2.48% of the total) and 2084 CCU relationships. Apart from CCU relationships, 226 co-occurrence relationships originated primarily from sources such as the National List for the Protection and Development of Ethnic Minority Villages with Distinctive Features during the 12th Five-Year Plan Period (2011–2015 year), the Holistic Protection of 28 Ancient Villages in Hunan (2014), the Jishou Comprehensive Tourism Plan (2022), and tourism linkage initiatives. Analysis of the co-occurrence data revealed that the concept of collaborative development among traditional villages began to develop significantly after the introduction of CCU (post-2020), whereas isolated development models were more common previously.

We perform a visual analysis of the CCUN using ArcGIS 10.2. To avoid redundancy, only the more informative weighted CCUN is shown here (Figure 3a). Spatial analysis reveals that collaborative development among traditional villages occurs mainly between nearby villages or within their respective CCU demonstration zone. Nationally, CCU practices for traditional villages are implemented with county-level administrative units (counties/districts) as the basic planning units. Within the study area, 18 county-level units have initiated or planned contiguous conservation planning, accounting for 49% of the total area. These units are mainly distributed in the central part of the area, largely overlapping with forested areas. This spatial correlation largely originates from the formation mechanism of traditional villages: forested land constrains inter-village accessibility, and lower accessibility leads to lower development intensity, which in turn minimizes encroachment on traditional village clusters. The emergence of such clusters subsequently provides a core prerequisite for designating CCU demonstration zone.

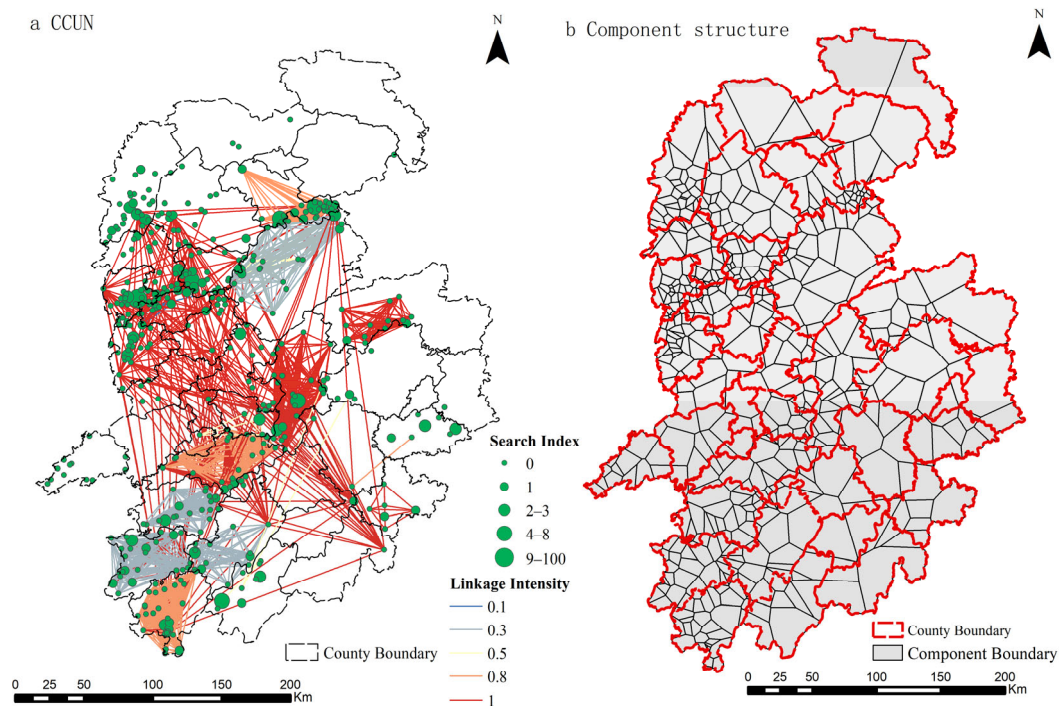


Figure 3. CCUN: network visualization (a) and component structure (b).

Is there potential for comprehensive cross-county and regional development in this area? The answer is yes, primarily thanks to the 226 long-distance cross-county, initiative-driven connections mainly established by 2014 policy of the Holistic Protection of 28 Ancient Villages in Hunan. This has effectively broken the constraints of administrative boundaries within the CCU framework, providing a vital foundation for regional collaboration among traditional villages. It thereby offers more diverse, multifunctional options for combined development models for traditional villages.

A component refers to a subgraph in which nodes within the subgraph are connected, while connections between different components are absent [41]. Component analysis (Figure 3b) reveals three distinct development statuses of traditional villages within the CCUN: (1) A total of 170 traditional villages, including those in Xiangxi, Yongding, Hongjiang, Huitong, and Tongdao, collaborate to form the largest cross-regional component, encompassing 40% of all villages in the region. (2) Villages in Yuanling, Xupu, and Anhua are internally agglomerated but lack cross-regional connections due to administrative boundaries. (3) Villages in peripheral counties, such as northern Zhangjiajie, all counties in Loudi, Chengbu, and western Huaihua, develop in relative isolation, exhibiting insufficient capacity for internal and external linkages.

3.2. Results of Social-Ecological Network Construction

3.2.1. Result of ERN Construction

The Wuling Mountain Area of Hunan Province is a typical ethnic minority settlement area. Among its 432 traditional villages, there are 365 villages inhabited by single ethnic groups: Miao (132 villages, 30.56%), Yao (16 villages, 3.7%), Tujia (85 villages, 19.68%), and Dong (49 villages, 11.34%), as well as 67 multi-ethnic traditional villages. Based on the ethnic homology among traditional villages, a binary Ethnic Relation Network (ERN) was constructed (Figure 4a). Network visualization reveals that unimpeded cultural exchange and information sharing are possible across the entire region. This is primarily because all traditional villages are directly or indirectly connected to others through Han or multi-ethnic villages, resulting in no isolated villages (a single component). Examining ethnic

types, traditional villages with Han residents number 109 and are distributed across the entire study area (Figure 4d). Comparing the spatial influence ranges of different ethnic groups shows the following order: Han > Miao > Tujia > Dong > Yao. Spatially, the Miao are primarily connected to the western part of the area, the Tujia to the north, the Dong to the south, and the Yao to the central region (Figure 4b,c,e,f). When the Han ethnicity is excluded from the analysis, a western component composed of 351 ethnic minority villages emerges, accounting for 81% of all villages (Figure 4g). This indicates that unimpeded communication among these 351 villages is facilitated by multi-ethnic villages acting as bridges. The eastern Loudi region contains 81 isolated traditional villages, characterized by a Han population that remains connected to other villages through ties with Han residents in the ethnic minority cluster.

