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Spatial Morphology Optimization of Rural Planning Based on Space of Flow: An Empirical Study of Zepan Village in China

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Abstract: The inadequate consideration of livable rural spatial morphology in rural planning has impeded the further advancement of the rural social system, resulting in a challenge for rural residents to establish an appealing living experience that distinguishes itself from urban areas. This situation calls for an urgent exploration of livable spatial morphology based on human-centered principles, as well as an investigation of planning spatial morphology optimization mechanisms that consider ecological backgrounds and human settlement needs. In response to this issue, this study employs the theory of flow space and constructs a framework for the optimization of rural spatial methodology. By integrating ecological and sociological analysis methods, the study identifies the "flow" structure of spatial association in rural ecosystems through ecological network analysis, and identifies the "flow" structure of behavioral association in rural human systems through social network analysis. Based on these findings, the complex network morphologies are evaluated and screened. To test the effectiveness of this framework, the study examines the spatial morphology of four planning options through case empirical analysis in Zepan Village, Hebei Province, China. The research results demonstrate that the framework can help achieve the goal of optimizing rural spatial morphology, improve existing planning practices that prioritize single plans and disregard the selection of multiple plans, and serve as an effective tool to aid planners in tackling complex planning problems by balancing scientific principles and empirical values.

Keywords: rural planning; programs optimization; rural spatial morphology; space of flow; ecological network analysis; social network analysis; network structure

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1. Introduction

China has undergone a remarkable period of rapid urbanization, with the urbanization rate soaring from 17.90% to 63.89% over the span of more than four decades, from 1978 to 2021 [1]. However, this has coincided with the gradual widening of the urban-rural divide and the deepening of rural deprivation [2]. In the first decade of the 21st century, the ratio of per capita disposable income between urban and rural areas rose from 2.74 to 2.98 [1], while rural areas suffered a decline in population and economic growth. In response, the Chinese government has consistently on prioritized rural issues, particularly the targeted poverty alleviation policy implemented in 2013. This policy has significantly improved the economic conditions in rural areas, and by the end of 2021, the Chinese government was estimated to have successfully lifted nearly 100 million people and 832 counties out of poverty [3,4]. Nevertheless, the improvement in economic conditions has not completely remedied the rural development issue in the context of the urban-rural relationship, given the increasing diversification of rural residents' desires for a better standard of living. In a dualistic system, the urban-rural divide is reflected in various economic, social, and cultural aspects. Compared to urban areas, the quality and coverage of infrastructure and public service provision in rural areas are relatively deficient, while the environment and picturesque scenery with rustic features have been degraded and destroyed by development and utilization. Consequently, rural areas are unable to offer their residents a distinctive living experience [5–7].

The widening urban-rural divide in China can be attributed to the inadequate creation of livable rural spatial morphology, a critical failure of rural planning [8,9]. The unattractiveness of rural areas is not only due to the economic downturn but also the lack of spatial morphology that can compete with urban areas. Historically, urban and rural planning regarded villages as the hinterland of cities, and the allocation of natural resources and country space in rural areas was carried out within the urban-rural economic system, emphasizing the supportive and guaranteeing functions of villages, such as food production and habitat protection, and industrial development as a supplement to the urban industrial system, often carrying backward industries with high pollution levels, high energy consumption, and low efficiency. Rural spatial morphology and shaping were neglected [10–13]. In the past, the policy objective of rural renewal was focused solely on building rehabilitation, with the image of the countryside consisting of uniform and monotonous rows of dwellings. This narrow approach has made it difficult to provide residents with a city-equivalent quality of life in terms of conveniences, natural scenery, and leisure activities [14–16]. Given these conditions, the continuing rural population decline is understandable. Therefore, rural planning should be reoriented toward meeting the needs of residents for a better life, shaping a unique spatial settlement morphology that considers the beautiful rural scenery and convenient living facilities, which are distinct from urban space. With the eradication of rural poverty, the revitalization of the rural economy, and the entrance of the countryside into a higher stage of development, the focus of rural planning must be on people's needs. This is emphasized in the 2023 Document No.1 of the Central Government, which mandates the improvement of village appearance based on vernacular characteristics, regional characteristics, and ethnic characteristics, stressing the need to strengthen village planning and building.

Extensive research has been conducted in the academic community regarding the optimization of rural spatial morphology, yet there remains a lack of consensus regarding the objective of achieving a "better rural spatial morphology" [17,18]. Contemporary research on rural spatial morphology frequently adopts a "space of place" paradigm, which maps human activities into spatial units and then assesses the overall quality of spatial morphology by summing or aggregating in various ways, leading to a loss of fluidity and completeness. In contrast, the space of flow theory suggests conceptualizing space as nodes and channels, characterizing spatial interactions as gravitational forces and potentials, and explicating gravitational "flows" or potential "flows" through channels to elucidate the practical significance of connections between points [19]. This approach sheds light on the practical meaning of links between sites by clarifying the gravitational "flow" or potential "flow" in the channel [19]. Cohen proposes a network structure consisting of three variables—land, buildings, and people—as an effective tool for explaining the "urban mixture" and the internal patterns of micro-elements. In this framework, land represents the natural morphology after human influence, while buildings constitute the primary space for human activities and a tangible manifestation of human behavior [20]. This framework is preferable because it offers the advantage of quantifying both natural ecological activities and human behaviors, not only in terms of specific spatial combinations of human and natural behaviors but also in terms of analyzing the dynamic flow of ecological elements and human behaviors from a systemic perspective [21,22].

In addition, it is important to note that this paper does not aim to propose engineering and technical solutions for village renewal plans. Rather, the main focus is on identifying superior village spatial morphology. Therefore, the aim is not to suggest specific technical implementation schemes, but rather to propose a framework by which the spatial morphology of such programs can be evaluated as superior or inferior. The paper puts forth four alternative village planning programs based on local development needs while maintaining a consistent scale ratio for each land use type across the four plans.

This study examines the dynamic flow connection between ecological elements and human behaviors in rural space, with the objective of defining the concept of "better spatial methodology" and proposing an evaluation framework for rural spatial methodology from the perspective of flow space. To achieve this aim, the study employs the ecological network analysis method to extract important ecological corridors for constructing the ecological network, while the social network analysis method is used to identify the behavioral boundaries of residents for developing the social network. The research site selected for empirical evidence is Zepan Village in Dongliang Town, Longyao County, Xingtai City, Hebei Province. Section 2 of this paper presents the theoretical considerations, defining the concept of a "better rural spatial methodology" and proposing the evaluation framework based on relevant studies. Section 3 discusses the study region and research methodology, introducing the study area and explaining the identification method and evaluation index of network structure. The empirical case is presented in Section 4, while Sections 5 and 6, respectively, provide the discussion and conclusions (see Figure 1).

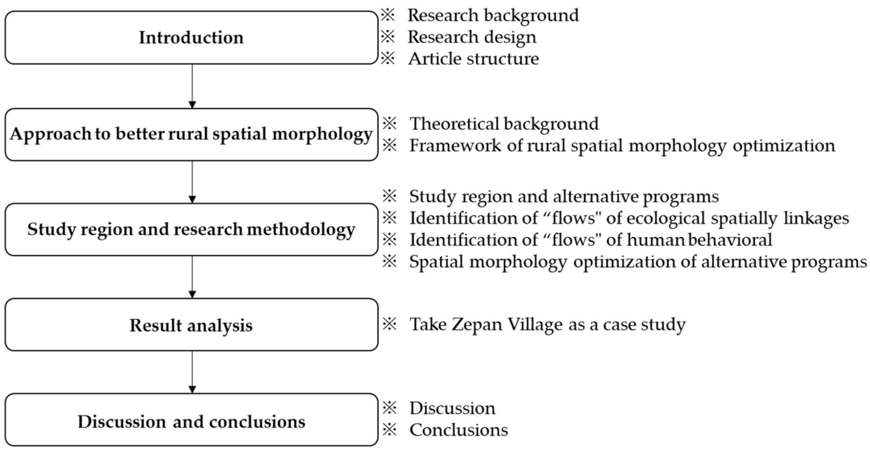

Figure 1. Flowchart of the research framework.

2. Approach to Better Rural Spatial Morphology

2.1. Conceptual Connotation of Rural Spatial Morphology

Rural spatial morphology refers to the distribution structure and pattern of spatial elements with socioeconomic and ecological attributes in rural space [23]. Rural spatial morphology not only changes the size, shape, and landscape connectivity of natural patches in rural areas, but also affects the socio-economic environment, such as homestead, road, and infrastructure, changes which directly reflect the intensity of human activity in rural space [24–26].

