forests

Article

Identification and Construction of Ecological Nodes in the Fuzhou Ecological Corridors

Jiqing Lin [1], Wufa Yang [2], Kunyong Yu [3,4], Jianwei Geng [3,4] and Jian Liu [3,4,*]

[1] Fujian Chuanzheng Communications College, Fuzhou 350007, China
[2] Fuqing Municipal Bureau of Natural Resources and Planning, Fuzhou 350300, China
[3] College of Forestry, Fujian Agriculture and Forestry University, Fuzhou 350002, China
[4] University Key Lab for Geomatics Technology and Optimized Resources Utilization in Fujian Province, Fuzhou 350002, China
* Correspondence: fjliujian@fafu.edu.cn; Tel.: +86-0591-863-92-212

Abstract: Ecological corridor construction is an important support of the current pursuit of high-quality urbanization. Fuzhou is a mountain–water city characterized by a unique spatial structure. However, rapid urbanization has exacerbated the rate of ecosystem fragmentation, negatively impacting the livable living environment. The construction of ecological corridors is of great significance for efforts to restore the broken landscape and form the urban ecosystem as an organic whole in Fuzhou. In the present study, Fuzhou was considered as the study area, and the water, green, and ventilation corridors, as well as surface temperature data, were analyzed using the kernel density analysis method to generate surface-temperature-based ecological nodes. The impacts of various corridors and surface temperatures on the construction of the Fuzhou ecological corridors were assessed using ecological theory, and the ecological resistance surfaces of the influencing factors were obtained. We constructed ecological corridors for the mitigation of the urban heat island in Fuzhou using the MCR model with four levels and then evaluated the network connectivity of the corridors. The results revealed the following findings: (1) The study area comprises 32 ecological nodes, including nine in Minhou County and Changle District, four in Mawei and Cangshan Districts, and two in Gulou, Taijiang, and Jin'an Districts. (2) Fuzhou contains 63 ecological corridors with a total length of approximately 494.65 km. These include 31 first-level (201.16 km), 11 second-level (98.56 km), 14 third-level (129.12 km), and 7 fourth-level (65.81 km) corridors. (3) The degree of closure (α), the point rate of lines (β), the degree of connectivity (γ), and the degree of connectivity (Cr) indexes of the network structure for the ecological corridors were 0.27, 2.03, 0.72, and 0.87, respectively. They indicate that the overall ecological effectiveness of the network is high and can provide a theoretical basis for the construction of ecological corridors in the future.

Keywords: ecological corridor; ecological node identification; minimum cumulative resistance (MCR) model; construction

Citation: Lin, J.; Yang, W.; Yu, K.; Geng, J.; Liu, J. Identification and Construction of Ecological Nodes in the Fuzhou Ecological Corridors. *Forests* **2022**, *13*, 1837. https://doi.org/10.3390/f13111837

Academic Editor: Helmi Zulhaidi Mohd Shafri

Received: 4 September 2022
Accepted: 2 November 2022
Published: 4 November 2022

1. Introduction

The continuous increases in the urban population [1] and urbanization worldwide [2] are associated with ecological and environmental issues, such as biodiversity loss, soil loss, flooding, and haze [3–5]. These issues negatively impact the living environments of humans. Governments and scholars have thus been led to consider the question of how to adopt low-carbon, energy-saving, green, and environmental protection methods in order to solve these problems. Ecological corridors consisting of vegetation, water, and other elements are of great interest to scholars. The ecological corridors are located in key areas of the urban ecosystem [6], which can serve as habitats, sources, and sinks, and they are the bridges and links between habitat plaques [7]. They are the key to realizing the sustainable development of the city [8–10]. They can reduce the distribution of pollutants and the heat island effect [11,12], enhance the connection between isolated plaques [13], and reduce the negative impact of plaque fragmentation [14].

According to analyses of different cities [15–17]), the water [18], green [19], and ventilation [20] corridors are ecologically beneficial to a city. Models such as the network, current, and hydrologic analysis methods are commonly used to highlight ecological processes and determine measures for the protection of ecological corridors [21–23]. Ecological nodes are vital points in an ecosystem, including the breakpoints and intersections of corridors, roads, bridges, catchment mouths, the junctions of valleys, and ridges [24–26]. Currently, ecological nodes are divided into the resource and structured types [27]. Resource-based ecological nodes generally comprise ecological source areas [28], whereas structural nodes mainly include the special areas of the ecological structure and areas that play important roles in biological migration [29]. Ecological nodes are identified using diverse methods. The study and recognition of resource-based ecological nodes are mainly conducted via the morphological spatial pattern analysis (MSPA) model [30]. The minimum cumulative resistance (MCR) model is used to identified structural nodes [31–33]. The structural ecological nodes focus on the dynamic change in the spatial position of the ecological nodes, which are significant for biological migration in the region.

The large-scale urbanization of Fuzhou has led to changes in land use, which has had direct impacts on the thermal and wind environments of the city. Studies have shown that [34–36] Fuzhou is among the four major hot cities in China, and the number of heat islands in the city are increasing. Fuzhou is a mountain–water city characterized by a unique spatial structure, which creates the conditions for the construction of urban ecological corridors. It is possible to integrate mountain and water resources to bring cold air from the southeast coast into the central city and alleviate the urban heat island effect. Consequently, the construction of ecological corridors in Fuzhou plays an important role in improving the urban heat islands and optimizing the living environment. In the present study, the length of the ecological corridor and characteristics of the ecological nodes in Fuzhou were investigated. The intersections were obtained by overlaying the grid map with the water, green, and ventilation corridors and the surface temperature as the ecological nodes, and then the important ecological nodes were determined by the kernel density analysis method. According to the characteristics and width of ecological corridors, ecological resistance surfaces were obtained by coupling the buffer zone between the water, green, and ventilation corridors, as well as the surface temperatures. Based on the MCR model, the ecological corridors of Fuzhou were determined and then evaluated using the network connection theory. This can provide a decision reference for achieving sustainable urban development in Fuzhou.

2. Study Area and Methods

2.1. Overview of the Study Area

Fuzhou is one of the central cities in the economic zone on the west coast of the Taiwan Strait, located in the lower reaches of the Minjiang River adjacent to the entrance to the sea on the east side, with typical estuarine basin landform characteristics. The overall topography is high in the northwest and low in the southeast. Influenced by the natural topography, southeasterly winds prevail all year round, followed by northwesterly winds. It has a subtropical monsoon climate, with long summers and short winter in Fuzhou. The present study is based on the area surrounded by the Wuhu Mountain, Qishan, Lianhua Mountain, and Gushan (Figure 1), and these include the Gulou, Jin'an, Taijiang, Mawei, Cangshan, and Changle Districts, as well as townships in the Minhou County (e.g., Ganzhe, Shangjie, Nanyu, and Nantong), covering an area of approximately 1759.4 km^2.