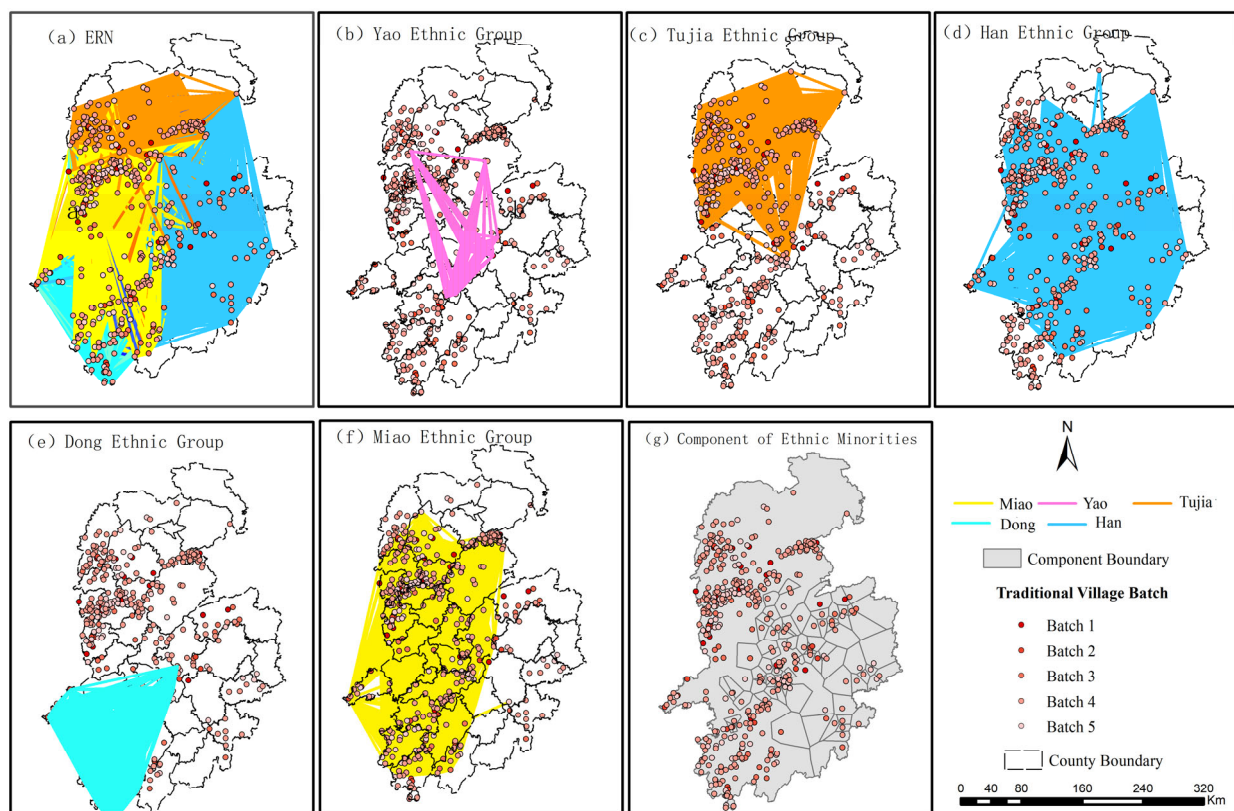


Figure 4. The ERN including: (a) all ethnic groups; (b–f) individual ethnic groups; and (g) components formed by ethnic minorities.

3.2.2. Result of SPN Construction

Based on the potential decay function, the SPN of the Wuling Mountain Area in Hunan Province was constructed (Figure 5a–d) to characterize the adjacency and spatial clustering relationships among traditional villages. Four SPNs were ultimately constructed under multiple scenarios involving different distance types (Euclidean distance or cost distance) and thresholds (15, 60, and 120 min). Due to space limitations, only two networks are displayed here. Construction using Euclidean distance (ED) (Figure 5a,b) revealed the formation of two spatially short-distance clustered village groups in the study area. The first and largest cluster comprises 215 villages in Xiangxi and Zhangjiajie, accounting for 50% of the total. The second is a well-connected, chain-like cluster formed by 150 traditional villages in Tongdao, Jingzhou, Huitong, Hongjiang, Chenxi, and Xupu through spatial correlations, representing 35% of the total.

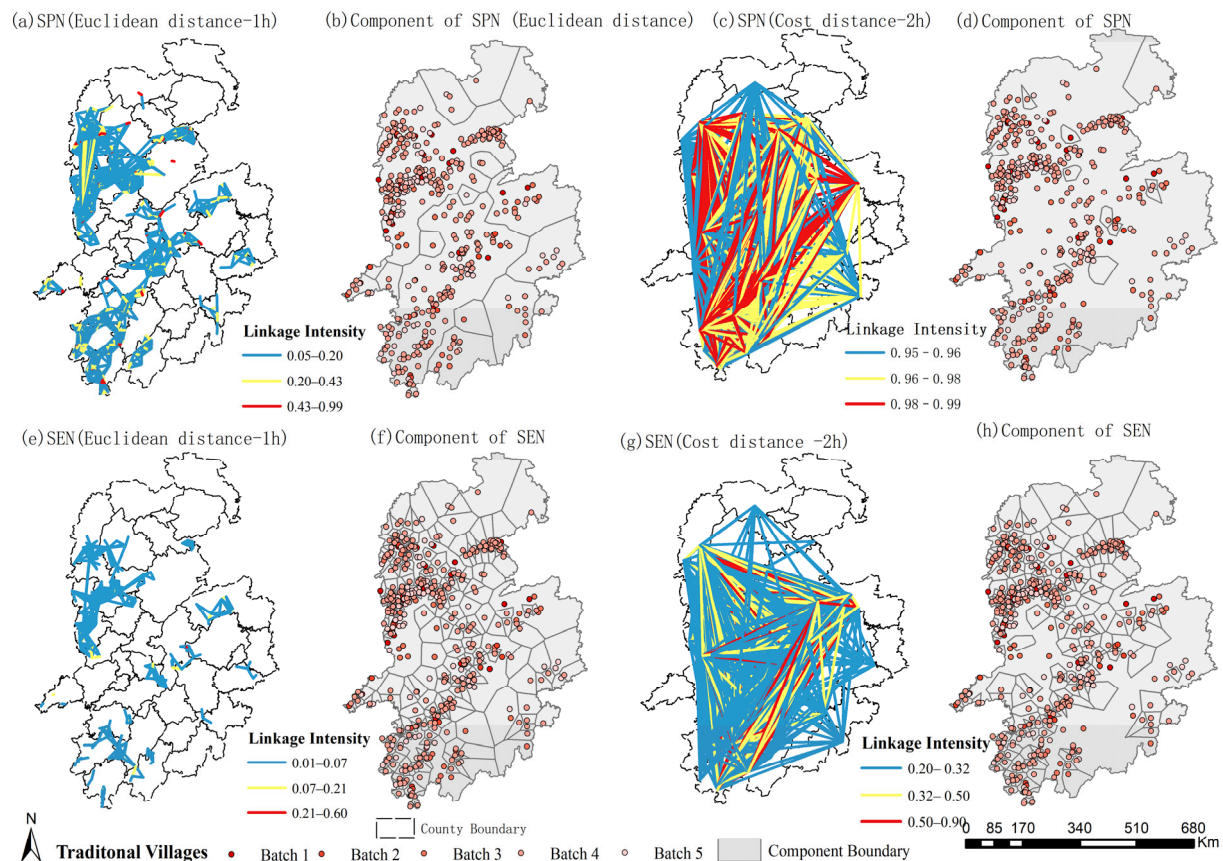


Figure 5. The SPN and SEN under different scenarios: (a,c,e,g) visualizations and (b,d,f,h) component structures.