The objective of optimizing a "better rural spatial morphology" lacks consensus among scholars, with various mainstream views observed in the academic community. These prevailing perspectives can be broadly categorized into three groups.

(1) More spatial morphology benefits. Early studies predominantly employed operations research logic, relying on resource size and technological productivity to assess outputs and advantages, with the morphology possessing a greater amount of high-value factor resources being considered superior [27–29]. This paradigm primarily involves quantitative structure measurement rather than spatial morphology measurement. Within this perspective, the notion of a "better spatial morphology" is defined as a scaling ratio of spatial elements that possess higher output efficiency, albeit at the expense of sacrificing critical spatial information.

(2) More appropriate spatial relationships. Subsequently, researchers began applying mathematical theories such as graph theory to deconstruct the information of spatial morphology, with landscape pattern index analysis serving as a sample technical method. The landscape pattern index of patches, corridors, and substrates is used to

quantify spatial morphology, with patch regularity, diversity, and high connectivity commonly deemed as merit principles [30–35]. Morphological analysis based on space syntax is also a common research method, such as the accessibility and intelligibility study of rural spatial morphology in Hejiachong Village, South Henan [36]. However, another group of experts argued that this method disregards spatial linkages at the micro level, with spatial morphology optimization emphasizing the importance of good spatial adjacency. For instance, ecological water resources should not be located near human production and living areas, as the ecological functions of the water sources could be compromised by home waste and production pollutants. Therefore, it is recommended that the adjacency cost matrix of different spaces be configured to ensure that spaces suited for adjacency are located as close together as possible [37,38]. This paradigm adopts a mechanistic approach to spatial morphology, where the notion of a "better spatial morphology" is fragmented into various spatial elements that are deemed to be appropriately related spatially, including adjacency, boundaries, connectivity, and others. This paradigm predominantly emphasizes the static features of space; however, it falls short of comprehensively accounting for the complex spatial relationships and connections. In this paradigm, the understanding of spatial morphology is limited to the level of grid-like land units, thereby neglecting the intricate interactions and associations between various spatial components. Moreover, while this paradigm does consider human behavior, it constrains the understanding of human behavior by forcibly translating it into specific properties of the land grid through its technical approach.

(3) Better spatial experience. With the introduction of the behavioral perspective, some scholars believe that the experience and perception of residents can better determine the merits of spatial morphology, such as habitat satisfaction and view constraints [39,40]. Manual visual interpretation methods have been employed in some studies to evaluate rural spatial morphology [41]. However, many of these studies have concentrated solely on human behavior and have neglected the correlation between human actions and spatial entities. Moreover, the data collected in these studies are typically retrospective in nature. Surveys seeking feedback from inhabitants regarding their satisfaction or preferences for various virtual alternatives can be challenging to implement effectively. The validity of the residents' responses may not be assured due to the difficulty they face in comprehending the alternatives. As a result, the utility of this method for selecting alternative planning programs is limited.

Various researchers have defined "better rural spatial morphology" differently, but the underlying rationale is to assess the scale of humans [42,43]. In essence, the needs of residents are a product of their behavior in shaping rural space, which is highly influenced by the physical environment of rural space and, in turn, has an impact on the spatial entities. Therefore, a better rural spatial morphology should ensure the orderly operation of ecological activities in natural systems, maintain the stability of ecological connections, and provide residents with a comfortable, convenient, and safe living environment that meets their basic requirements for survival and development. This definition emphasizes the relationship between human behavior and rural space, rather than simply focusing on a single demand, thus making it more comprehensive. The subsequent study integrates sociological and ecological approaches using a network analysis framework to provide a compatible framework for selecting rural spatial morphology. The current definition emphasizes the interrelatedness between human behavior and rural space, instead of reducing it to a single need, thus making it more comprehensive with regard to the benefits of space, spatial relationships, and spatial experiences. This characteristic is further exemplified in the subsequent study that merges sociological and ecological approaches through a network analysis framework, thereby presenting a compatible foundation for the selection of rural spatial methodology.

2.2. Framework of Optimization of Rural Spatial Methodology

The space of flow theory emphasizes that the "flows" generated by the trajectories of human production and living activities in spatial morphology form a spatial field resembling a network. In rural regions, the "flow" that occupies the most space is the spatially connected "flow" of ecosystems. The ecological spaces in rural areas constitute the spatial network of rural ecosystems, as opposed to the isolated ecological spaces in urban areas. The continuous ecological spaces in rural regions morphology a densely interconnected ecological network that enables rural ecosystems to maintain stability and adapt to external disturbances, thus forming a distinctive rural landscape [44]. According to this perspective, it is not just the number of ecologically functional spatial resources, such as woods, rivers, and green spaces, that are scattered throughout rural areas that is important, but also whether these ecological spatial resources can maintain well-functioning ecosystems through connections. Rural areas have developed a spatial morphological identity that is difficult to replicate in urban areas [45]. On the other hand, the "flow" of human behavior reflects the daily production and life trajectory of rural residents. Although for the ecosystem, human activities are more reflected as "interference", rural residents should enjoy convenient, safe, and comfortable production and living facilities and services as urban residents. In light of the above, this article puts forth a proposed assessment framework to evaluate the value of rural spatial morphology (refer to Figure 2). The framework is composed of three main components. Firstly, the triadic relationship between the human behavior system and the rural ecological system within rural space is analyzed. This analysis involves examining the interplay between human behavior, land, and architecture. Secondly, the logical characteristics of the spatial association flow of the natural system and the behavioral association flow of the human system are identified through the use of ecological network analysis (ENA) and social network analysis (SNA). These analytical methods are employed separately to recognize the logical features of each association flow. Finally, the evaluation is conducted based on the principle of tightness of spatial association.

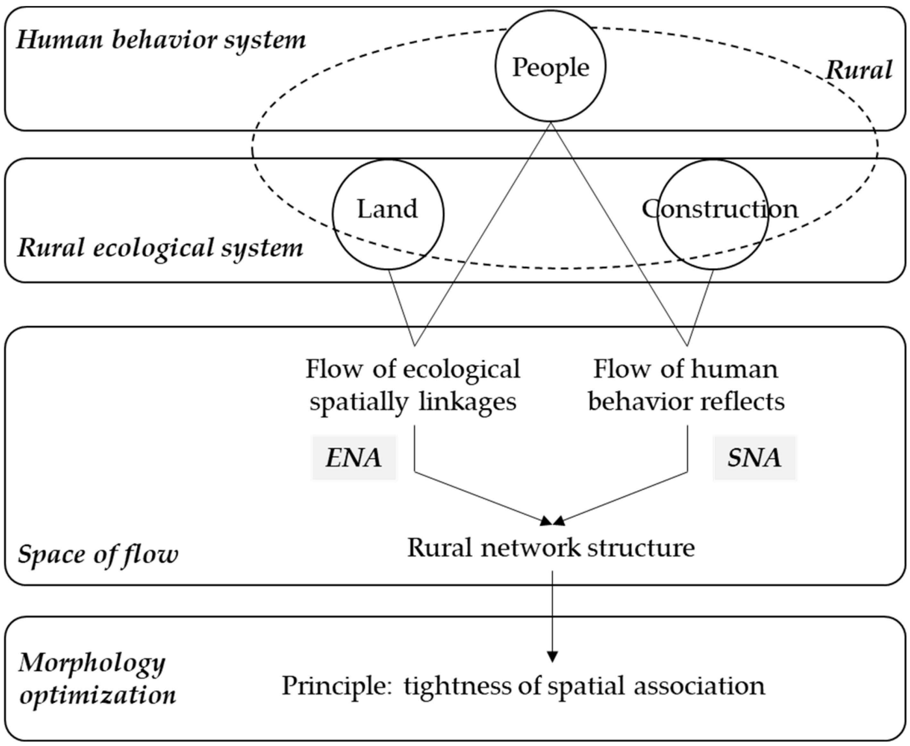

Figure 2. Logical framework for the evaluation of rural spatial morphology optimization based on space of flow.

(1) In Cohen's triadic structure of "human behavior–land–architecture," rural spaces are shaped by human behavior in two significant ways [20]. Firstly, human behavior impacts rural ecosystems through the exploitation, utilization, and preservation of natural resources that depend on the land. Secondly, the behavior of individuals or groups and their movements through space can be visualized using the temporal geography framework. Although it may be challenging to precisely describe the complex trajectory of multiple individuals under planning scenarios, it is possible to construct the boundaries of human behavior systems using building points that serve production and living functions. In other words, while it may be challenging to precisely capture the behavioral trajectory of a group of villagers or an individual at a particular time in the future, their trajectory must fall within the network structure formed by connecting building points with relevant functions.