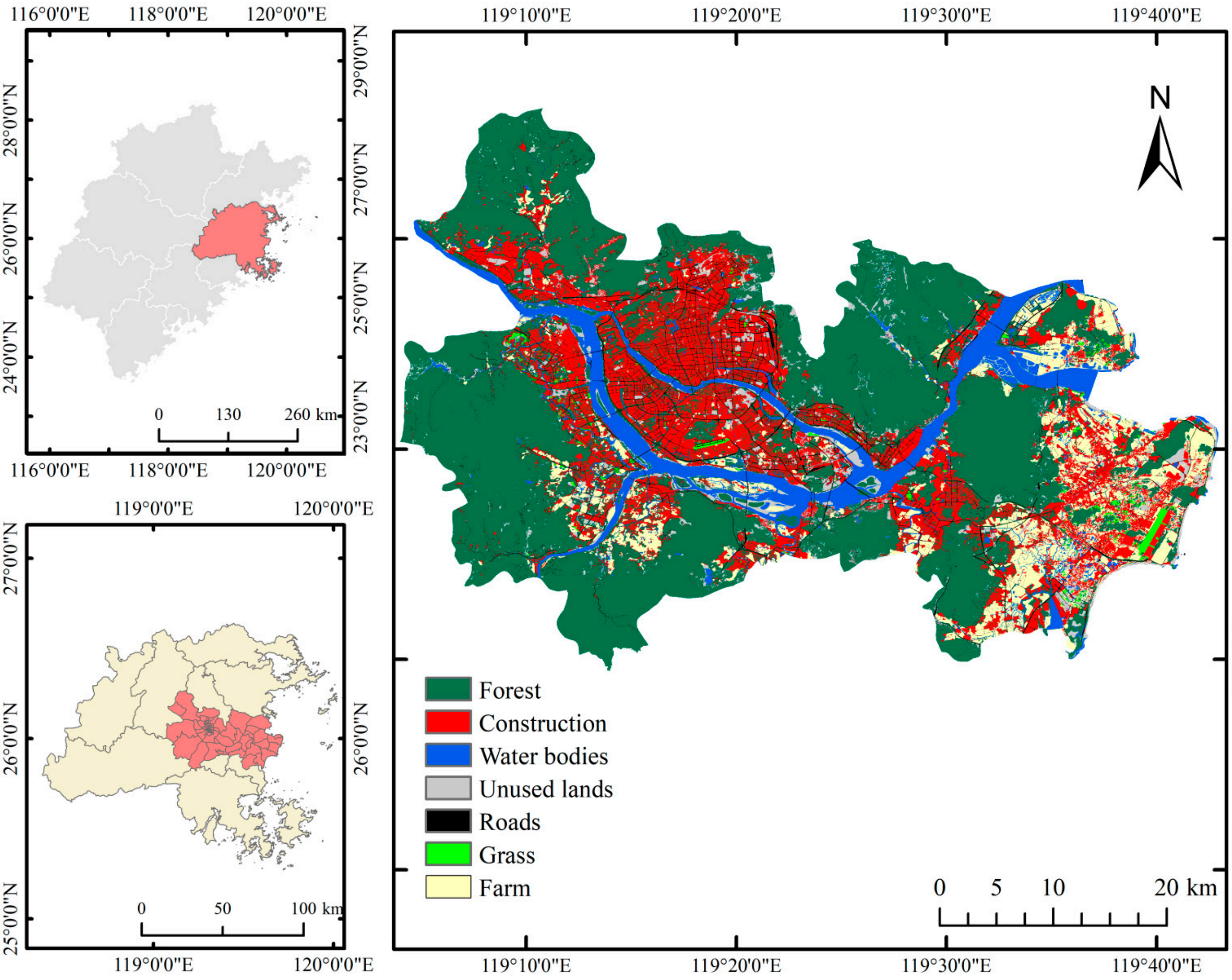


Figure 1. Study area.

2.2. Study Area Data

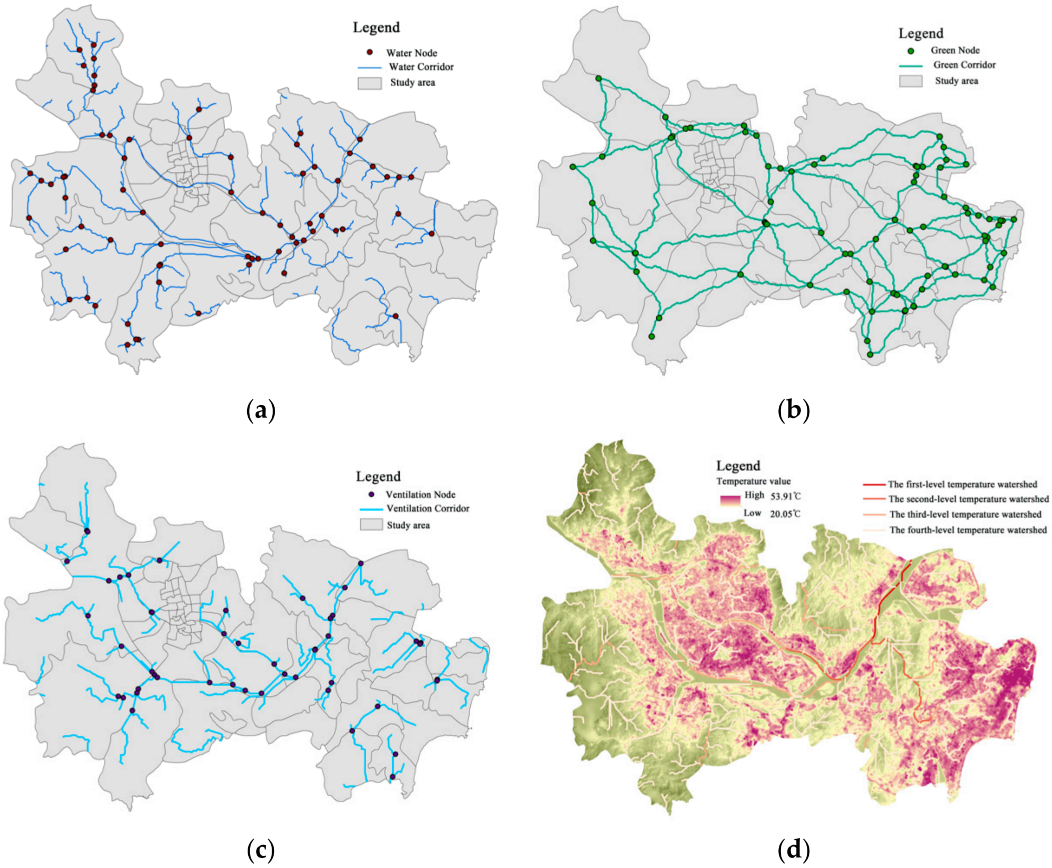
In 2019, a 2.5 m high-precision image of Fuzhou (downloaded from the Google Maps resource-sharing platform) was obtained using supervised classification and visual interpretation methods. With reference to the national standard of the Current Land Use Classification (GB/721010-2017), combined with the current characteristics of land use in Fuzhou, based on the landscape classification system, the land use types were classified into a total of seven categories, including forest land, buildings, water bodies, unused land, roads, farmland, and grassland, after an in-depth discussion of the natural, ecological, and landscape characteristics of the land use. The overall accuracy of the classification is 89.84%, and it has a kappa coefficient of 0.85. Thus, the classification results meet the accuracy requirements. On 22 September 2019, a low-noise Landsat 8 OLI remote sensing image showing minor geometric variability and a cloud cover of <2% (downloaded from the website of the US Geological Survey) was obtained using an atmospheric correction Fa-rectification of the surface temperature. The water corridor map, green corridor map [37] and ventilation corridor map [38] of Fuzhou were provided by the University Key Lab for Geomatics Technology and Optimized Resources Utilization in Fujian Province. In addition, a 30 m-resolution DEM remote sensing image (obtained from the China Geographical Space Data Cloud Website) and planning documents for Fuzhou, such as the Fuzhou General Planning (2010–2020), Fuzhou New District General Planning (2015–2020), Fuzhou Metropolitan Area Development Planning (2020–2035), Fuzhou Land and Space

General Planning (2021–2035), Fuzhou Urban Comprehensive Transportation Planning (2021–2035), and other documents, were also utilized.

2.3. Methods

2.3.1. Ecological Node Extraction and Assessment

Ecological nodes are vital locations associated with the ecological processes that occur between plaques in ecological corridors [39]. In general, in the weakest part of a corridor, the connected ecological nodes can transform structural linkages into functional connections between plaques [40,41]. Ecological nodes can represent the intersections between minimum expense paths [42,43], convergence points of corridors, and intersections between different levels of corridors [44]. The temperature watershed is the use of hydrological analysis to simulate the motion path and convergence characteristics of the surface temperature. The specific approach to its temperature flow direction, the high and low temperature values of the temperature field, are used as the base raster cells, and the inverse surface temperature vector number is converted to raster format. The flow direction raster is created using the flow direction tool, and the flow direction is determined by finding the steepest descent direction on the image element. Each image element is encoded with the image element ID of its flow direction, and the ID number is a power of 2. A pooling network is produced using the flow accumulation tool, and the image elements with higher sink values are extracted to form a temperature pooling network in the form of a raster. Based on the water, green, and ventilation corridors and temperature watershed (Figure 2), intersections are obtained by overlaying each of them. These intersections are not only the intersections within a single corridor but also the common intersections between two corridors or three corridors.



(**a**) (**b**)

(**c**) (**d**)

Figure 2. Corridors and temperature watershed maps. (**a**) Water corridors. (**b**) Green corridors. (**c**) Ventilation corridors. (**d**) Temperature watershed.