In contrast, the network constructed using cost distance (CD) (Figure 5c,d) is characterized by long-distance connections and the presence of internally isolated villages. The existing road network efficiently facilitates these long-distance connections, linking 415 (96%) of the area's traditional villages. However, some villages located in the central forested regions suffer from poor accessibility, exhibiting a prominent “isolated island” effect.

3.2.3. Result of SEN Construction

By comprehensively considering the attributes of traditional villages (designation batch, population, income, Baidu search volume) and their accessibility, SENs for the Wuling Mountain Area of Hunan were constructed under different scenarios (inherited from the SPN framework) using a modified Potential Connectivity (PC) index (Figure 5e–h). Again, only two representative networks are illustrated here. As shown in Figures 4f and 5e, the SEN (ED) exhibits eight distinct spatial clusters over short distances. Each cluster is centered around villages with high composite attribute values (e.g., Fenghuang, Shibadong, Dehang, Reba, Laosiyang, Lüdong, Gaoyi, and Huangdu), which demonstrate significant cultural heritage value and broad public recognition. When the role of road transport is incorporated (Figure 5g,h), long-distance connectivity is notably enhanced. However, connectivity within the central forested area remains poor, maintaining an isolated state. This indicates that villages in this region are characterized by both low accessibility and low development potential. Compared to the SPN, the connectivity within the SEN is markedly reduced when socio-ecological attributes are factored in. This attenuation primarily results from a spatial mismatch: high adjacency does not necessarily correspond to high attribute values. For instance, two traditional villages may be spatially proximate, yet if both possess low attribute values, their connectivity within the SEN will be correspondingly low.

3.2.4. Result of WSN Construction

Using a search radius of 1500 m, 153 traditional villages spatially adjacent to water bodies were identified. Taking these villages as nodes and linear rivers as connecting edges, a binary water system network (WSN) was constructed (Figure 6a). As shown in Figure 6a, this network exhibits low connectivity, with only 145 connecting edges. Furthermore, due to its reliance on rivers, it displays distinct linear linkage characteristics. The low density (Figure 6a) of WSN reveals that the connectivity function of the water system is not prominent, although the formation and distribution of traditional villages are spatially associated with water. Moreover, the WSN shows a high degree of spatial coupling with watershed boundaries, while the threshold effects of administrative divisions and spatial distance have limited influence on it. A comparison among different water systems indicates that the interaction between villages in the Yuanshui River system is more significant. Importantly, beyond connectivity, we must consider how ecological disruptions arising from traditional village tourism are transmitted via the water network.

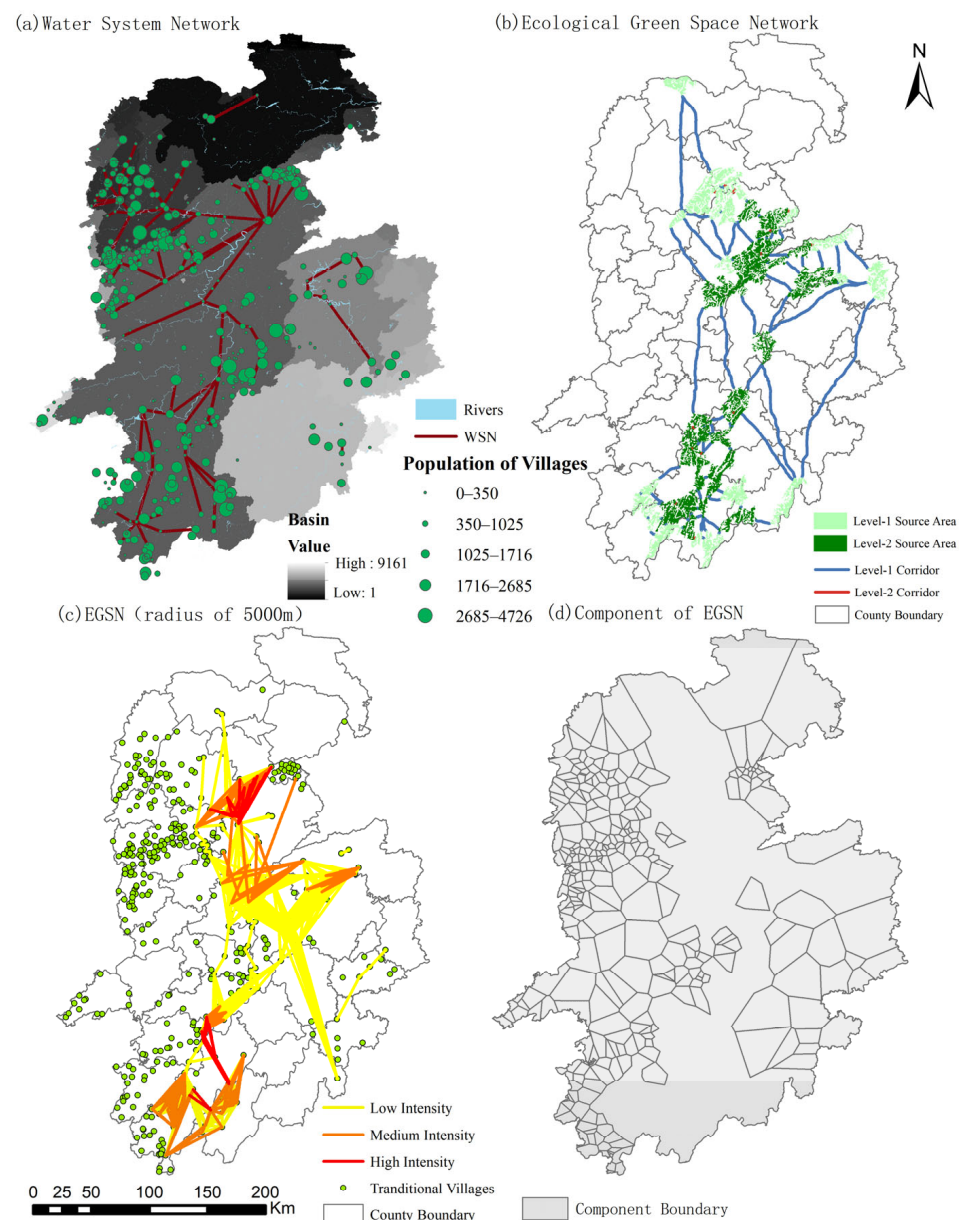


Figure 6. (a) WSN; (b,c) EGSN with ecological sources (b) and traditional villages (c) as nodes, respectively; (d) component structure of the EGSN.