(2) The morphology of flows within the ecosystem is the result of the division of labor and cooperation among various types of spaces in the region, which undertake distinct ecological functions and participate in material and energy cycles. Spatially, this is manifested in the morphology of differentiated and continuous combinations of land use and cover types. Accordingly, this study utilizes the ecological network analysis method to identify significant ecological corridors as "flows", and the corridor network index and landscape pattern index to measure the degree of connectivity within the spatial association network of the ecosystem. Similarly, the morphology of flows within the human system's behavioral connections is the result of the production processes of regional producers acquiring raw materials, processing and producing products, and the living processes of regional inhabitants working, dining, consuming, entertaining, and living. The establishment of links in ecological space enables the internal circulation and external exchange of various natural resources and material elements, which are spatially represented as a series of behavior tracks with each building as a node. To identify the spatial connection "flow" of each living space, this study employs the social network analysis method commonly used in social relations research.

(3) The interplay between rural ecosystems and human systems is complex and diverse, resulting in various morphology of spatial linkages and flows that coalesce to form a complex network. To ensure the continuity of landscape systems, maintaining spatial vitality has become a central concern in spatial planning [46]. Rogers (1999) argued that spatial isolation is antithetical to vitality and that the value of "Open Space" lies in its ability to establish connections between specific spaces and people. The stronger the connection, the more stable the structure and function, and the greater the spatial superiority [47]. Thus, this study employs the principle of tightness of spatial association to evaluate the spatial pattern of the network constructed by the spatial and behavioral connections of rural ecosystems and human systems.

3. Materials and Methodology

3.1. Study Area and Alternative Planning Programs

Zepan Village is located in the middle of Dongliang Town, Longyao County, Xingtai City, Hebei Province, China. Zepan Village covers an area of 1244.11 hm^2, with a resident population of 8745 and an annual per capita income of about RMB 6000. The village has a flat topography, completely dominated by a plain, and about 90% of the land is agricultural land. Rice and lotus roots are the primary crops in the area, and the secondary businesses consist primarily of lotus root processing and rubber processing (see Figure 3).

The data were collected during the author's participation in the drafting of village-level planning in Zepan Village. Based on the village's basic data (including land, economy, people's livelihood, infrastructure data, etc.), villagers' wishes, and upper planning arrangements, several categories of development scenarios are formed. Distinct disparities exist in the diverse land use scenarios within these development frameworks. In order to concentrate on the fundamental research subject of spatial morphology optimization, the

NSGA-II genetic algorithm was employed to filter the assorted quantitative structures and identify four of the Pareto optimal programs. These four programs served as alternatives for optimizing spatial morphology. In addition, Baidu Map POI data are used to determine the infrastructure service points within the village, including corporate, healthcare services, shopping services, catering services, etc. Based on the four categories of development scenarios, four alternative planning programs with the same quantitative structure were created as evaluation objects to prevent the influence of varied scales of various resource elements (see Figure 4).

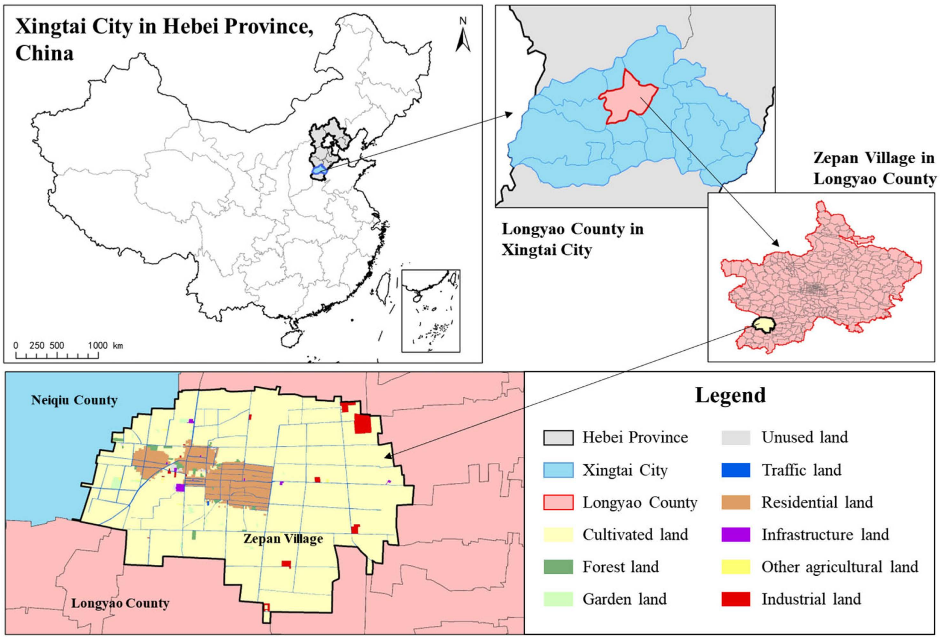

Figure 3. Location map of the study area.

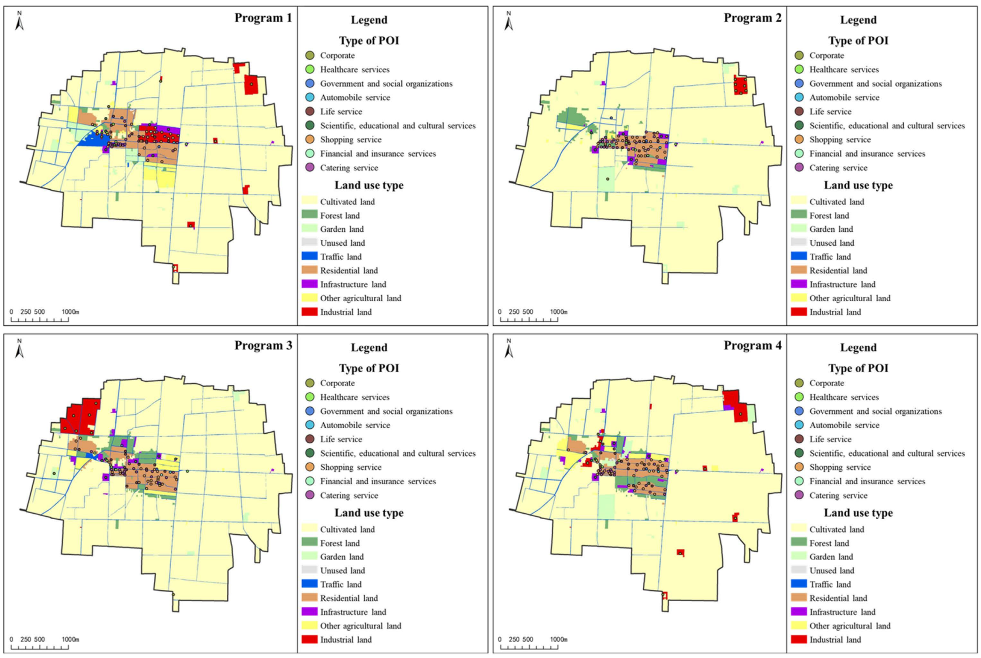

Figure 4. Alternative planning programs for Zepan Village.

Both Program 1 and Program 3 center on the local specialty of the lotus root processing industry as the primary source of people's livelihoods. These programs entail a significant allocation of industrial land (i.e., lotus root processing area) and agricultural land (i.e., main lotus root growing area). The key distinction between the two lies in the concentration of industrial land in the northwestern part of the village in Program 3, while the lotus root processing plant in Program 1 is situated in the northeastern corner of the core area, with other industries primarily located in the northern part of the village. Program 1 encompasses a small-forested area and a substantial amount of traffic land, with extensive traffic land along the No.252 township road dedicated to bus stations and auxiliary facilities. Program 4 emphasizes ecotourism and features over 80 hectares of ecological space, with a contiguous woodland ecological space forming the central axis of the village core.

3.2. Identification of Flows of Ecological Spatially Linkages Based on Ecological Network Analysis

Morphological spatial pattern analysis (MSPA) has been used to identify cores with important ecological functions in rural ecosystem space, and eliminate the fine and fragmented patches among them [48–52]. In this study, Conefor 2.6 was used to measure the patch importance index of cores in order to select the parts with better ecological functions and better connectivity levels. The calculation method was as follows:

$$\mathrm{dPC} = \frac{PC - PC_r}{PC} \times 100\%$$

$$\mathrm{PC} = \sum_{i=1}^{n} \sum_{j=1}^{n} \frac{a_i \cdot a_j \cdot p_{ij}^*}{A^2}$$

where n represents the total number of patches, a_i and a_j represent the area of patches I and j, respectively, p_{ij}^* represents the maximum distance that organisms spread in different patches, A^2 represents the total area of the landscape, and PC_r represents the overall connectivity index of the landscape after the removal of a patch.