The kernel density analysis is a non-parametric method. Using this method, the distribution density of an element in space was mainly evaluated by calculating the density of the surrounding space. The spatial distribution of the ecological nodes was then analyzed via the weighted kernel density, and the density of an attribute at each location was then superimposed. Based on the identification of the ecological nodes in the study area, the distribution densities of all the elements in the area were obtained. Through screening, areas with a high concentration of ecological nodes were identified, and the degree of aggregation of the ecological nodes in the spatial distribution was then obtained. In general, the attribute density in the central position was the highest, and this density gradually decreased as the distance from the center increased. The impairment can thus be obtained based on the kernel density function using the following expression [45,46]:

$$f(x) = \frac{1}{nh} \sum_{i=1}^{n} K\left(\frac{x_i - x}{h}\right) \tag{1}$$

where *f(x)* is the kernel density estimation function at x in the research space, K is the space weight function value, h is the search interval threshold of the kernel density function, n is the number of samples, and $x_i - x$ is the sample point x to the spatial distance of the sample point x_i.

2.3.2. Construction of Ecological Corridors

According to previous studies on the characteristics and widths of ecological corridors [47], for the green, water system, and ventilation corridors, as well as the temperature watershed, the distances of 0–30, 30–80, 80–120, 120–150, and >150 m are five-level width buffers highlighting the resistance factors in such corridors (Table 1). The resistance factors were then superimposed to obtain a comprehensive buffer ecological resistance surface that reflects the movement resistance and trend of the ecological flow using the following expression:

$$R_i = \sum_{j=1}^{n} (C_{ij} \times W_{ij}) \tag{2}$$

where R_i is the comprehensive resistance value of the ecological corridor unit i, C_{ij} denotes the resistance factor j of the ecological corridor unit i, W_{ij} represents the weighted value of the resistance factor j that corresponds to the ecological corridor unit i, and n is the number of resistance factors.

Table 1. Resistance factors and resistance values.

Value Range	Resistance Values			
	Water Corridor	Green Corridor	Ventilation Corridor	Temperature Watershed
0–30 m	1	1	1	1
30–80 m	2	2	2	2
80–120 m	3	3	3	3
120–150 m	4	4	4	4
>150 m	5	5	5	5

Ecological resistance refers to the resistance of species and the ecological flow to spreading outside [9]. The higher the resistance is, the more difficult the ecological process will be [48], and this facilitates the loss in ecological services and functions. In the present study, the spatial characteristics and resistance associated with the MCR model were utilized to construct an ecological corridor network. ArcGIS was used to set the start and end points of target ecological nodes via the Linkage Mapper spatial analysis function and the Build Network and Map Linkages model builder tools. The costs associated with the path connections between ecological nodes on the comprehensive ecological resistance surface of the grid (distance calculation) and the minimum cost back (minimum expense path) were calculated to extract the linear or strap continuous paths connected via units characterized by a low ecological resistance between plaques, that is, the ecological corridor. This was determined as follows:

$$C_i = \sum\nolimits_{j=1}^{n} \left(D_i \times F_j\right) \tag{3}$$

where C_i is the accumulated distance of the ecological corridor units i (i = 1, 2, 3, . . . , m) to the ecological sources, that is, the calculated minimum cost. D_i represents the distance from the ecological corridor unit i to the ecological source, and F_j denotes the migration resistance of the species in the space of the ecological corridor unit j (j = 1, 2, 3, . . . , n).

2.3.3. Network Structure Indexes of the Ecological Corridors

Based on the connection theory of the ecological network, the α, β, and γ indexes, as well as the cost ratio (Cr), were calculated to evaluate and analyze the landscape structure and degree of connection in the Fuzhou ecological corridor network. The degree of connection refers to the extent of the links between the nodes in an ecological network. A high connection of landscapes helps to maintain the ecological processes and biological diversity [49]. The degree of connection is characterized using the following indexes:

(1) α index

The α index highlights the degree of closure in the network, and it ranges from values of 0 to 1. The closer the α value is to 1, the better the network closure is, and the higher the efficiency of the information and energy flow is. This index is calculated using the following formula:

$$\alpha = \frac{e - v + p}{2v - 5p} \tag{4}$$

where e represents the number of network cables, v is the number of network nodes, and p denotes the number of unconnected sub-diagrams in the network, and the value is commonly 1.

(2) β index

The β index is the point rate of lines in the network, and it is an indicator of the complexity of the structure of the network. Its values vary between 0–3, and the network improves as the index increases. The β index is determined using the following formula:

$$\beta = \frac{e}{v} \tag{5}$$

where e is the number of network cables and v represents the number of network nodes.

(3) γ index

The γ index reflects the degree of connectivity in the network, and its values range between 0–1. A γ index close to 1 indicates that almost all nodes in the network are connected. This index can be calculated using the following formula:

$$\gamma = \frac{e}{3(v - 2p)} \tag{6}$$

where e represents the number of connections, v is the number of network nodes, and p denotes the number of unconnected sub-diagrams in the network, and its value is commonly 1.

(4) Cost Ratio (Cr)

The Cr is an indicator of the cost of constructing a corridor in the network that is being investigated, and its values vary from 0 to 1. A Cr close to 1 indicates a high cost of construction of a corridor in the network. This ratio is determined as follows:

$$Cr = 1 - \frac{1}{d} \tag{7}$$

where l represents the number of corridors in the network and *d* is the length of the corridor in the network.

3. Results and Analysis

3.1. Analysis of Ecological Nodes in the Corridor

According to data displayed in Figure 3 and presented in Table 2, areas with the most ecological nodes in the green corridor were Changle District (42), Minhou County (14), and Mawei District (13). Ecological nodes were uncommon in the center of the urban area, including Taijiang District (0). In turn, for the ventilation corridor, Minhou County (16) contained the highest number of ecological nodes, whereas Jin'an (1) and Taijiang (1) Districts, in the center of the urban area, showed the least number, and the presence of nodes was mainly affected by the density of the buildings and land use in the study area. In the water corridor, the highest number of ecological nodes were identified in Minhou County (37), whereas the least were in Gulou (1) and Taijiang (1) Districts, and the urban heat island effect in the area was significant.

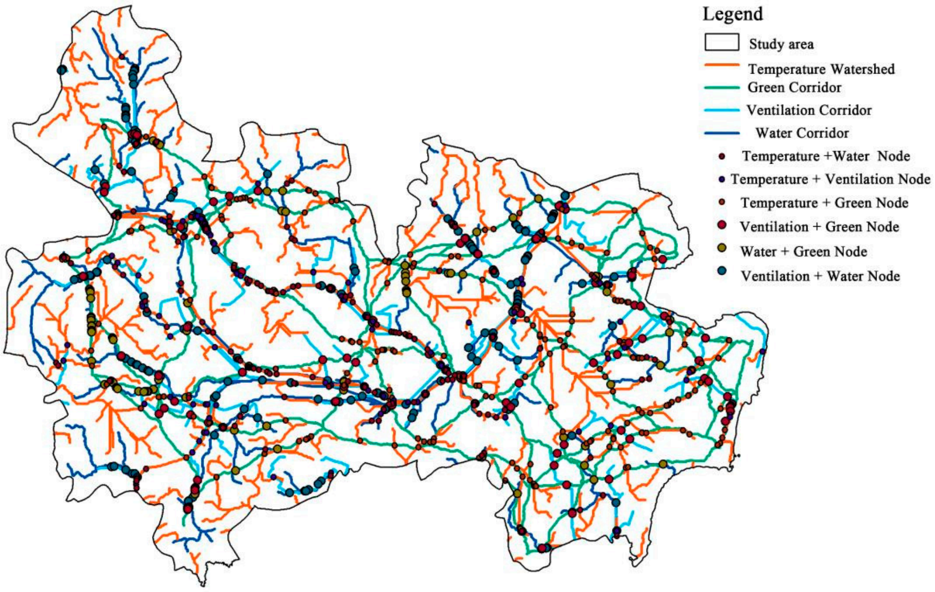


Figure 3. Corridors overlayed: ecological node distribution.