3.2.5. Result of EGSN Construction

Based on the ecological network framework, the EGSN in the Wuling Mountain Area of Hunan Province was constructed (Figure 6c). Traditional villages located within the search radius (1500 m, 5000 m) of ecological sources and corridors were identified as nodes in the EGSN, with spatial affiliation relationships as edges. (1) Ecological Sources: These are mainly distributed in central areas such as Yuanling, Chenxi, Anhua, Xupu, Dongkou, Suining, and Chengbu (Figure 6b). (2) Ecological Resistance: High-resistance areas are associated with urban zones and major transportation routes. For example, large built-up areas such as Hecheng, Wugang, and Lianyuan experience high ecological pressure, which tends to impede species dispersal (Figure 6b). (3) EGSN with ecological sources as nodes; the northern, eastern, and southern regions are connected via long-distance ecological corridors. This area plays a critical role in ecological migration and energy exchange. The network closure α index is 0.60, the average connectivity β index is 2.12, and the γ index (ratio of actual corridor quantity to maximum possible corridor quantity) is 0.74. These indicators collectively indicate smooth species migration and a robust network structure in the study area. (4) EGSN with traditional villages as nodes (Figure 6c); the linkages and exchanges between the southern and northern regions are more pronounced. Traditional villages in the central region, particularly those in Yongding and Hongjiang, assume a highly important role in ecological energy exchange. A crucial species migration component has formed, comprising 126 traditional villages (30% of the total) across Yongding, Yuanling, Xupu, Hongjiang, Chengbu, and Jingjiang (Figure 6d).

3.3. Result of Relationship Analysis

3.3.1. Correlation Matrix

We used a correlation matrix to determine whether relationships exist between the CCUN and socio-ecological networks and, if so, whether they represent trade-offs or synergies (Table 3). QAP correlation analysis revealed that the CCUN is correlated with the socio-ecological system, showing an overall low-level synergistic correlation (mean $r = 0.14$). Specifically, the CCUN exhibited correlations with village spatial proximity ($r_{csp} = 0.31$), ethnic relationships ($r_{cer} = 0.13$), socio-economic linkages ($r_{cse} = 0.12$), water system relationships ($r_{cw} = 0.07$), and ecological green space distribution ($r_{ceg} = 0.12$). This suggests that traditional villages within the CCUN possess modest multifunctionality, integrating spatial proximity, ethnic diversity, high attribute values, and ecological conservation values. Current CCU practices in the area are mainly organized within administrative boundaries, which inherently emphasizes spatial proximity. This proximity thus becomes a core advantage for the clustered development of traditional villages within the region. Due to the spatial mismatch between proximity-based clustering and villages of high attribute value, the synergy strength between the CCUN and the SEN ($r_{cse} = 0.12$) is significantly lower than that between the CCUN and the SPN ($r_{csp} = 0.31$). Comparing correlation coefficients between the CCUN constructed with different weighting schemes (binary vs. weighted) revealed no significant variation (mean $r = 0.14$ in both cases). This indicates that the results are not sensitive to the specific weighting of the CCUN. Therefore, subsequent analyses focus on weighted networks, which contain richer information.

Differences in the relationships between the CCUN and various social-ecological networks were not pronounced (Coefficient of Variation = 0.65), especially compared with the SPN (CD) ($CV = 1.39$) and SEN (CD) ($CV = 1.28$). This is mainly because, aside from maintaining strong spatial proximity with traditional villages ($r_{csp} = 0.31$), the CCUN sustains a similar correlation level with other functions ($r_{cer} = 0.13$, $r_{cse} = 0.12$, $r_{ceg} = 0.12$). The high variation in SPN (CD) is primarily due to its limited number of statistically significant correlation coefficients. SEN (ED-1 h) and SEN (CD) exhibit a three-tier variation pattern.

The first tier arises from the computation method, showing a relative high correlation with accessibility ($r = 0.34$), a moderate correlation with the CCUN and ERN ($r \approx 0.1$), and a near-zero correlation with the ecological network ($r = 0$). This indicates that traditional villages with high attribute values generally do not coincide with those of high ecological functionality.

Table 3. QAP correlation coefficient matrix.

Network Name		CCUN (Weighted)	CCUN (Binary)	ERN	SPN (ED-1 h)	SPN (CD)	SEN (ED-1 h)	SEN (CD)	WSN	EGSN (Search Radius: 5000 m)	Mean	CV
CCUN (Weighted)	QAP	1.00	0.94	0.13	0.31	0.01	0.12	0.07	0.07	0.12	0.14	0.65
	<i>p</i> -value	--	0.00	0.00	0.00	0.09	0.00	0.00	0.00	0.00		
CCUN (Binary)	QAP	0.94	1.00	0.13	0.33	0.02	0.15	0.05	0.07	0.12	0.14	0.65
	<i>p</i> -value	0.00	--	0.00	0.00	0.09	0.00	0.00	0.00	0.00		
ERN	QAP	0.13	0.13	1.00	0.16	−0.01	0.04	0.02	0.04	0.07	0.09	0.64
	<i>p</i> -value	0.00	0.00	--	0.00	0.38	0.00	0.17	0.00	0.00		
SPN (ED-1 h)	QAP	0.31	0.33	0.16	1.00	0.03	0.34	0.01	0.06	0.15	0.15	0.86
	<i>p</i> -value	0.00	0.00	0.00	--	0.00	0.00	0.01	0.00	0.00		
SPN (CD)	QAP	0.01	0.02	0.01	0.03	1.00	0.02	0.34	0.00	0.01	0.13	1.39
	<i>p</i> -value	0.09	0.00	0.38	0.00	--	0.00	0.00	0.48	0.10		
SEN (ED-1 h)	QAP	0.12	0.15	0.04	0.34	0.02	1.00	0.10	0.00	0.03	0.11	1.12
	<i>p</i> -value	0.00	0.00	0.00	0.00	0.00	--	0.00	0.17	0.00		
SEN (CD)	QAP	0.07	0.05	0.02	0.01	0.34	0.10	1.00	0.01	0.00	0.11	1.28
	<i>p</i> -value	0.00	0.00	0.17	0.01	0.00	0.00	--	0.05	0.27		
WSN	QAP	0.07	0.07	0.04	0.06	0.00	0.00	0.01	1.00	0.01	0.04	0.76
	<i>p</i> -value	0.00	0.00	0.00	0.00	0.48	0.17	0.05	--	0.01		
EGSN (Search radius: 5000 m)	QAP	0.12	0.12	0.07	0.15	0.01	0.03	0.00	0.01	1.00	0.08	0.78
	<i>p</i> -value	0.00	0.00	0.00	0.00	0.10	0.00	0.27	0.01	0.00		

Regarding the relationships among socio-ecological systems, correlation analysis revealed that the ERN ($r_{ersp} = 0.16$), SEN ($r_{spse} = 0.34$), and EGSN ($r_{rspeg} = 0.15$) all showed some correlation with the SPN (mean $r = 0.15$). However, networks such as the ERN (mean $r = 0.09$), WSN (mean $r = 0.04$), and EGSN (mean $r = 0.08$) generally exhibited weak functional interactions with others, suggesting a lack of pronounced collaborative integration across these different systems. This suggests that in this region, the overlap and conflict between the socio-economic functions (high accessibility, high recognition, high cultural value) and the ecological function (high ecological importance) of traditional villages are not substantial.