Zepan Village and its surrounding villages are situated in a plain area, with flat topography and primarily farmland. Currently, with the exception of the lotus root pond, the area of water is very small. There is no grassland, and the area of forest land is insufficient. To improve the analysis effect, garden land, other agricultural land, and unused land with relatively little human disturbance and low production intensity are also taken as ecological space. Six types of land use were placed in the foreground: garden land, forest land, grassland, other agricultural land, water, and unused land. The programs are converted to a binary raster in ArcGIS, and a 10 m × 10 m fishing net was used to split the study area into 142,952 basic units based on the actual circumstances of the study area. After removing the finely fragmented patches, the relevance of each patch was determined using the patch importance index, and patches with a dPC of at least 5 were chosen as core ecological sources.

Referring to relevant studies, the resistance factors were selected based on natural and socio-economic conditions: the natural resistance factors included elevation, slope, landscape type, vegetation cover, distance to rivers, geological hazards, water abundance, etc.; the socio-economic resistance factors included the distance to construction land, distance to roads, nightlight intensity, etc. [53–55].

$$MCR = f_{min} \sum_{j=n}^{i=m} \left(D_{ij} \times R_i\right)$$

Considering data availability and the actual situation of the study area, the indicators were further screened. At the level of natural resistance factors, two indicators, elevation and landscape type, were chosen based on the availability of data and the actual circumstance of the study area. Since Zepan Village is located on a plain, the terrain is level and the slope variation is minimal, the slope factor was not chosen as the resistance factor. There are no large rivers and reservoirs, nor were there any major geological disasters during the observation period, and water resources are more evenly distributed, so the three factors of distance were not considered further. In addition, as the data represented simulations of future conditions, it was difficult to compute vegetation cover, and so vegetation cover was not employed as a resistance factor. At the level of socioeconomic resistance factors, three indicators of distance to construction land, distance to main roads, and distance to branch roads were selected based on data availability and practical demands. The nightlight image data were difficult to obtain because of the data being simulations of the future situation and the lack of microeconomic indicators. Due to the grading of village roads, the distance was estimated individually, utilizing the No.252 township road as the main road and other village and farm roads as branch roads.

Based on this premise, the natural breakpoint approach paired with the literature method was utilized to estimate the resistance grading of each indication and assign a resistance value between 1 and 5, with the grading thresholds shown in Table 1.

Table 1. The classification threshold, resistance value, and weight of the resistance factor index.

Factor Type	Indicators	Classification of Indicators	Resistance Value Assignment	Indicator Weights
Natural factor	Elevation	[33, 36)	1	0.05
		[36, 38)	2	
		[38, 40)	3	
		[40, 43)	4	
		[43, 47)	5	
	Landscape type	Forest land, grassland	1	0.5
		Cultivated land, garden land, other agricultural land	2	
		Unused land	3	
		Water	4	
		Industrial land, residential land, traffic land, infrastructure land	5	
Socio-economic factors	Distance to construction land	[1129, 1805)	1	0.3
		[770, 1129)	2	
		[487, 770)	3	
		[230, 487)	4	
		[0, 230)	5	
	Distance to main road	[3400, 4250)	1	0.1
		[2550, 3400)	2	
		[1700, 2550)	3	
		[850, 1700)	4	
		[0, 850)	5	
	Distance to branch roads	[600, 1448)	1	0.05
		[250, 600)	2	
		[100, 250)	3	
		[30, 100)	4	
		[0, 30)	5	

The resistance value was assigned according to the degree of the positive and negative influence of resistance factors on ecological linkage and weighted to form a comprehensive resistance surface as the cost of the ecological corridor. The minimum cumulative resistance surface was constructed based on the MCR model. The calculation method was as follows:

$$MCR = f_{min} \sum_{j=n}^{i=m} (D_{ij} \times R_i)$$

where f_{min} represents a positive correlation function, D_{ij} represents the distance between patches I and j, and R_i represents the resistance value between patches i and j. Ecological corridors are identified based on the magnitude of gravitational forces G_{ij} between ecological sources, measured using the gravity model [56]. Larger gravitational values indicate greater interaction forces between ecological sources and less resistance to the flow of ecological between ecological sources.

$$G_{ij} = \frac{N_i N_j}{D_{ij}^2} = \frac{\left[\frac{\ln(S_i)}{P_i}\right]\left[\frac{1}{P_j \times \ln(S_j)}\right]}{\left(L_{ij}/L_{max}\right)^2} = \frac{L_{max}^2 \ln(S_i S_j)}{L_{ij}^2 P_i P_j}$$

where i and j represent two different patches, G_{ij} represents the ecological gravitational value between i and j, N_i and N_j represent their weight, D_{ij} represents the standard value of corridor resistance between i and j, P_i and P_j represent the resistance value of ecological sources i and j, S_i and S_j represent the area of ecological sources i and j, L_{ij} represents the cumulative resistance value, and L_{max} represents the maximum resistance value.

3.3. Identification of Flows of Human Behavior Reflects Based on Social Network Analysis

The connection between spaces lies not only in the geographical distance and geographical association but also in the social association formed by human activities in the space, giving the objective physical space a rich connotation that transcends distance accessibility. The social network analysis paradigm was therefore used to abstract the various spaces of human behavior in rural areas as network nodes, and the human behavior between network nodes was used as the connecting line to construct the network structure of human behavior in rural spaces, as well as to guide the adjustment and optimization of a spatial layout by analyzing its merits and demerits [57–60].

Human behavioral trajectory data are difficult to gather; hence, road trajectories are typically utilized to simulate behavior. Referring to Llano-González and Christakis (2012), two nodes are considered to have a linkage relationship when residents can reach one node directly from another node without passing through other nodes mainly by road [61]. An $M \times M$ binary symmetric matrix was built for M nodes, with the value set to 1 when there was a linkage relationship between two nodes and 0 otherwise.

3.4. Optimization of Spatial Morphology Based on Association Tightness

Based on the principle of tightness of spatial association, the spatial morphology of the ecological linkage network was related to the ecological source, ecological corridor, and structure of the formed network. The network morphology was measured using indicators of three dimensions: ecological source structure, ecological corridor structure, and ecological network structure [62]. Additionally, the morphology of the social network structure was related to the structural morphology of the network structure itself and its coverage of the residential space. Meanwhile, the network morphology was measured using the corridor composite index and the accessibility index [63–65]. The standard deviation standardization method was adopted to standardize and adjust the direction of the indexes, and the Delphi method was used to give weights for the spatial morphology optimization evaluation index system, as shown in Table 2.

Table 2. Spatial morphology optimization evaluation index system of rural areas.

Network	Dimensionality	Indicators	Direction	Weights
Ecological linkage network morphology	Structural morphology of the ecological source	PARA_MN	+	0.20
	Structural morphology of the ecological corridor	D_M	+	0.20
	Structural morphology of the network	α index	+	0.08
		β index	+	0.04
		γ index	+	0.08
Human behavior network morphology	Network structure	Network density	+	0.04
		Network relevance	+	0.04
		Clustering coefficient	+	0.04
		Average nearest distance	-	0.04
		Point degree central tendency	+	0.04
	Service structure	Reachability index	+	0.20

The indicators were measured as follows.

(1) Structural morphology of the ecological source

The core ecological source average shape index (PARA_MN) was used to characterize the structure of the ecological source; the shape index was the perimeter-to-area ratio. For two patches with the same area, the longer the perimeter, the more irregular the shape, and the larger the shape index. The more complicated the shape of the ecological source, the closer the link to the outside, and the more evident the ecological function of the ecological source.

(2) Structural morphology of the ecological corridor

The average point degree (D_A) of the core ecological source is used to characterize the source–corridor relationship, i.e., the number of corridors directly connected to each ecological source. A larger point degree indicates that the ecological source is more connected to the outside and more likely to become a core source, and a larger average point degree indicates that the overall connectivity between ecological sources is stronger.

(3) Structural morphology of the network

The α-index, β-index, and γ-index are common methods for the analysis of ecological corridor network morphology.