Alternatively, overlaying the ventilation and green corridors, Changle District (40) and Minhou County (31) contained the highest number of ecological nodes, whereas Jin'an and Taijiang Districts were associated with none. This distribution was unsuitable for the construction of an ecological corridor network. In turn, overlaying the ventilation and water corridors, Minhou County (65) and Mawei District (40) were characterized by many ecological nodes, whereas Gulou (2), Jin'an (3), and Taijiang (3) Districts contained few. This distribution also creates a significant resistance to the generation of a road path in the ecological corridor network. Overlaying the green and water corridors, Minhou County (66), Changle District (36), and Mawei District (36) contained many ecological nodes, whereas nodes were scarce in Gulou (1) and Taijiang (1) Districts.

Overlaying the green, ventilation, and water corridors, as well as the surface temperature, the areas with high numbers of ecological nodes were Minhou County (124) and Changle District (106), and this is beneficial for the formation of an ecological corridor. Whereas Jin'an (23), Taijiang (23), and Gulou (16) showed few nodes, the presence of these nodes was controlled by the land use type, and few ecological plaques and nodes hindered the connections in the ecological corridor network.

Table 2. Corridors overlayed: ecological node distribution statistics.

Corridor	**Ecological Nodes in Administrative Regions (Unit: Number)**						
	Cangshan District	**Gulou District**	**Mawei District**	**Jin'an District**	**Taijiang District**	**Minhou County**	**Changle District**
Green corridor	3	2	13	6	0	14	42
Ventilation corridor	5	3	11	1	1	16	11
Water corridor	4	1	14	2	1	37	10
Ventilation + green corridor	8	4	25	0	0	31	40
Ventilation + water corridor	12	2	40	3	3	65	14
Green + water corridor	9	1	36	5	1	66	36
Green + ventilation + water + temperature watershed	62	16	72	23	23	124	106

The kernel density values ranged between 0 and 8.87. The kernel density was proportional to the concentration of ecological nodes in an area. Concerning the settlements associated with the ecological nodes, the darker the color of the center of the settlement area is, the higher the range of radiation in the area is. The ecological node settlements with high kernel density values, a deep color, and large radiation range were selected, and then the geometric center points were analyzed by ArcGIS. At last, 32 ecological nodes were obtained (Figure 4), which were distributed in different administrative regions. Regarding the overall space of the study area, the main urban area and the surrounding forest areas were favorably distributed with respect to the construction of a multi-corridor ecological network. However, in the eastern coastal areas, the distribution was less favorable, and this affected the construction of the ecological corridors.

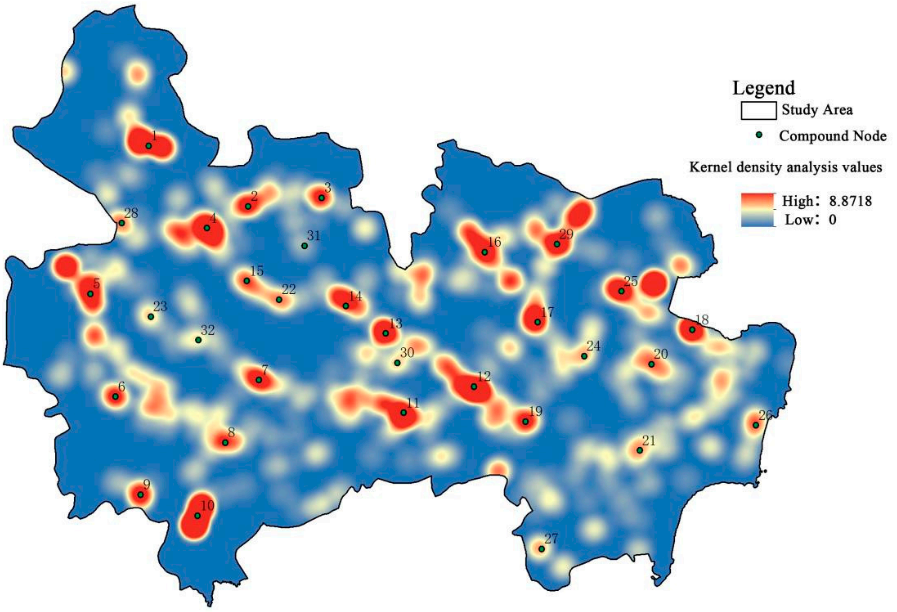


Figure 4. The kernel density analysis results—spatial distribution of the ecological nodes.

The data presented in Table 3 show that Minhou County (9) and Changle District (9) contain the highest number of ecological nodes, followed by Mawei (4) and Cangshan (4) Districts, and Gulou (2), Jin'an (2), and Taijiang (2) Districts. The number, location, and distribution of all the ecological nodes in each administrative region are presented in Table 3.

Table 3. Spatial distribution of the ecological nodes.

Administrative Region	**Ecological Nodes**	
	Quantity	**Location (Numbering)**
Gulou District	2	Fu Shan Country Park (2), North Park of Minjiang Park-Jinshan Bridge (15)
Taijiang District	2	Minjiang Colorful Garden (22), Minjiang River-Gushan Bridge (14)
Jin’an District	2	Dengyun Lake (3), Jinjishan Park (31)
Cangshan District	4	Beach Park (4), Wulong River-Wanbian Bridge (7), Minjiang River-Qingliang Mountain (11), Tietou Mountain (30)
Mawei District	4	Minjiang River-Chuanzheng Cultural Scenic Area (12), Minjiang River-Kuipu Bridge (13), Xili Stream (16), Tail of Tiger and Wolf Mountain (29)
Changle District	9	Dongtian Rock in Monkey Island (17), Minjiang Estuary National Wetland Park (18), Chang’an Park (19), Changle West Lake Park (20), Niushan Park (21), Tiantai Mountain Park (24), Hongguang Lake Park (25), Changle Hulu Mountain (26), Taiping Mountain (27)
Minhou County	9	Stalagmite Mountain (1), Lianlu Mountain (5), Qishan National Forest Park (6), Shangzhou Park (8), Dazhangxi-Diaoluoding Mountain (9), Eighteen Streams Scenic Area (10), Xiyuan River-Qi’an Village (23), Minjiang River-Liyuzhou Hotel (28), Wulong River-Pushang Bridge (32)

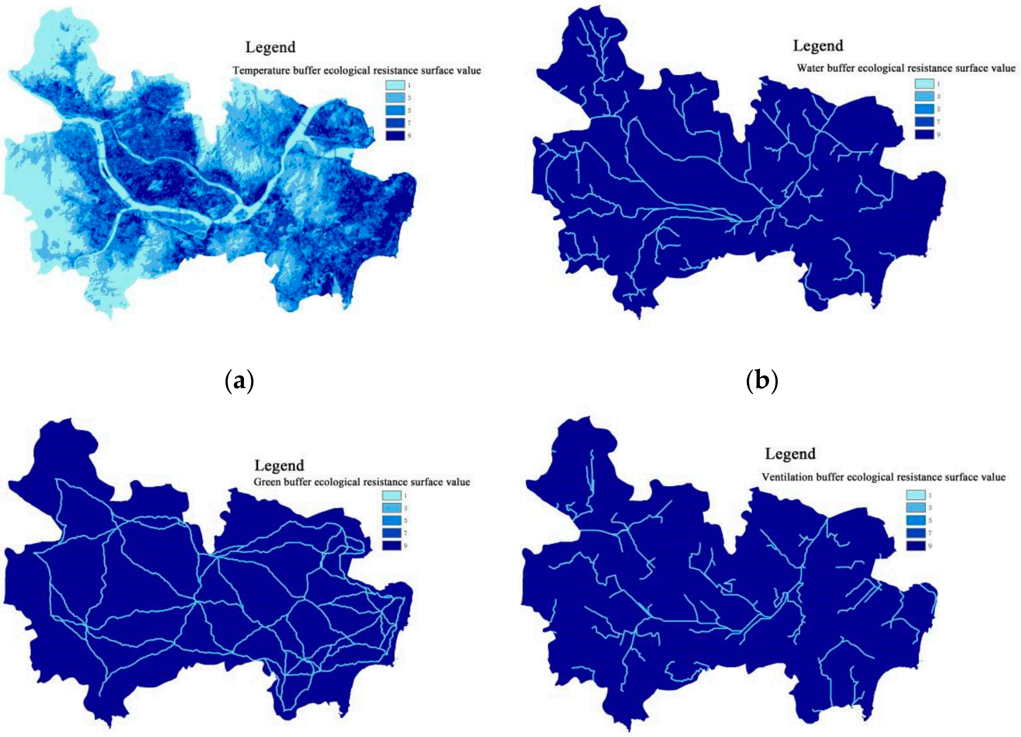
3.2. Ecological Corridor Analysis

Through the superposition of the ecological resistance factors (Figure 5), a comprehensive ecological resistance surface of the buffer area was obtained (Figure 6). The darker the color is, the higher the value of the comprehensive resistance surface is, the greater the resistance of the corridor path is, and the more conducive it is to the generation of the corridor. Areas with high comprehensive resistance values in the buffer area included Gulou, Taijiang, Jin’an, Cangshan, Mawei, and the local areas of the Changle District, as well as the Shangjie University, Nantong, and Qingkou towns, and the High-Tech Development Zone in Minhou County.