3.3.2. Network Structure Analysis

In this section, we analyze the synergy/trade-off relationships from the perspective of network structure using six network-level metrics (Table 4). Regarding network characteristics, the CCUN forms a typical structure characterized by high clustering (Average Clustering Coefficient = 0.96) and a lack of long-distance connections (low density = 0.02). This indicates that despite the presence of 226 long-distance, cross-county, initiative-driven connections [39,46] (Figure 2), its overall cross-regional collaborative connectivity remains limited. The CCUN exhibits a low degree of centralization (Degree Centralization = 0.08; Betweenness Centralization = 0.08), suggesting a relatively balanced structure without significant power concentration in a few specific villages. The ERN is highly integrated (Average Clustering Coefficient = 0.92, Number of Components = 1) and efficient (Average Path Length = 1.64), indicating that communication through Han and multi-ethnic villages can occur seamlessly across the region [30]. The SPN forms large, multi-member clusters (Number of Components = 3) with high efficiency (Average Clustering Coefficient = 0.91) through short-distance links, although these clusters are spatially dispersed (Density = 0.02). Multi-scenario threshold analysis (15, 60, and 120 min) showed that as the threshold increases, the network connectivity improves, and the number of isolated villages decreases sharply (Table 4). When the threshold is extended to 2 h, all

traditional villages in the area achieve comprehensive spatial interconnection, with the exception of just two remaining isolated villages. When road conditions are considered, long-distance connections increase significantly (Density = 0.21), accessibility improves markedly (Average Path Length = 1.30), and certain villages gain distinct advantages (Degree Centralization = 0.25). Other networks, namely the SEN and EGSN, demonstrate varying degrees of fragmentation (Number of Components = 237, 303), low connectivity (Density $\approx$ 0), and clustering features (Average Clustering Coefficient = 0.88, 0.69). The water system network (WSN) is the most loosely connected (Density = 0, Average Clustering Coefficient = 0), with no pronounced connectivity pattern.

Table 4. Overall network characteristics of traditional village systems.

Network Type	Density	Average Clustering Coefficient	Average Path Length	Number of Components	Degree Centralization	Betweenness Centralization
CCUN	0.02	0.96	2.92	174	0.08	0.04
ERN	0.37	0.92	1.64	1	0.48	0.05
SPN (ED-15 min)	0.00	0.58	2.30	244	0.00	0.35
SPN (ED-1 h)	0.01	0.70	5.54	17	0.01	0.06
SPN (ED-2 h)	0.02	0.74	5.02	3	0.03	0.18
SPN (CD)	0.21	0.91	1.30	18	0.25	0.01
SEN (ED-15 min)	0.00	0.60	1.10	414	0.00	0.00
SEN (ED-1 h)	0.00	0.68	2.12	338	0.01	0.00
SEN (ED-2 h)	0.00	0.73	3.63	276	0.01	0.02
SEN (CD)	0.01	0.88	1.74	237	0.10	0.02
WSN	0.00	0.00	2.90	344	0.01	0.00
EGSN (Search radius: 1500 m)	0.00	0.69	4.65	361	0.02	0.01
EGSN (Search radius: 5000 m)	0.00	0.64	5.69	303	0.03	0.04

Regarding relationships, the CCUN exhibits both synergistic and trade-off relationships with other networks. Synergies are observed primarily between the CCUN and the ERN, SPN, EGSN, and WSN. The ERN, which enables barrier-free linguistic and cultural communication across the region (Number of Components = 1), provides an essential foundation for promoting county-level or cross-county development of the CCUN. The clustered distribution of traditional villages (Number of Components = 3, Average Clustering Coefficient = 0.91 of SPN) and favorable transportation conditions (Density = 0.21 of SPN-CD) serve as prerequisites for the concentrated and contiguous development of traditional villages. The low connectivity (Density $\approx$ 0) and high fragmentation of the EGSN (Number of Components = 303) indicate that only a subset of villages carries significant ecological functions, which greatly reduces potential conflicts between village utilization and ecological conservation. A similar logic applies to the water system network.

Trade-offs may primarily exist between the CCUN and the socio-economic networks. Compared to the SPN, the SEN exhibits extremely low connection density (density $\approx$ 0) and increased network fragmentation (number of components > 237) across all scenarios. This indicates that connectivity becomes significantly weaker when nodal attributes are taken into account. It further suggests that few traditional villages simultaneously possess both spatial proximity and high socio-economic attributes (e.g., income, population, designation batch, Baidu search volume). Consequently, the CCUN—confined mainly within county-level boundaries—cannot be effectively driven by interactions among high-attribute villages. This is also a key issue that must be prioritized in the future CCU planning and development of traditional village.

3.3.3. Role Matching Relationship Analysis

This section evaluates the spatial matching of core traditional villages across functional networks to reveal the synergies and trade-offs between CCU and the social-ecological system.

First, the core traditional villages in each network were identified through core-periphery structure analysis. In detail, given the redundancy with the bivariate spatial autocorrelation results, only the kernel density analysis results for the core villages from the most representative CCUN (Figure 7a) and EGSN (Figure 7b) networks are displayed here. The core-ness values were summarized by region to inform CCU practices for each partition (Table 5). As shown in Figure 7a and Table 5, the core villages for CCUN are primarily distributed in Tongdao (total core-ness = 4.06), Yongding (1.90), Xupu (1.18), Hongjiang (1.04), and parts of Xiangxi (e.g., Fenghuang 0.32, Guzhang 0.27, Jishou 0.21, Huayuan 0.20). The core of the ethnic relation network is mainly located in Xiangxi (Huayuan 1.97, Fenghuang 1.40, Guzhang 1.33), Jingzhou (1.26), and Baojing (1.12) (Table 5). This suggests that some traditional villages in this area exhibit multi-ethnic integration features and serve as bridges connecting other single-ethnic villages. Analysis of the SPN (ED) reveals that traditional villages in Xiangxi (Huayuan 1.35, Jishou 1.46, Baojing 1.22, Guzhang 0.78, Fenghuang 0.68, Longshan 0.68), Yongding (1.22), and Tongdao (0.48) occupy core positions. This indicates a pronounced clustered distribution pattern of traditional villages in the region. According to the SPN (CD), the road accessibility has significantly improved in Huayuan (1.35), Tongdao (1.30), Yongding (1.16), Huitong (1.13), and Longshan (1.05). The analysis of SEN (ED) identifies spatially clustered villages with high attribute values in Xiangxi (e.g., Fenghuang 1.65, Longshan 1.58, Jishou 1.03, Huayuan 0.93) and Baojing (0.76), indicating a solid foundation for CCU development. Meanwhile, the SEN (CD) highlights that Longshan (1.97), Huayuan (1.26), and Tongdao (1.14) combine favorable transportation with high-attribute villages, demonstrating potential for cross-regional synergistic development. The water network core is situated near the You River in Longshan (2.03) and Baojing (0.97), and near the Yuan River in Huitong (0.83) and Hongjiang (0.71). These areas exhibit strong hydrological connectivity, serving dual roles in transportation and water environment conservation. The ecological core is distributed across Chenxi (1.34), Xupu (1.15), Yuanling (1.02), Yongding (0.84), Suining (0.57), and Anhua (0.55) (Figure 7b, Table 5), suggesting this zone plays a crucial role in ecological migration and energy exchange.