The α index is a network loopness index, characterizing the degree of corridor closure into loops rather than dispersion in the network, as the ratio of the actual number of loops existing to the maximum possible number of loops formed, with a value range from 0 to 1. When α = 0, it means that there are no loops in the network, and when α = 1, it means that there are maximum possible loops in the network. The calculation formula is as follows.

$$\alpha = \frac{L-(V-1)}{3(V-2)-(V-1)} = \frac{L-V+1}{2V-5}$$

where L represents the actual number of corridors in the network, $(V-1)$ represents the number of connected corridors in the loop-free network, which is the ratio of the number of actual loops to the maximum number of loops that can be formed, $3(V-2)$ represents the maximum number of corridors that the network may be connected to, and the difference with $(V-1)$ represents the maximum possible number of loops that can be formed.

The β index is the corridor density index, which can also characterize the corridor circularity, meaning the level of difficulty of a node to connect with other nodes. The calculation formula is as follows.

$$\beta = \frac{2L}{V}$$

The γ index is the network connectivity index of the corridor, which indicates the degree of connectivity of the nodes in the network, and is the ratio of the actual number of corridors to the maximum possible number of corridors, with a value range of 0~1. When γ = 0, it means that each node is not connected to any other, and when γ = 1, it means that each node in the network is closely connected to other nodes. The calculation formula is as follows.

$$\gamma = \frac{L}{L_{max}} = \frac{L}{3(V-2)}$$

(4) Network density

Network density describes how close the actual association of the network structure is to the ideal situation, and can usually be characterized by the ratio of the two. The closer the actual association is to the ideal situation, the more holistic and connected the network structure is, and the more obvious the interaction effect between nodes is. The calculation formula is as follows.

$$D_i = \frac{N}{M(M-1)}$$

where N represents the number of relationships between nodes and M represents the number of nodes.

(5) Network relevance

Network relatedness indicates the level at that each node in the network is in contact with those around it, and the more pathways between nodes, the higher the degree of point relatedness. For each node, if there are more pathways contacting other nodes, there is high cohesion of the whole network. For example, the increase in the number of core nodes will increase the density of the network but not the degree of association, and the increase in the number of connection paths between established nodes will increase the degree of association. The calculation formula is as follows.

$$\mathrm{C} = 1 - [\frac{2V}{M(M-1)}]$$

where V represents the number of unreachable pairs of points in the network structure and I is the number of nodes.

(6) Small-world characteristic

The small-world characteristic is a characterization of network connectivity and includes two main metrics: the agglomeration coefficient and average path length.

The former reflects the average aggregation degree of the network structure. For node i, the aggregation coefficient indicates the degree of the point directly connected to other points. For the network structure, the average value of the aggregation coefficient of all points is taken as the global aggregation coefficient; the larger the aggregation coefficient, the more compact and aggregated the network space. The calculation formula is as follows.

$$\mathrm{C} = \frac{1}{M} \times \sum_{i-1} \frac{2k}{M(M-1)}$$

where k represents the number of all directly connected edges at the node and M represents the number of nodes.

The latter is a characterization of the connectivity between nodes and is usually used to measure the level of holisticness between network nodes. A longer average path length indicates a longer connection path between nodes, and more nodes that humans need to pass through to move from one node to another. The formula is as follows.

$$\mathrm{L} = \frac{2}{M(M-1)} \sum_{i \geq j} d_{ij}$$

where d_{ij} represents the shortest link between nodes i and j, and M represents the number of nodes.

(7) Point degree central tendency

Centrality is a metric that describes the importance of a node in the network, including degree centrality, closeness centrality, betweenness centrality, and eigenvector centrality. Central tendency is an index derived from centrality, which indicates the degree of network dependence on a node. The greater the central tendency, the more obvious the tendency is for the whole network to be built around a node, and conversely, the stronger the spatial equilibrium is, so the degree of centrality potential is used to characterize the structural integrity of the network.

$$\mathrm{DC} = \frac{\sum_{i=1}^{M} (DC_{max} - DC_i)}{\max\left[\sum_{i=1}^{M} (DC_{max} - DC_i)\right]}$$

where DC_i represents the number of nodes directly connected to node i, DC_{max} represents the max DC_i of all nodes in the network structure, and M represents the number of nodes.

(8) Service structure

The service structure mainly considers the service coverage of each node in the network to the living space, and the service radius is uniformly 100 m. The 100-m buffer zone of each service point location is constructed by the buffer in ArcGIS [42]. Additionally, the rural residential land that is within the buffer zone is identified, and the proportion of this land area to the total area of rural settlement sites is calculated.

4. Results

4.1. Flows of Ecological Spatial Linkages in Zepan Village

4.1.1. Identification of Core Ecological Source in Zepan Village

The results of the study reveal that the ecological source sites in the four programs consist of a few dominant patches with large areas and strong connectivity, as well as numerous fragmented and scattered tiny patches with weak connectivity. Specifically, in Program 1, the core ecological source sites (dPC > 5) are composed of nine patches with a total area of 34.56 hm^2, which are primarily distributed around the village settlement sites. These patches are concentrated in the western and southern parts of the village's core construction space and consist mainly of garden land and other agricultural land. In Program 2, the core ecological source land (dPC > 5) comprises eight patches with a total area of 28.90 hm^2. Similar to Program 1, this ecological source land is concentrated in the western and southwestern parts of the village's core construction space and mainly comprises two core groups. The western group is continuous forest land, while the southwestern group consists mainly of garden land. In Program 3, the core ecological source land (dPC > 5) is divided into two continuous green belts in the north and south, comprising 10 patches with a total area of 33.45 hm^2. The northern green belt begins from the woodland on the western side of the No.252 township road and extends eastward along the northern edge of the village's core construction space. Finally, in Program 4, the core ecological source land (dPC > 5) includes 11 patches with a total area of 48.57 hm^2. These patches mainly consist of four major groups, located in the west, north, central, and southwest of the village's core construction space. The western group is mainly other agricultural land, the northern group is a mixture of forest land and other agricultural land, the central group is mainly forest land, and the southwestern group is primarily garden land (see Figure 5).

4.1.2. Construction and Identification of the Ecological Corridors in Zepan Village

The resistance values are allocated based on the degree of the positive and negative influence of the resistance factors on the ecological linkage, and after weighing, the comprehensive resistance surface is created (see Figure 6.). Since the scale of adjustment of the core layout of the village construction space is very limited in each program, the overall resistance value distribution characteristics of each scheme are remarkably similar and resemble the circle distribution characteristics in which the resistance value decreases gradually from the center to the periphery.

The construction of the ecological corridor was based on the MCR model, where the path's cost was determined by the path's grayscale in Figure 6. The significance of the ecological corridor was proportional to the proximity of the grayscale to the black. Conversely, a higher resistance value indicates a weaker function of the corridor. The results indicate that the potential ecological corridor network of the four alternatives exhibits distinct differences. Program 1's potential ecological corridor network is highly concentrated in and around the village's core area, with low resistance corridors mainly clustered in the northwest-southeast corridor in the southwest of the village's core area, while the northeast corridor has a higher resistance value. Program 2's potential ecological corridor network is the most widely distributed, covering almost the entire village area, with high resistance corridors primarily distributed in the north of the village. Program 3 exhibits a more extensive distribution of potential ecological corridor network, with a morphology similar to that of Program 1 but with a lower density and a wider distribution. The high resistance corridors are primarily several long-distance corridors that extend to the northeast. Program 4 demonstrates an inverted triangular shape, with high-resistance corridors mainly distributed in the northern part of the village and low-resistance corridors densely distributed in the core area (see Figure 7).

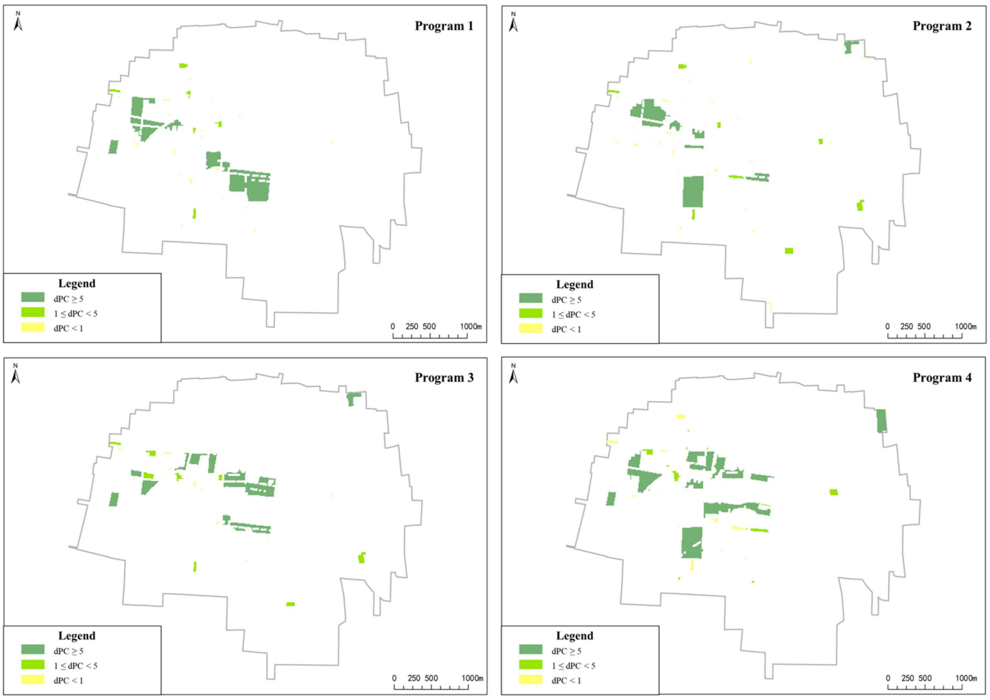

Figure 5. Identification of ecological sources for alternative planning programs in Zepan Village.