In the MCR model, a weighted cost method was used for the evaluation and analysis of the paths to generate the ecological corridor network. Using the Linkage Mapper tool of the ArcGIS, the minimum number of connected paths between the ecological nodes was set to 1, 2, 3, or 4. Based on the situation observed in the study area, excess paths were then merged or deleted.

Figure 7 shows 63 ecological corridors with a total length of 494.65 km. The first-level ecological corridors, which are shown in red, represent the first path, and the length of these 31 corridors was approximately 201.16 km, accounting for 40.67%. These corridors connect important ecological sources and plaques in the study area, such as Qishan National Forest Park, Gushan Natural Scenic Area, Wuhu and Lianhua mountains, and the Minjiang River Basin. These features constitute the basic skeleton of the ecological corridors in the entire study area. The second-level ecological corridors that are shown in yellow represent the second path, and these 11 corridors that measure approximately 98.56 km in length, accounting for 19.93%, were primarily in the western part of Minhou County and east of the Changle District. Notably, no secondary ecological corridor was present in the center of the study area. In turn, the third-level ecological corridors that are depicted in green comprise the third path. These 14 corridors, which measure approximately 129.12 km in length, accounting for 26.10%, were widely distributed in the study area, and these essentially completed the corridor network. The seven fourth-level ecological corridors, which are shown in light blue, represent the fourth path, and their total length is approximately 65.81 km, accounting for 13.30%. These corridors were mainly in Minhou County and

Gulou and Cangshan Districts. Even though the corridors reflect an overall decentralized layout, several administrative regions in the east contain no corridor.



(**a**) (**b**)

(**c**) (**d**)

Figure 5. Ecological resistance surface: (**a**) temperature buffer ecological resistance surface factor; (**b**) water buffer ecological resistance surface factor; (**c**) green buffer ecological resistance surface factor; (**d**) ventilation buffer ecological resistance surface factor.

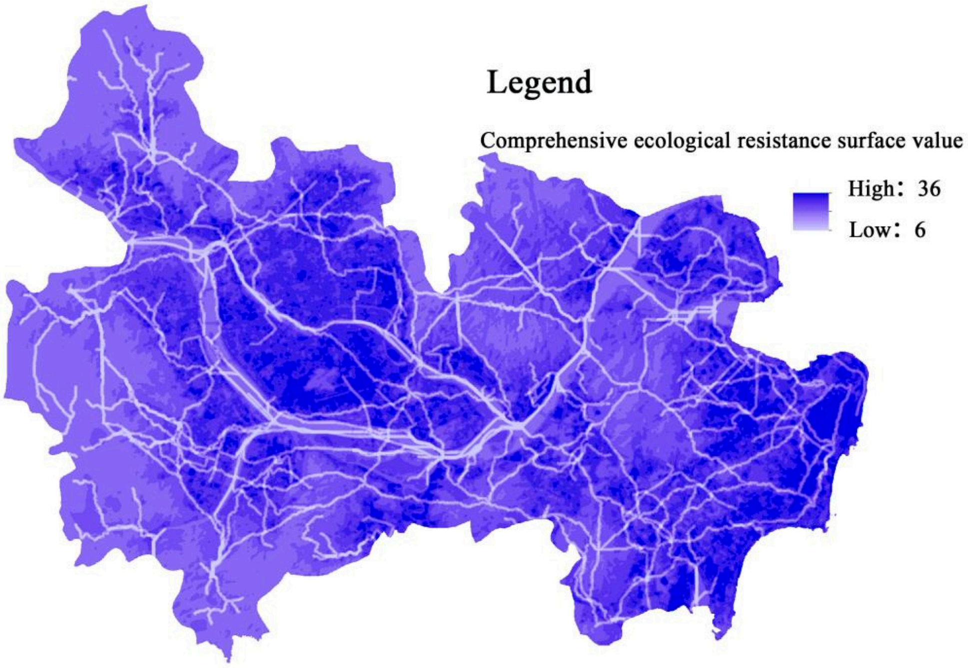


Figure 6. Comprehensive ecological resistance surface.

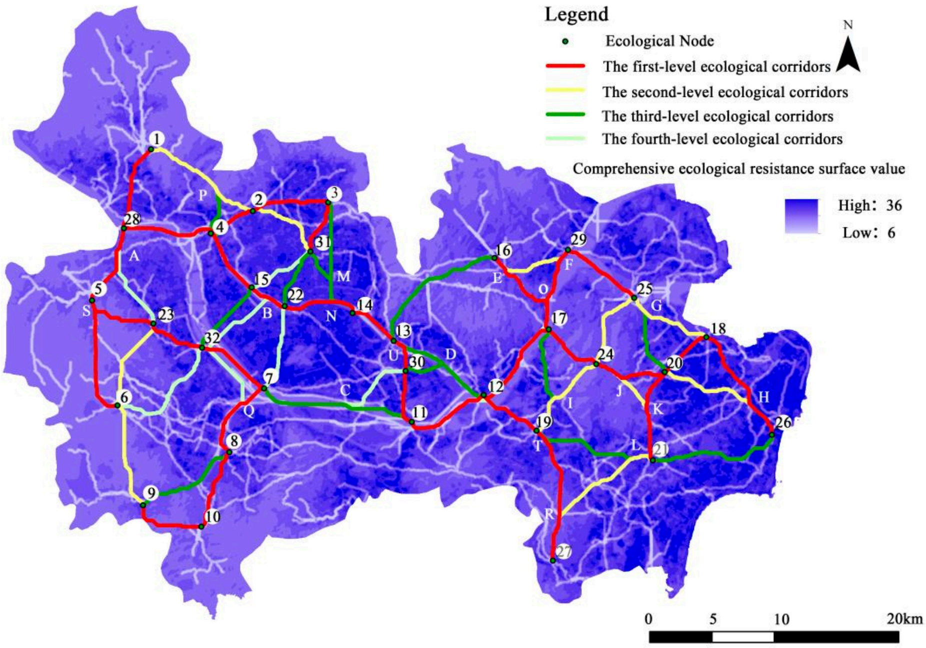


Figure 7. Distribution map of the ecological corridors.

The 63 main ecological corridors were counted to determine the number of ecological corridors at each level connected to each ecological node. As shown in Table 4, the ecological node of Dongtian Rock in Monkey Island (17) connects four first-level ecological corridors. The regional cumulative resistance is low, and the quality of the ecological corridors is high. The area is located on the edge of the Min River, with lush plants and less impact of urbanization, which is more conducive to the flow of ecological information and maintenance of a better ecological connectivity. Beach Park (4), Lianlu Mountain (5), Minjiang River-Chuanzheng Cultural Scenic Area (12), Changle West Lake Park (20), and Minjiang River-Liyuzhou Hotel (28) are connected to three first-level ecological corridors. Nos. 12, 20, and 28 are located near the Minjiang River, No. 4 is located near the Wulong River (open water and good ventilation reduce the cumulative resistance), and No. 5 in is located in Lianlu Mountain, an area dominated by forests, with a low level of development and small cumulative resistance. Tiantai Mountain Park (24) connects three second-level ecological corridors, namely Hongguang Lake Park (25), Chang'an Park (19), and Niushan Park (21), of which No. 25 is located at the estuary and No. 19 is located by the Minjiang River. No. 21 is a mountain park, and the water bodies and plants in the park effectively reduced the cumulative resistance. Niushan Park (21) and Minjiang River-Kuipu Bridge (13) are connected to two third-level ecological corridors. As they are affected by factors such as terrain and airport construction, the ecological corridors have greater resistance, and the quality of the corridors has declined. The ecological node of Wulong River-Pushang Bridge (32) connects three four-level ecological corridors, which are located in Qishan National Forest Park (6) and Shangzhou Park (8) and near the North Park of Minjiang Park (15).