Then, we used bivariate spatial autocorrelation analysis to examine the spatial matching between core villages in the CCUN and other networks (Figure 7c–i). The analysis between the CCUN and the ERN shows that CCU practices in Xiangxi (e.g., Huayuan, Jishou, Guzhang), Yongding, Xupu, Jingzhou, Suining, and Tongdao exhibit multi-ethnic attributes (H–H, 62 pixels). These areas possess rich multi-ethnic characteristics and have potential for cross-regional cultural exchange. This diversity can provide villages with distinct thematic focuses and development pathways. In contrast, core villages of the CCUN in Anhua (H–L, 40 pixels) are mostly single-ethnic and have limited cultural exchange with other groups, which hinders cross-regional collaboration. Regarding the SPN (ED), core villages of the CCUN in Xiangxi (e.g., Huayuan, Jishou, Guzhang, Longshan) and Yongding show a clustered distribution (H–H, 38 pixels). This indicates a solid foundation for CCU development, enabling potential collaboration among a large number of traditional villages. Conversely, core villages of the CCUN in Huitong and Anhua are dispersed (H–L, 40 pixels). For these areas, a key focus of CCU practice should be facilitating efficient interaction and connectivity among the separate villages. Analysis of the SPN (CD) reveals that the G65 highway, which passes through Tongdao, Suining, Huitong, Hongjiang, and Xupu, and the G352 highway, which connects Huayuan, Jishou, Guzhang, and Yongding, significantly enhance the accessibility of core CCUN traditional villages (H–H, 66 pixels).

These two transport routes create potential for cross-regional CCU cooperation across the entire area. For the SEN (ED), core villages of the CCUN in Xiangxi (e.g., Fenghuang, Huayuan, Jishou, Guzhang, Longshan), Yongding, and Tongdao show both a clustered distribution and high attribute values (H–H, 40 pixels). These are the areas with the highest potential for optimal socio-economic development. In contrast, core villages in Anhua and Huitong (H–L, 40 pixels) are spatially dispersed and lack high-attribute villages, making it difficult to drive sustainable CCU development. Analysis via the SEN (CD) shows that some core villages of the CCUN along the two key highways also show high attribute values. These villages play a crucial bridging role in forming cross-county and cross-regional CCU relationships (H–H, 78 pixels). Furthermore, road connectivity effectively mitigates the problem of scattered village distribution in Huitong. The L–H area (394 pixels) has good transport conditions and high-attribute villages, indicating potential for further CCU development. Anhua exhibits a mix of both L–H and H–L patterns, showing clear overall trade-off characteristics.

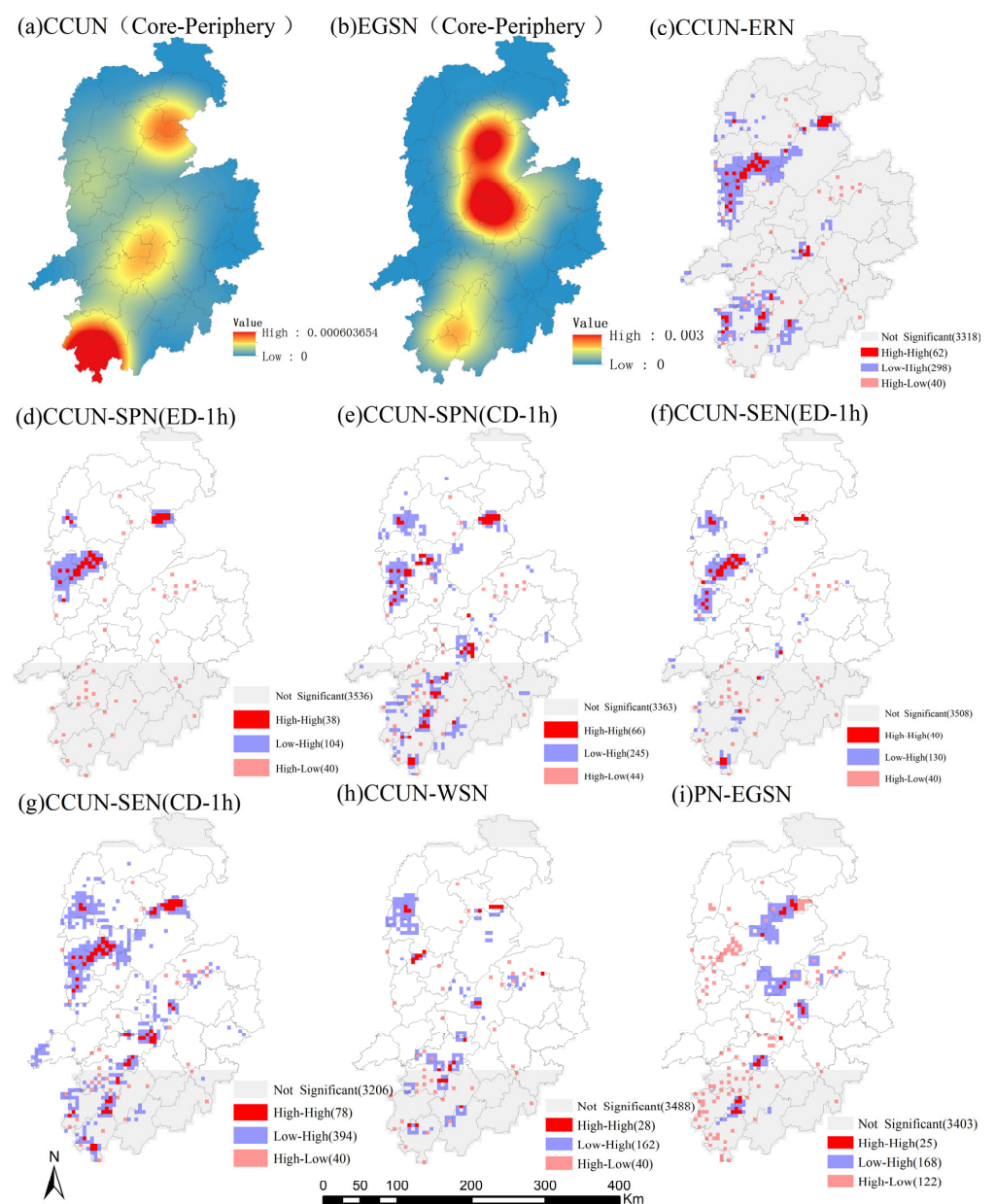


Figure 7. Core-periphery structure of the CCUN (a) and EGSN (b), and bivariate spatial autocorrelation analysis of core villages between networks (c–i).

Table 5. County-Level Total Coreness of Different Networks.