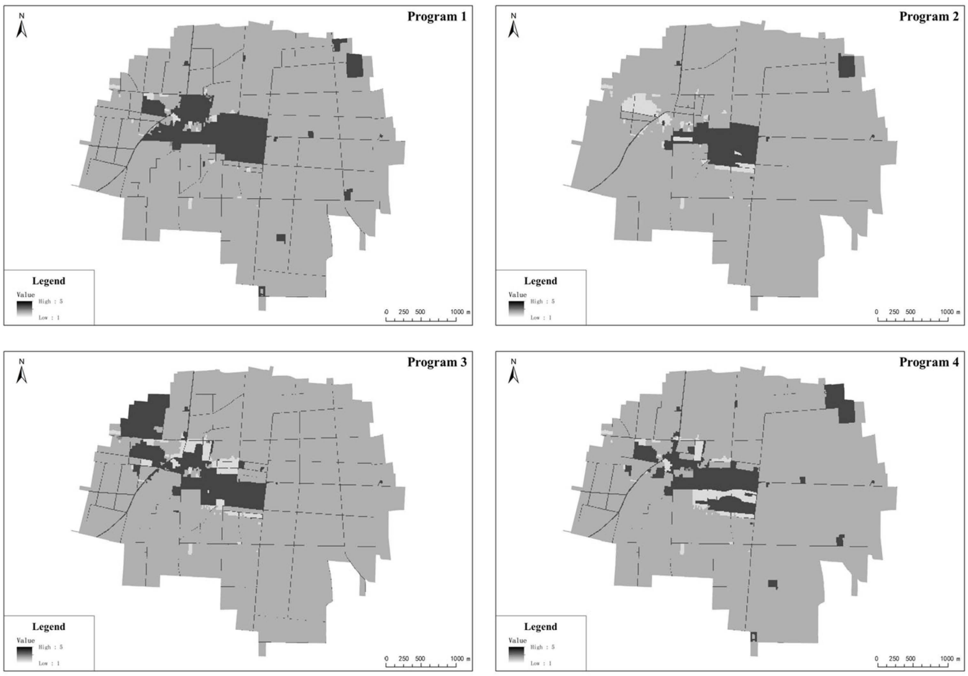

Figure 6. Comprehensive resistance surface of the alternative planning programs of Zepan Village.

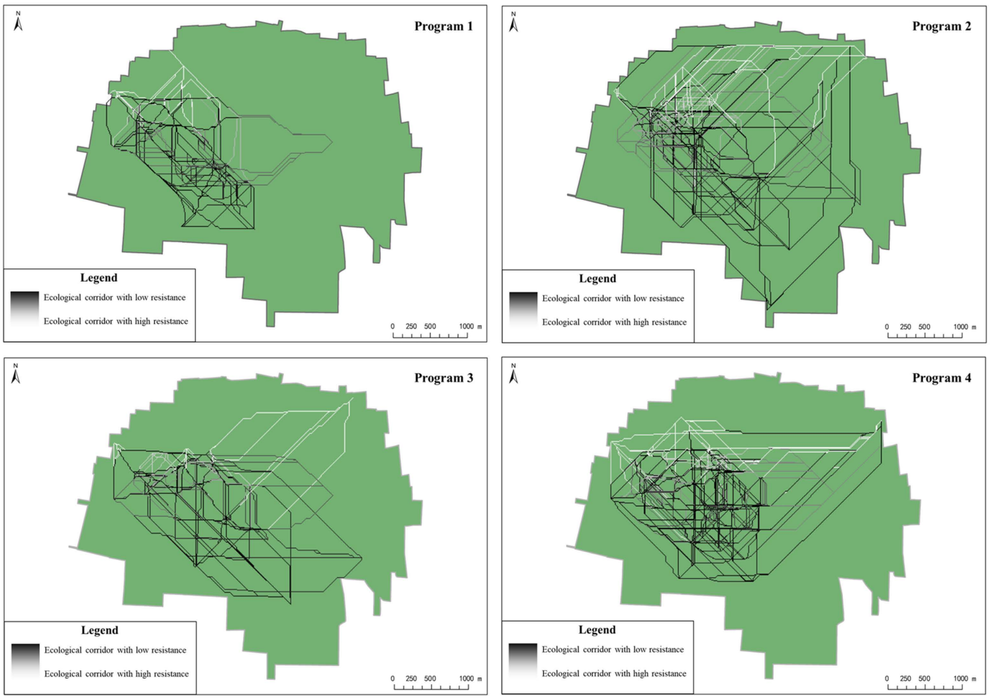

Figure 7. Potential ecological corridors for the alternative planning programs of Zepan Village.

Based on the gravity model equation to calculate the spatial linkage strength between each ecological source, the interaction matrix between the ecological source of each program is obtained to determine the core ecological corridors ($G_{ij} \geq 1000$) and general ecological corridors ($100 \leq G_{ij} \leq 1000$). The results indicate that the interaction gap between each ecological source is evident. With the exception of Program 4, which has a high degree of homogeneity, the standard deviation of gravity values exceeds 10,000, that for Program 3 exceeds 40,000, and the extreme deviation of gravity values for Programs 2 and 3 exceeds 100,000. This indicates the need for additional grading of ecological corridors, and the principal corridors were chosen for analysis (see Figure 8). The focus is on the source sites of dark green blocks (dPC $\geq$ 5), core ecological corridors (dark red lines), general ecological corridors (light red lines), and the network structure they form.

The results indicate that the ecological space covering the area of Program 1 is comparatively insufficient, as is the connectivity between the corridor's two segments. Four core ecological corridors in the region are located on the southwest side of the settlement site, west of No.252 township road. There are 10 general ecological corridors that support the ecological functions of the core ecological corridors and are primarily located around the core ecological corridors and extend eastward.

Program 2 encompasses a vast region of biological space, and corridors are strongly interconnected. There are 5 core ecological corridors, with the western corridor distributed to the west of the NO.252 township road in a ring-like pattern, the central corridor located on the northwest side of the settlement site on the east side of No.252 township road with a shorter length, and the eastern corridor located in the south side of the settlement site on the east side with a longer length and an overall east-west distribution. There are 10 general ecological corridors, which are primarily dispersed between the three core corridors and make intimate connections with each core node of the western and central corridors.

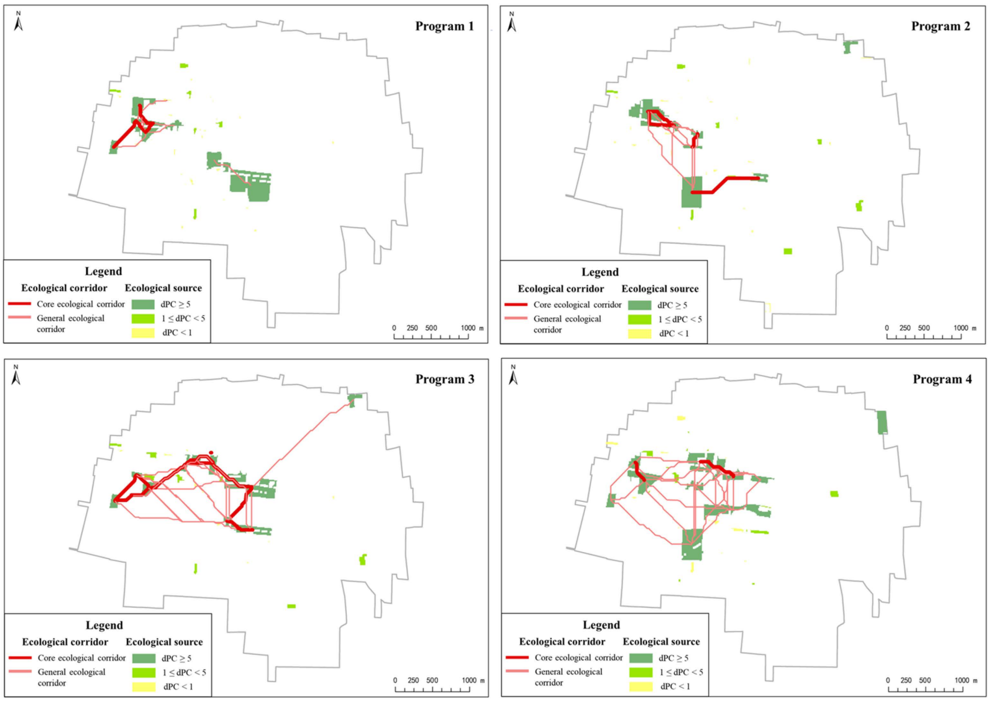

Figure 8. Identification of ecological corridors in the alternative planning programs of Zepan Village.