Table 4. Number of ecological corridors connected by ecological nodes at each level.

Ecological Node	The First-Level Corridors (Strip)	The Second-Level Corridors (Strip)	The Third-Level Corridors (Strip)	The Fourth-Level Corridors (Strip)
1	1	1	0	0
2	2	2	0	0
3	2	0	1	0
4	3	0	1	0
5	3	0	0	0
6	1	2	0	1

Table 4. *Cont.*

Ecological Node	The First-Level Corridors (Strip)	The Second-Level Corridors (Strip)	The Third-Level Corridors (Strip)	The Fourth-Level Corridors (Strip)
7	2	0	1	1
8	2	0	1	0
9	1	1	1	0
10	2	0	0	0
11	2	0	1	0
12	3	0	1	0
13	2	0	2	0
14	2	0	0	0
15	2	0	1	1
16	1	1	1	0
17	4	0	1	0
18	2	1	0	0
19	2	1	2	0
20	3	1	1	0
21	1	1	2	0
22	2	0	1	2
23	2	1	0	1
24	2	3	0	0
25	1	2	1	0
26	1	1	1	0
27	1	1	0	0
28	3	0	0	1
29	2	1	0	0
30	2	0	1	1
31	1	1	2	1
32	2	0	1	3

The Fuzhou General Planning (2010–2020), Fuzhou New District General Planning (2015–2020), Fuzhou Metropolitan Area Development Planning (2020–2035), Fuzhou Land and Space Master Planning (2021–2035), Fuzhou Urban Comprehensive Transportation Planning (2021–2035), and other documents were used to verify the rationality of the land use function. The path of the ecological corridor conformed to the overall planning of the urban land and was consistent with the planning of the urban green space and road networks.

3.3. Evaluation of the Ecological Corridor Network Structure Indexes

The α index at a general level, as shown in Table 5, is 0.27, and the corridors form a network. Overall, the network is closed, and it was characterized by a high degree of connection. The β index of 2.03 also indicates a network involving a high degree of connection. In addition to a high degree of connection between the ecological nodes in the network, the γ index of 0.72 revealed that, internally, the network is complex. The *Cr* of 0.87 indicates that the cost of building the ecological corridor is high.

Table 5. Evaluation of the ecological corridor network structure indexes.

Ecological Corridors	Network Structure Indexes					
Number of corridors	Number of nodes	Overall length of corridor	α index	β index	γ index	*Cr* index
63	31	494.65 km	0.27	2.03	0.72	0.87

In summary, the overall degree of connection of the ecological corridor network that was constructed in the present study is high. Considering the obvious circuits between the ecological nodes, the integrity and complexity of the corridor network are also high. This network is conducive to the migration and exchange of energy between different creatures.

This migration and exchange promote the interactions between diverse functional flows in the study area, and these significantly enhance the protection of biodiversity and the ecological efficiency. The ecological corridor network integrates the functions and structures of the water, green, and ventilation corridors and, thus, it is characterized by stable and comprehensive spatial characteristics. The inclusion of the surface temperature in the construction of the corridor network improves the cooling effect.

The cost of the ecological corridor network is higher than that revealed by the index; thus, its construction is limited. Therefore, in the planning and construction of this network, the economic, ecological, and social benefits must be comprehensively considered.

4. Discussion

With the increasing severity of the widespread ecological problems in China, the management concept of mountains-water-forests-lakes-grasses-sand was proposed to achieve ecological systematization and integrity in order to solve regional ecological network problems and improve the human living environment. The ecological corridors of different types, functions, and structures constitute an extremely complex ecological network, creating direct or indirect connections in space and biological processes with the external environment through the internal environment, forming a complete and complex ecosystem. The construction of a single ecological corridor ignores the coupling of ecological processes with other ecological spaces and does not fully ensure the protection and restoration of the ecological network. Studies have shown that ecological networks have the ability to stabilize ecosystems, improve the regional ecosystem service capacity, and maintain regional security [50,51]. In recent years, scholars have conducted further studies on ecological networks and formed a relatively mature research system. The studies on the ecological corridors in Fuzhou mainly focus on the analysis of the current situation, ecological protection and utilization, etc. This study investigates the construction of ecological corridors at the level of the heat islands. The results show that urban rivers and water bodies can effectively reduce the summer temperatures, increase humidity, and regulate the urban climate [52]. Therefore, in this study, we constructed ecological corridors by integrating water, green, and sea breeze resources for the purpose of alleviating the heat island in Fuzhou.

In terms of the land use types (Figure 1), there is less green space in the central part and more green space in the surrounding mountains, which leads to an uneven distribution of the thermal environment. The heat islands are concentrated in the central and eastern parts of the city. The high building density, impermeable pavements, and human activities in the central part of the city aggravate the heat island, while the eastern part is influenced by urban expansion and the orderly phase II construction of the airport, which aggravates the breadth and depth of the heat island space and is consistent with previous studies [53]. Land use is an important component affecting the biological landscape movements, and the strength of the integrated ecological resistance surface in the buffer zone (Figure 6) is related to the land use type. The resistance value of the building land is higher than that of the water body, which is consistent with the previous studies [54]. To alleviate the current situation, characterized by a large integrated ecological resistance surface in the central buffer zone, new low-carbon, energy-saving, and emission-reducing technologies and techniques, such as green roofs, rain gardens, and green buildings, can be adopted in future urban planning and architectural design. In addition, they can be combined with the use of wind power, which is energy-efficient and environmentally friendly, in the eastern region. Studies have shown that the wind plays an important role in regulating the urban surface temperature [55]. Fuzhou has a typical estuarine basin landform feature, and the overall topography is high in the northwest and low in the southeast. The southeast wind prevails in the summer and brings cool, moist, fresh, cold air into the central city along the Minjiang and Wulong Rivers through the reasonable building forms [56], plant matching [57], etc.

Ecological nodes are an important part of the ecological corridor and can maintain the stability of the network structure. In total, 32 ecological nodes were obtained using the kernel density analysis method, which were mainly distributed in the Minjiang River, Wulong River, and the surrounding mountains. A total of 63 ecological corridors were obtained, which were divided into three path modes: the partially overlapping, similar parallel, and two-point connection. Some ecological corridors were dominated by the two-point connection path mode and supplemented with the partially overlapping path mode, such as 28-5 and 28-23, and some were complemented by similar parallel path modes, such as 32-15 and 32-B. Twenty-one new ecological nodes were added (Figure 7): five in Minhou County (A, Q, C, P and S), one in Cangshan District (B), two in Jin'an District (M, and N), five in Mawei District (D, E, F, O, and U), and eight in Changle District (G, H, J, K, I, L, R and T). The new ecological nodes were mostly located on the periphery of the city, with only three being closer to the city center. Although the number is small, the complexity of the corridors is enriched. A new fourth-level ecological corridor was created at point B, and three new third-level ecological corridors were created at point M. The generation of intersections facilitated the flow of energy and enriched the diversity of ecological corridors. The construction of the ecological corridor of the surrounding mountains should protect the mountains through ecological protection measures, which can be used as a springboard for the migration of species [58]. The construction of ecological corridors should avoid agricultural land and follow national development strategies.

The connectivity of ecological nodes affects the species flow and species diversity [59]. Currently, scholars often use connectivity to evaluate the advantages and disadvantages of ecological corridor construction. For example, the connectivity and complexity of the ecological networks in eastern China were analyzed using graph theory [60]. In this paper, we add the cost ratio to make the construction of the ecological corridors more realistic. Fuzhou is an important coastal province in China, and with the rapid economic growth observed in recent years, the ecological environment has become damaged. The construction of ecological corridors is a purposeful ecological restoration strategy and a long-term practice. Although it is costly, it can improve the ecological environment of the city and achieve the sustainable use of resources by enhancing the connectivity of the water, green, and ventilation spaces through reasonable resource allocation.