County	No. of Villages	Avg. Monthly Baidu Search Index	Population	CCUN	ERN	Total Coreness by Network Type				WSN	ERGN (5000 m)
						SPN (ED-1 h)	SPN (CD)	SEN (ED-1 h)	SEN (CD)		
Tongdao	28	1173	23,817	4.06	0.62	0.25	1.30	0.47	1.14	0.49	0.38
Yongding	25	3042	14,706	1.90	0.89	1.22	1.16	0.29	0.98	0.44	0.84
Xupu	20	2147	25,136	1.18	0.67	0.07	0.64	0.23	0.78	0.42	1.15
Hongjiang	22	583	9347	1.04	0.62	0.11	0.61	0.26	0.88	0.71	0.36
Fenghuang	22	891	14,711	0.32	1.40	0.68	0.85	1.65	0.97	0.08	0.00
Guzhang	24	2802	20,643	0.27	1.33	0.78	0.63	0.41	0.94	0.19	0.32
Jishou	14	792	5996	0.21	0.85	1.46	0.56	1.03	0.58	0.21	0.00
Huayuan	31	25,833	20,400	0.20	1.97	3.71	1.35	0.93	1.26	0.41	0.00
Huitong	20	857	14,113	0.14	0.88	0.09	1.13	0.26	0.78	0.83	0.13
Suining County	13	1282	20,932	0.14	0.82	0.04	0.77	0.25	0.54	0.35	0.57
Jingzhou	23	1488	18,354	0.13	1.26	0.07	0.78	0.26	0.90	0.10	0.20
Anhua	13	451	12,796	0.12	0.42	0.01	0.39	0.20	0.51	0.41	0.55
Longshan	29	1738	14,907	0.10	0.85	0.48	1.05	1.58	1.97	2.03	0.00
Yongshun	19	806	13,077	0.09	0.63	0.11	0.63	0.26	0.76	0.21	0.13
Longhui	2	92	2118	0.09	0.03	0.00	0.10	0.03	0.08	0.00	0.02
Chenxi	15	696	3675	0.09	0.27	0.05	0.71	0.17	0.59	0.20	1.34
Luxi	10	210	7529	0.09	0.65	0.13	0.23	0.11	0.39	0.04	0.05
Xinning	1	6	1324	0.09	0.03	0.00	0.04	0.01	0.04	0.00	0.01
Hecheng	1	2	958	0.09	0.03	0.00	0.07	0.01	0.04	0.00	0.00
Wugang	1	87	2400	0.09	0.03	0.00	0.05	0.01	0.04	0.00	0.00
Baojing	23	1246	19,684	0.08	1.12	1.22	0.54	0.76	0.96	0.97	0.00
Yuanling	19	1024	11,163	0.03	0.86	0.18	0.66	0.21	0.74	0.20	1.02
Shaoyang	6	434	4356	0.01	0.19	0.00	0.26	0.07	0.23	0.04	0.00
Chengbu	9	2984	11,839	0.00	0.59	0.02	0.59	0.11	0.35	0.13	0.28
Xinhua	6	289	2042	0.00	0.18	0.01	0.26	0.09	0.26	0.05	0.26
Dongkou	3	16	2034	0.00	0.04	0.02	0.09	0.03	0.12	0.07	0.14
Zhongfang	4	404	8984	0.00	0.13	0.02	0.26	0.06	0.16	0.07	0.00
Sangzhi	3	14	2365	0.00	0.05	0.00	0.12	0.03	0.12	0.04	0.00
Mayang	4	66	1137	0.00	0.24	0.00	0.14	0.10	0.16	0.05	0.00
Xinhuang	12	125	7377	0.00	0.36	0.01	0.34	0.14	0.48	0.02	0.00
Xinshao	7	1298	9451	0.00	0.22	0.00	0.31	0.08	0.27	0.01	0.00
Lianyuan	1	6	1652	0.00	0.03	0.00	0.02	0.01	0.04	0.00	0.00
Cili	1	9	816	0.00	0.04	0.00	0.00	0.01	0.04	0.00	0.00

Comparison with the WSN shows that the core villages of the CCUN along the You River (Longshan, Jishou, and Huayuan) and near the Yuan River (Huitong, Hongjiang, Tongdao, and Yongding) possess the dual attributes of essential ecological functions and transport (H–H, 28 pixels). In Chenxi and Yuanling (L–H, 162 pixels), core villages of the CCUN generally have low utilization intensity. Although these areas bear the important task of water environment protection, the conflict with conservation is not yet pronounced. As for the EGRN, core villages of the CCUN in Yongding, Xupu, Hongjiang, Suining, and Jingzhou possess good ecological resources. However, they simultaneously face the dual tasks of traditional village utilization and ecological protection, making them high-conflict zones (H–H, 25 pixels). In Xiangxi (e.g., Huayuan, Jishou, Fenghuang, Baojing, Guzhang), areas with well-preserved traditional villages do not overlap with key ecological zones (H–L, 122 pixels). This suggests lower ecological pressure for development in this region. However, it should be noted that this lack of ecological resources could also become a limiting factor for its development. Although Chenxi and Yuanling face significant ecological protection functions, the current low intensity of village use means no obvious conflict has yet emerged (L–H, 168 pixels).

4. Discussion and Conclusions

4.1. Discussion

- (1) How are synergies and trade-offs manifested within the different functional systems of traditional villages?

Traditional villages form a multifunctional development system centered on cultural inheritance, which is deeply integrated with villagers' daily lives, local economic industries, and ecological conservation [1,4,15]. The types and interrelationships of these functions exhibit considerable diversity [1,12]. How, then, should we understand these functional

combinations? Chen et al. (2024) suggest that in villages of the “Coordinated Development” type, all functions—cultural, economic, residential, and ecological—are highly developed and have entered a phase of rapid synergy [1]. However, a high level of ecological conservation functionality can also signify elevated ecological risk. We argue that such a combination may in fact represent a state of trade-off and conflict, which could hinder the comprehensive and in-depth CCU development of traditional villages within the demonstration zone. Achieving balanced and high-quality development of CCU is thus the core issue for the region. Consequently, we posit that synergies and trade-offs are not unidirectional. In detail, the relationships among various functions in traditional villages are not simply positive synergies or negative conflicts. Instead, they are dynamic, context-dependent relationships involving both synergy and trade-off. Their ultimate effect depends on the research perspective, spatial scale, and specific implementation path. For example, from a biodiversity perspective, high ecological functionality indicates rich ecological and species resources—a clear synergy. From an ecological redline perspective, however, it implies development restrictions and high conflict risk—a definite trade-off. Similarly, strong ethnic characteristics possess a dual nature: they highlight cultural diversity but also risk a loss of distinct focus. Therefore, in the practice of CCU for traditional villages, the focus should not be solely on eliminating trade-offs or pursuing synergy. Instead, it is essential to deeply understand the roots of these dialectical relationships. This understanding allows for differentiated and precise guidance of CCU practices to achieve sustainable development [1].

- (2) Is it reasonable to use administrative divisions as the sole units for delineating CCU in traditional villages?