Program 3 generates a network structure with high connectivity that is concentrated in the middle of the town. There are 10 core ecological corridors distributed in a "z" pattern around the village settlement sites, crossing the settlement sites twice. There are 25 general ecological corridors, the majority of which are dispersed between the core corridors' zigzagging corridors and serve to reinforce the relationship.

Program 4 contains 3 core ecological corridors, all of which are small in length. At the center of the village, 28 general ecological corridors form a dense and complex network structure that connects the main corridors with a high degree of connectedness.

4.2. Flows of Human Behavior Reflects in Zepan Village

Through the analysis of social network construction based on village infrastructure and public service points, the results indicate that Program 1 exhibits a high density of relationships, without any discernible core nodes. The overall network structure presents a reticulated distribution, with each node exhibiting a high level of connectivity. Each node is connected tightly in Program 2, which has a ring-shaped overall distribution with the core nodes spread in the inner ring. Many nodes are only connected to a small number of adjacent nodes in Program 3. Program 4 is broken into two major groups and has the shape of a butterfly. The "two wings" are joined by three core nodes, and the nodes in each "wing" are rather closely connected. The left "wing" appears as a tree with fewer branches, while the right appears as a ring (see Figure 9).

4.3. Spatial Morphology Optimization of Alternative Planning Programs in Zepan Village

The results of evaluating the four programs are presented in Table 3. The results indicate that, in terms of the network morphology of ecosystem spatial association, Program 3 has superior morphology, with high connectivity and tightness, and a high ecological radiation effect, scoring 0.9113, while Programs 4 and 2 have an acceptable morphology, scoring between 0 and −0.2, with −0.0831 and −0.1272, respectively. Thus Program 1 is the worst, with low connectivity and ecological radiation effect, scoring −0.5460. In terms of network morphology associated with human system behavior, Program 2 has the superior morphology with a score of 0.3477, higher network connectivity and service accessibility, and a higher level of coverage of village residential space services, whereas

Program 3, Program 1, and Program 4 have similar scores of −0.0128, −0.1140, and −0.1882, respectively, with Program 1 having a higher score for network structure morphology but a lower coverage of living space. Overall, Program 3 and Program 2 had positive scores of 0.8985 and 0.2204, whilst Program 4 and program 1 received negative scores of −0.2713 and −0.6600, respectively.

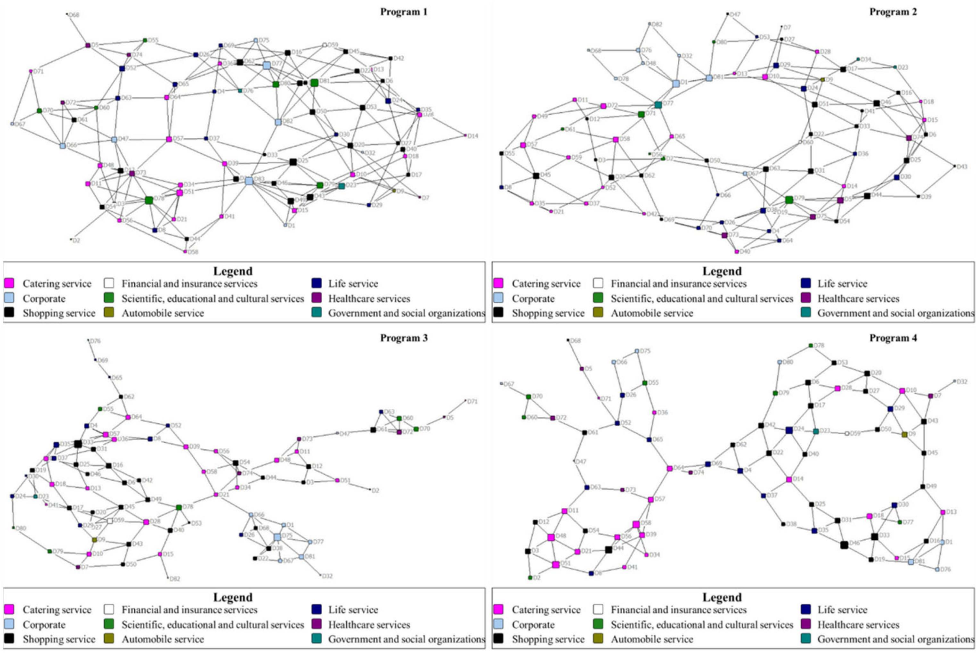

Figure 9. Structure of the human system behavior association network for the alternative planning programs in Zepan Village.

Table 3. Evaluation results of the spatial morphology of each alternative planning program in Zepan Village.

Network	Dimensionality	Indicators	Direction	Weights	Program 1	Program 2	Program 3	Program 4
Ecological linkage network morphology	Structural morphology of the ecological source	PARA_MN	+	0.20	−0.0902	0.1255	0.2564	−0.3300
	Structural morphology of the ecological corridor	D_M	+	0.20	−0.2237	−0.1337	0.3240	0.1319
	Structural morphology of the network	α Index	+	0.08	−0.0930	−0.0457	0.1332	0.0446
		β Index	+	0.04	−0.0463	−0.0281	0.0645	0.0257
		γ Index	+	0.08	−0.0928	−0.0452	0.1332	0.0447
	Total score			0.60	−0.5460	−0.1272	0.9113	−0.0831
Human behavior network morphology	Network structure	Network density	+	0.04	0.0655	0.0090	−0.0361	−0.0474
		Network relevance	+	0.04	0.0000	0.0000	0.0000	0.0000
		Clustering coefficient	+	0.04	0.0355	−0.0193	0.0045	−0.0657
		Average nearest distance	-	0.04	0.0498	0.0285	−0.0204	−0.0651
		Point degree central tendency	+	0.04	0.0247	0.0210	0.0028	−0.0779
	Service structure	Reachability index	+	0.20	−0.2894	0.3084	0.0363	0.0680
	Total score			0.40	−0.1140	0.3477	−0.0128	−0.1882
Total score				1.60	−0.6600	0.2204	0.8985	−0.2713

Therefore, the overall spatial morphology evaluation findings of the four alternative programs can be classified into three groups, with Program 3 being the optimum, Program 2 and 4 being moderate and acceptable, and Program 1 receiving the lowest morphology score and being discarded.

5. Discussion

5.1. Multi-Program Optimization to Improve Planning Practicability

From a public policy perspective, the selection of planning programs involves a decision-making process that comprises two elements at the vertical scale: option development and option selection. Option development involves the provision of planning solutions or a set of alternatives for decision-making through various planning techniques, tools, strategies, and supporting analytical systems. On the other hand, option selection emphasizes the selection of the "satisfactory" consensus solution from multiple alternatives based on a certain goal-oriented and value-based logic, taking into account the interests of stakeholders [66,67].

This paper focuses on finding a better spatial morphology rather than on morphological meritocracy, which is essentially a multi-optional problem. Therefore, the paper does not concentrate on deriving feasible results from the initial state using algorithms such as cellular automata (CA) and the genetic algorithm (GA), as traditional land use structure optimization studies do. Such model derivation methods usually have black boxes, making it difficult to understand the mechanism of model results formation, especially when there are multiple or conflicting adaptation conditions or model rules. Additionally, if the model derivation is used, the results must be fully respected, and adjustments based on the planner's technical experience are clearly against scientific principles unless the adaptation conditions and model rules are reset by returning to the model construction stage. This creates a situation where we can only judge whether the results of model derivation meet the requirements and choose to accept or reject them, without the possibility of fine-tuning them based on the planner's technical experience. However, many planning practices have demonstrated that the technical experience and personal experience of planners and stakeholders are crucial for effective planning [68]. This creates a contradiction between science and practicality.