Due to the limitations of the study, future research will be conducted in the following two areas. Firstly, the surface temperature is an important factor in the construction of an ecological corridor network. Studies of ecological corridors are influenced by external factors, such as humans and time. During the first phase, which involves the use of remote sensing data for the analysis, a comprehensive understanding of the actual situation in a region is difficult. The surface temperature data for different months in a year, including the summer, provide better basic data to support the construction of an adequate ecological corridor network. Secondly, ecological corridors and ecological nodes are the focus of the study of ecological security patterns, which are significant for maintaining the sustainable development of the region [61]. Ecological corridors are linear or ribbon landscape elements, which are vulnerable to disturbance from the external environment and should have corresponding corridor widths and buffer zones, but since the width of ecological corridors is closely related to the level, one must consider the design objectives and landscape type of the corridor. The setting of the ecological corridor width will be further discussed in the subsequent study.

5. Conclusions

Based on the data for the water, green, and ventilation corridors and temperature watershed, 32 ecological nodes were screened out by the kernel density analysis method, and 63 ecological corridors and 26 new ecological nodes were constructed using the MCR model and GIS software. The total length of the ecological corridors is 494.65 km. The α, β, and γ index values indicate that the selected ecological sources have a good connectivity with each other and have a high network efficiency.

In the context of urbanization, the spatial distribution of ecological nodes shows an uneven distribution, with less distribution in the central urban area and more distribution in the western Changle District and the eastern Minhou District. The ecological corridors also show similar unevenness, with the weak connectivity of the local ecological corridors influenced by urban expansion. Studies have shown that the ecological safety pattern of the city can effectively control urban expansion and has a positive effect on the optimization of the urban pattern [62–64]. Therefore, under the guidance of the eastward and southward expansion policy in Fuzhou, Changle District has ushered in a new construction boom, with large areas of land being converted to construction land and a substantial increase in the building density, which has created a greater resistance to the introduction of wind sources and ventilation inlets. In the process of general urban planning and construction, the impact of expansion on the urban ecology is monitored, strategic plans for development are formulated, and the impact on the change in the land forms for the ventilation corridors is fully evaluated. The main wind inlets and important ventilation paths into the inner part of the city are protected by various measures, and the planning arguments against conflicting interests are strengthened [65].

Author Contributions: Conceptualization, W.Y., K.Y. and J.L. (Jiqing Lin); methodology, W.Y. and J.L. (Jiqing Lin); software, J.G.; validation, W.Y. and J.L. (Jiqing Lin); formal analysis, J.L. (Jiqing Lin) and W.Y.; investigation, W.Y. and J.G.; resources, K.Y.; data curation, W.Y.; writing—original draft preparation, J.L. (Jiqing Lin); writing—review and editing, W.Y., K.Y. and J.L. (Jian Liu); visualization, J.L. (Jiqing Lin); supervision, K.Y. and J.L. (Jian Liu); project administration, J.L. (Jian Liu); funding acquisition, K.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (grant number 31770760) and Fujian Provincial Department of Science and Technology (grant number 2020N5003).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: We wish to thank the anonymous reviewers and editors for their detailed comments and suggestions.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. UNDESA. Urban and rural population growth and world urbanization prospects. In *World Urbanization Prospects: The 2018 Revision*; UN: New York, NY, USA, 2019; pp. 9–31.
2. Seto, K.C.; Michail, F.; Burak, G.; Reilly, M.K. A meta-analysis of global urban land expansion. *PLoS ONE* **2011**, *6*, e23777. [CrossRef] [PubMed]
3. Li, Y.; Sun, X.; Zhu, X.; Cao, H. An early warning method of landscape ecological security in rapid urbanizing coastal areas and its application in Xiamen, China. *Ecol. Model.* **2010**, *221*, 2251–2260. [CrossRef]
4. Lovell, S.T.; Taylor, J.R. Supplying urban ecosystem services through multifunctional green infrastructure in the United States. *Landsc. Ecol.* **2013**, *28*, 1447–1463. [CrossRef]
5. Cao, Y.; Kong, L.; Zhang, L.; Ouyang, Z. The balance between economic development and ecosystem service value in the process of land urbanization: A case study of China's land urbanization from 2000 to 2015. *Land Use Policy* **2021**, *108*, 105536. [CrossRef]
6. Forman, R. Some general principles of landscape and regional ecology. *Landsc. Ecol.* **1995**, *10*, 133–142. [CrossRef]
7. Fu, B.; Chen, L.; Ma, K. *The Principles and Application on Landscape Ecology*; Science Press: Beijing, China, 2011; pp. 60–81.
8. Zhao, S.; Ma, Y.; Wang, J.; You, X. Landscape pattern analysis and ecological network planning of Tianjin City. *Urban For. Urban Gree.* **2019**, *46*, 126479. [CrossRef]
9. Wang, S.; Wu, M.; Hu, M.; Fan, C.; Wang, T.; Xia, B. Promoting landscape connectivity of highly urbanized area: An ecological network approach. *Ecol. Indic.* **2021**, *125*, 107487. [CrossRef]
10. Zhang, R.; Zhang, L.; Zhong, Q.; Zhang, Q.; Ji, Y.; Song, P.; Wang, Q. An optimized evaluation method of an urban ecological network: The case of the Minhang District of Shanghai. *Urban For. Urban Gree.* **2021**, *62*, 127158. [CrossRef]
11. Bryant, M. Urban landscape conservation and the role of ecological greenways at local and metropolitan scales. *Landsc. Urban Plan.* **2006**, *76*, 23–44. [CrossRef]
12. Haaren, V.; Reich, C. The German way to greenways and habitat networks. *Landsc. Urban Plan.* **2006**, *76*, 7–22. [CrossRef]
13. Hilty, J.; Lidicker, W.; Merenlender, A. Corridor Ecology: The Science and Practice of Linking Landscapes for Biodiversity Conservation. *Biol. Conserv.* **2008**, *141*, 1165–1166.