By 2022, national policy mandated the selection of two to three concentrated demonstration counties in each province [4,17,18]. This policy aims first to support the development of these counties, then to stimulate surrounding areas, and finally to summarize and share replicable conservation and development experiences nationwide [17]. Consequently, key questions arise: how should these counties be selected, and how should the contiguous development areas within them be delineated [6]? However, the rationality of using counties as the unit for CCU practice is seldom discussed. Our case study in the Wuling Mountain Area of Hunan Province reveals that using the county as a cluster unit offers certain advantages. These include spatial proximity, shared ethnic origins, and unified administration for traditional village groups at a certain scale [18]. Yet, this model faces two core challenges. First, how can demonstration counties drive regional and national development? Our research identified a potential solution: using 28 highly recognizable, nationally protected traditional heritage sites as hubs. Linking various demonstration counties through these hubs and integrating regional resources could foster a coordinated network for all traditional villages in the area. However, a mismatch exists between spatial proximity and the distribution of these high-value villages. Protection practices confined by administrative boundaries may fragment collaboration among high-level traditional villages. Therefore, a key challenge for county-based CCU practice is fostering collaborative relationships both within and across county borders. Second, using counties as units may lead to homogenization due to spatial proximity and ethnic similarity. It is therefore crucial to manage the relationship between preserving village “distinctiveness” and avoiding “homogenization” within the county.

- (3) Policy implication

By applying the proposed methodological framework to the Wuling Mountain area of Hunan Province as a case study, four distinct relationship types among traditional villages were identified: (a) Coordinated Development Type: This type is characterized

by strong CCU relationships, high socio-economic status, and low ecological importance, with Xiangxi serving as a representative case. Within the Xiangxi CCU demonstration zone, traditional villages feature diverse ethnic composition and a spatially clustered distribution. They benefit from high accessibility and high attribute values, while showing no overlap with key ecological zones. This area exhibits the most coordinated multifunctionality in the region, with no significant ecological conflicts. The policy focus should be on leveraging existing resources to promote the high-quality development of CCU; (b) Conflict Type: Represented by Yongding, this type is marked by high CCU interaction, high socio-economic value, and high ecological importance. Traditional villages here maintain high-frequency CCU relationships and possess significant development potential, yet they also bear critical ecological functions. The conflict between development and conservation is pronounced. Consequently, policy must prioritize striking a balance between these competing demands; (c) Restricted Type: Exemplified by Anhua County, this type combines high CCU interaction with low economic potential and high ecological importance. The area features a single ethnic group, a scattered distribution of traditional villages, low accessibility, and a lack of distinctive features, alongside high ecological conservation pressure. Thus, the primary challenges involve identifying viable development pathways while effectively addressing ecological protection; (d) Potential Type: Represented by Xinhuang, this type is defined by low current CCU interaction but a good socio-economic foundation and no overlap with ecological protection zones. The policy direction should focus on utilizing existing socio-ecological assets to foster and strengthen CCU relationships among traditional villages.

The classification and policy implications derived from this case study are generalizable. The methodological framework for identifying these four relationship types is universally applicable to regions with traditional village clusters. Its core logic rests on evaluating three key dimensions: the intensity of existing inter-village relationships (e.g., CCU links), socioeconomic foundations, and ecological conservation importance. By assessing these three dimensions, planners and policymakers in other provinces or countries can categorize their own traditional villages into the four types. Subsequently, they can formulate targeted CCU strategies according to the findings of this study. However, it should be noted that, similar to the implications of trade-offs and synergies, these composite types are not fixed. They also depend on the development priorities of local governments and the specific resource conditions of the region. Therefore, in applying this classification to specific traditional villages, it is essential to fully incorporate local characteristics and make targeted, differentiated adjustments.

4.2. Conclusions

This paper innovatively focuses on the relationship between CCU and the social-ecological system, proposing a network-based methodological framework to identify the synergy/trade-off relationships between them. Using 432 traditional Chinese villages in the Wuling Mountain Area of Hunan Province as a case study, the research conducts an empirical analysis. The main conclusions are as follows: (1) The CCUN exhibits a structure characterized by low density, local clustering, and limited long-distance connections, spatially coinciding with the distribution of forested land. (2) The socio-economic functional system of traditional villages within the region demonstrates features such as barrier-free cultural exchange, spatially clustered distribution, transportation-dependent development, and a scattered distribution of high-value villages. Additionally, the central part of the region plays a significant role in ecological conservation. (3) Correlation analysis reveals an overall low-level synergistic correlation between the CCUN and the socio-economic system. By analyzing the spatial matching of core villages, diverse multifunctional combinations

are identified and categorized into four primary types: Coordinated Development, Conflict, Restricted, and Potential.

Empirical research demonstrates that the network-based methodological framework proposed in this study offers practical value for local governments in guiding CCU practices. First, it can effectively diagnose the spatial patterns of CCU engagement among traditional villages. For example, the study shows that CCU activities limited to individual counties can be integrated through 28 nationally protected heritage sites. This helps shape a coordinated development framework for the entire region, providing a pathway for collaborative development among traditional villages. Second, the framework can assess the existing foundations for CCU development. By systematically evaluating socioeconomic conditions, it identifies the strengths and weaknesses of each traditional village. Finally, this method helps clarify the key priorities for village development. For instance, it identifies development as the core task in Xiangxi, while in Yongding, the focus is on balancing development with ecological conservation. In practical application, two points should be emphasized. First, the classification of socio-ecological functions should be adapted to local conditions. Second, co-occurrence data, which serves as the essential foundation, can be collected more efficiently using methods such as big data technologies. The use of new data types and methods is also encouraged to better characterize the real interactive relationships among traditional villages.

In rural studies, especially at the village level, data collection has always been a significant challenge. This study also encountered considerable difficulty in obtaining co-occurrence data for traditional villages. Due to data availability constraints, co-occurrence records were collected primarily through direct searches on Baidu. Where conditions permit, it is advisable to synthesize information from multiple sources such as Google, government documents, and various planning reports. The absence of comprehensive CCU plans for traditional villages likely had the greatest impact on the analysis of CCU status and interrelationships. For example, while Xiangxi has formulated a regional cluster protection plan targeting 90 traditional villages for cultural tourism development, our search tools failed to capture corresponding records for these villages. This omission may lead to two issues: first, some core traditional villages in Xiangxi with established interactive relationships may not have been identified; second, the strength of linkages between CCU and other functional systems, such as the potential high-high clustering pattern between CCU and SEN, may be underestimated. Additionally, ecological conflicts in certain villages within this important water conservation area may have been overlooked. Furthermore, due to data limitations, only five types of socio-economic networks were constructed. Future research should incorporate more representative and policy-relevant networks, such as government collaboration and cultural tourism linkage networks, which is a key direction we intend to explore. Refining data through additional field investigations will also enhance the accuracy of future findings. Finally, the low resolution of current land use data within the area may introduce biases into the analysis. This is particularly affects cost-distance calculations, as lower-grade roads are not captured in low-resolution datasets. Consequently, some otherwise accessible villages in central areas appear geographically inaccessible in the model. This may also explain why the SEN within the central forested area maintains an isolated state. Similarly, this data constraint hinders the analysis of network patterns in the SEN and EGSN.

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