Therefore, this paper argues that a combination of scientific and practical principles should be achieved by providing several alternative options. The paper determines the scale ratio of various land use types in the planning year of Zepan Village with reference to relevant policies and superior planning in the area where Zepan Village is located. It controls factors other than spatial morphology and then designs four spatial morphology options based on different development strategy choices obtained from research. The main focus is on providing a technical logic for judging the advantages and disadvantages of the spatial morphology of multiple planning options.

5.2. Guidance of the Best Alternative Program

If only focusing solely on the optimization process, the framework presented in this paper serves as a guide for program decision-makers to choose the best shape among multiple alternatives that appear to be similar. However, the meaning of the alternatives themselves is not as significant, as the aim is just to choose the relatively superior alternative. However, planning practice is more complex and involves considering additional factors. In planning practice, the guidance provided by the better alternative program needs to be reasonable and feasible. While the guidance provided by the best alternative in this study is intricate, it remains a reasonable and practical planning guide for alternative programs. The theoretical section of this research examines three well-established research perspectives on spatial morphology, namely the benefits of greater "morphology" benefits, more appropriate morphological relationships, and superior morphological experiences. The optimal alternative selected through the framework proposed in this paper effectively meets the demands of the residents, who are the beneficiaries of the morphological meritocracy. Rural residents, who actively seek to inhabit natural environments, require good ecological conditions and convenient living arrangements. These needs are deconstructed into a more compact morphology organization through the framework presented in this research, and the selected optimal alternative perfectly embodies this planning strategy. Specifically, the natural system in rural areas should be configured in a relatively compact manner. If a compact network cannot be formed, the pursuit of spatial connectivity is necessary to ensure the formation of high-density, long-distance core ecological corridors that link rural morphology while providing attractive natural programs for residents. Regarding human systems, the core planning principle is still a compact network, but the excessive pursuit of connectivity is not required. This approach supports the nesting of the two systems, but priority must be given to the connection of natural systems to create a valuable landscape corridor around the core village settlement.

5.3. Different Perspectives on Rural Planning Meritocracy

Planning meritocracy is a complex issue that can be examined from both a vertical and horizontal perspective. Section 4.1 of this paper focuses on the vertical perspective, which involves the decision-making process in planning program selection. In contrast, the horizontal perspective focuses on the judgment of planning schemes, including spatial morphology. This section focuses on the horizontal perspective of planning meritocracy, which involves the judgment of spatial morphology as a component of planning schemes. Previous scholarship has primarily analyzed rural planning meritocracy in two dimensions: the quantitative scale and spatial distribution, both of which contribute to the identification of the optimal land use structure [69]. To streamline this study, we treat the quantitative structure as an antecedent and exogenous factor of spatial morphology meritocracy. However, some scholars suggest that the quantitative structure should be considered a part of spatial morphology meritocracy. To this end, scholars have proposed converting spatial information into quantitative information and constructing maximization functions, such as adaptation coefficient and compactness coefficient, that account for spatial information [70,71].

However, the logic of planning optimization cannot be confined to the "quantity-space" dichotomy alone. This approach involves an implicit assumption that only the maximization of benefits is relevant. However, in rural areas, structural adjustment and optimization involve benefits and risks. The development of grasslands in China's early history serves as a typical example: although large-scale reclamation of grasslands increased the area of cultivated land, boosted food production, and resolved subsistence issues, it simultaneously created significant ecosystem risks. Therefore, rural areas with substantial agricultural land and collective land resource assets must also give due consideration to the potential risks posed by planning programs.

5.4. Superposition of "Flows" of Ecosystems and Human Systems

Research into the "flows" of ecosystems and human systems, which are spatially and behaviorally linked, is kept relatively separate. We find that integrating the two types of flows does not provide direct benefits but rather leads to confusion in program evaluation logic because their relationships are contradictory instead of mutually reinforcing. It is difficult to judge which spatial relationship between the two types of "flows" is superior—overlapping, diverging, or intersecting. On the one hand, we hope that the spatial overlap between the two types of "flows" is not too high and that human activities should be kept away from important ecological corridors, otherwise human behavior will undoubtedly affect the functions of nearby ecological corridors. On the other hand, for residents, the proximity of the two types of "flows" can ensure a more livable living environment, natural beauty, and species diversity. Other more complex spatial relationships need not be discussed. This logical conflict makes it impossible to determine which spatial pattern is superior for the two types of "flows". In contrast, the framework adopted in this article can ensure the normal functioning of ecosystems while supporting human activities and needs in an orderly manner.

Achieving an integrated perspective on the evaluation of overlapping ecological and social networks entails addressing the logical inconsistencies that arise in their assessment. A potential solution to these contradictions involves subdividing the two types of "flows" to enable a finer-scale appraisal of residents' preferences for the overlapping relationships of these flows. Specifically, low-intensity human activity "flows" should be aligned better with landscape-based ecological "flows," while high-intensity human activity "flows" ought to be distanced from ecologically vulnerable spaces. Although this approach is conceptually straightforward, its operational implementation is challenging. The various types of "flow" structures are not easily discernible, and determining which corridors should be subdivided into ecologically fragile patches poses difficulties. Hence, further in-depth discussions are imperative to address these challenges.

6. Conclusions

The depopulation of rural areas is not solely caused by economic downturns but also stems from the neglect of spatial planning in rural areas. In light of the limited availability of infrastructure and public services, the countryside must offer a distinctive and pleasant living experience in order to effectively compete with urban areas for population allocation. Previous research has erroneously interpreted spatial morphology as serving economic purposes, such as the organization of farmland and production infrastructure. However, given the current global decline in primary industry, particularly in China where per capita land area is scarce, such economic improvements alone will not alleviate the rural slump issue. It is important to note that this paper does not disregard the importance of rural economic development; rather, economic growth and poverty reduction are critical in driving rural areas into a new phase of development. Nevertheless, the key to changing the urban-rural population dynamics is through the creation of a scenic and habitable rural spatial morphology. Rural areas should possess a unique spatial settlement that features pleasant natural landscapes and convenient amenities that are distinct from those found in urban areas.

Thus, this study focuses on defining "better spatial morphology" based on flow space theory with a human-centric approach instead of an economic-centric one. It aims to explore how to optimize rural planning spatial morphology selection logic for enhancing human livability and discovering rural charm. The research area chosen is Zepan Village in Dongliang Town, Longyao County, Xingtai City, and Hebei Province, and four alternative spatial morphology programs are evaluated based on their ecological and social network analysis. Using ecological network analysis (ENA) and social network analysis (SNA), this study measures the spatial morphology of alternative planning programs based on the correlations between ecological elements and human behavior. ENA is used to identify the key ecological source and build ecological corridors to analyze the connectivity and effectiveness of the ecological network for each planning program. Meanwhile, SNA is used to connect human behavior through building POI points and analyzing the connectivity and integrity of the formed network. In addition, this study uses the landscape pattern index, corridor analysis index, spatial analysis, and social network overall analysis methods to analyze the advantages and disadvantages of each planning program based on the dimensions of source morphology, corridor morphology, network morphology, and service morphology while opposing isolation. The overall scores of the four programs are −0.6600, 0.2204, 0.8985, and −0.2713, respectively, with Program 3 being the best, Program 2 and Program 4 at the moderate level, and Program 1 having the lowest score.

In local planning practice, the multiple-program merit selection process provides a practical and informative basis for decision-making. Given the assumption that there are four relatively superior programs, the selection process aims to identify the best of the best by valuing the reference nature of each program. Therefore, the multi-program selection process presents a sequence of alternatives rather than a single best alternative, each of which can support the final planning decision. While Program 3 may score the highest, Programs 2 and 4 are also worthy of consideration, and even Program 1 may be acceptable in certain circumstances. This necessitates a comprehensive trade-off by the planning decision-maker, who is afforded the freedom to exercise their rich experience in planning practice. To preserve this freedom, the multi-program trade-off process retains the planning information of the initial programs at the end, rather than the results of calculations based on a black-box model. This is because we value the important role of planners in planning decisions, and believe that the process of translating complex planning principles into mathematical logic may diminish the value of planners. Consequently, the analytical framework proposed in this paper can be viewed as an effective tool to aid planners in tackling complex planning problems by balancing scientific principles and empirical values.

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