14. Wilson, E.O.; Willis, E.O. *Ecology and Evolution of Communities*; Cody, M.L., Diamond, J.M., Eds.; Harvard University Press: Cambridge, MA, USA, 1975; pp. 522–534.
15. Yamamoto, Y. Measures to mitigate urban heat islands. *Q. Rev.* **2006**, *18*, 65–83.
16. Aflaki, A.; Mirnezhad, M.; Ghaffarianhoseini, A.; Ghaffarianhoseini, A.; Omrany, H.; Wang, Z.; Akbari, H. Urban heat island mitigation strategies: A state-of-the-art review on Kuala Lumpur, Singapore and Hong Kong. *Cities* **2017**, *62*, 131–145. [CrossRef]
17. Wang, Y.; Berardi, U.; Akbari, H. Comparing the effects of urban heat island mitigation strategies for Toronto, Canada. *Energy Build.* **2016**, *114*, 2–19. [CrossRef]
18. Mostofa, T.; Manteghi, G. Influential factors of water body to enhance the urban cooling islands(UCIs):a review. *Int. Trans. J. Eng. Manag. Appl. Sci. Technol.* **2020**, *11*, 1–12.
19. Shih, W. Greenspace patterns and the mitigation of land surface temperature in Taipei metropolis. *Habitat Int.* **2017**, *60*, 69–80. [CrossRef]
20. Ng, E. Policies and technical guidelines for urban planning of high-density cities—Air ventilation assessment (AVA) of Hong Kong. *Build. Environ.* **2009**, *44*, 1478–1488. [CrossRef]
21. McRae, B.; Dickson, B.; Keitt, T.; Shah, V. Using circuit theory to model connectivity in ecology, evolution, and conservation. *Ecology* **2008**, *89*, 2712–2724. [CrossRef]
22. Wang, H.; Zhang, L. A GIS, landscape pattern and network analysis based planning of ecological networks for Xiamen island. *Chin. J. Plant Ecol.* **2005**, *29*, 144–152.
23. Liang, J.; Ding, Z.; Xiao, R.; Zou, J.; Hu., H. Location design of wildlife corridors based on animal movement path identification: A case study of the Wuhan-Shenzhen highway. *Acta Ecol. Sinica.* **2016**, *36*, 8145–8153.
24. Harris, L.D. *The Fragmented Forest: Island Biogeography Theory and the Preservation of Biotic Diversity*; University of Chicago Press: Chicago, IL, USA, 1984.
25. Xu, W.; Chen, C.; Zhang, Z.; Shao, X.; Zhang, Y. Ecologic corridor construction based on important ecological nodes in Duliujian River basin. Res. *Environ. Sci.* **2018**, *31*, 805–813.
26. Zhang, H. Study on the Construction of Ecological Network for the Life Community of Mountain-Water-Forest-Farmland-Lake-Grass in Taishan Area Based on Multi-Objective Optimization. Master's Thesis, Shandong Jianzhu University, Jinan, China, 2020.
27. Lu, P. Study on identification of key eco-section of land ecosystem security—A case study of Wuxi city. Master's Thesis, Nanjing Agricultural University, Nanjing, China, 2011.
28. Wu, W.; Lu, P. Identification of resource major portion of land ecosystem: A case study of Wuxi, the Yangtze River delta area. *J. Nat. Resour.* **2012**, *27*, 1860–1869.
29. Wu, W.; Lu, P.; Liu, L. Identification of the Resource Critical Portion of Land Ecosystem:A Case Study of Huimin County, the Yellow River Delta Area. *Geogr. Geo-Inf. Sci.* **2012**, *28*, 71–74.
30. Nimmo, D.G.; Mac Nally, R.; Cunningham, S.C.; Haslem, A.; Bennett, A.F. Vive la résistance:reviving resistance for 21st century conservation. *Trends Ecol. Evol.* **2015**, *30*, 516–523. [CrossRef] [PubMed]
31. Knaapen, J.P.; Scheffer, M.; Harms, B. Estimating habitat isolation in landscape planning. *Landsc. Urban Plan.* **1992**, *23*, 1–16. [CrossRef]
32. Etherington, T.; Holland, E. Least-cost path length versus accumulated-cost as connectivity measures. *Landsc. Ecol.* **2013**, *28*, 1223–1229. [CrossRef]
33. McRae, B.H.; Hall, S.A.; Beeier, P.; Theobald, D.M. Where to restore ecological connectivity? Detecting barriers and quantifying restoration benefits. *PLoS ONE* **2012**, *7*, e52604. [CrossRef]
34. Huang, R.; Xu, H. A study on the relationship between land cover/use and urban heat environment using landsat ETM+ satellite imagery. *Remote Sens. Inf.* **2005**, *5*, 36–39.
35. Ye, L.; Xu, H. Remote sensing of spatio-temporal land use dynamics in Fuzhou District during the last 20 years. *J. Geo-Inf. Sci.* **2008**, *10*, 80–87. [CrossRef]
36. Zheng, C. Study on dynamical changes of wetland landscape patterns and responses of ecological security—Taking Puxiazhou region of Fuzhou city for example. *Saf. Enviro. Eng.* **2009**, *16*, 1–6.
37. Yang, W.; Yu, K.; Zhao, G.; Geng, J.; Zhao, Q.; Yang, L.; Liu, J. Optimization of greenways in Fuzhou based on heat island effect. *J. Zhejiang Agric. For. Univ.* **2022**, *39*, 876–883.
38. Yang, W.; Yu, K.; Geng, J. Selection and optimization of ventilation corridor lines in Fuzhou. *J. Chin. Urban For.* **2022**, *20*, 123–128.
39. Zhang, Y.; Yu, B. Analysis of urban ecological network space and optimization of ecological network pattern. *Acta Ecol. Sin.* **2016**, *36*, 6969–6984.
40. Yu, Q.; Yue, D.; Yang, D.; Ma, H.; Zhang, Q.; Yi, B. Layout optimization of ecological nodes based on BCBS model. *Trans. Chin. Soc. Agric. Mach.* **2016**, *47*, 330–336, 329.
41. Wu, N.; Zhang, Y.; Cao, R.; Shang, S. Identification and analysis of ecological nodes of urban and suburban areas based on 3S technology. *Enviro. Sci. Technol.* **2014**, *37*, 184–189.
42. Meng, J.; Wang, X.; Zhou, L. Integrated landscape pattern optimization in arid region: A case study of middle reaches of Heihe River. *Acta Sci. Natur. Univ. Pekin.* **2017**, *53*, 451–461.

43. Pan, J.; Liu, X. Assessment of landscape ecological security and optimization of landscape pattern based on spatial principal component analysis and resistance model in arid inland area: A case study of Ganzhou District, Zhangye City, Northwest China. *Chin. J. Appl. Ecol.* **2015**, *26*, 3126–3136.
44. Chen, X. Construction of ecological network in Poyang Lake eco-economic zone. Master's Thesis, Jiangxi Agricultural University, Nancang, China, 2016.
45. Liu, J.; Deng, Y.; Wang, Y.; Huang, H.; Du, Q.; Ren, F. Urban nighttime leisure space mapping with nighttime light images and POI data. *Remote. Sens.* **2020**, *12*, 541. [CrossRef]
46. Zhou, L.; Shi, Y.; Zheng, J. Business Circle Identification and Spatiotemporal Characteristics in the Main Urban Area of Yiwu City Based on POI and Night-Time Light Data. *Remote Sens.* **2021**, *13*, 5153. [CrossRef]
47. Zhu, Q.; Yu, K.; Li, D. The width of ecological corridor in landscape planning. *Acta Ecol. Sin.* **2005**, *25*, 2406–2412.
48. Tong, H.; Shi, P. Using ecosystem service supply and ecosystem sensitivity to identify landscape ecology security patterns in the Lanzhou-Xining urban agglomeration, China. *J. Mount. Sci.* **2020**, *17*, 2758–2773. [CrossRef]
49. Koen, E.L.; Bowman, J.; Sadowski, C.; Walpole, A.A. Landscape connectivity for wildlife: Development and validation of multispecies linkage maps. *Methods Ecol. Evol.* **2014**, *5*, 626–633. [CrossRef]
50. Samways, M.J.; Bazelet, C.S.; Pryke, J.S. Provision of ecosystem services by large scale corridors and ecological networks. *Biodivers. Conserv.* **2010**, *19*, 2949−2962. [CrossRef]
51. de Montis, A.; Caschili, S.; Mulas, M.; Modica, G.; Ganciu, A.; Bardi, A.; Ledda, A.; Dessena, L.; Laudari, L.; Fichera, C.R. Urban-rural ecological networks for landscape planning. *Land Use Policy.* **2016**, *50*, 312−327. [CrossRef]
52. Yang, K.; Tang, M.; Liu, Y.; Wu, A.; Fan, Q. Analysis of microclimate effects around rivers and waterbody in Shanghai urban district. *J. East China Norm. Univ. (Nat. Sci. Ed.)* **2004**, *3*, 105–114.
53. Yang, L.; Yu, K.; Ai, J.; Liu, Y.; Yang, W.; Liu, J. Dominant Factors and Spatial Heterogeneity of Land Surface Temperatures in Urban Areas: A Case Study in Fuzhou, China. *Remote Sens.* **2022**, *14*, 1266. [CrossRef]
54. Xu, L.; Zhang, Z.; Tan, G.; Zhou, J.; Wang, Y. Analysis on the Evolution and Resilience of Ecological Network Structure in Wuhan Metropolitan Area. *Sustainability* **2022**, *14*, 8580. [CrossRef]
55. Mills, G. Urban Climatology: History, Status and Prospects. *Urban Clim.* **2014**, *10*, 479–489. [CrossRef]
56. Ding, Y.; Li, B.; Shen, Y.; Su, Y. Simulation for the Effect of Building Plan and Orientation on Natural Ventilation. *J. Civ. Archit. Environ. Eng.* **2010**, *32*, 90–95.
57. Nor, A.N.M.; Corstanje, R.; Harris, J.A.; Grafius, D.R.; Siriwardena, G.M. Ecological Connectivity Networks in Rapidly Expanding Cities. *Heliyon* **2017**, *3*, e00325. [CrossRef]
58. Aouissi, H.A.; Petrişor, A.-I.; Ababsa, M.; Boştenaru-Dan, M.; Tourki, M.; Bouslama, Z. Influence of Land Use on Avian Diversity in North African Urban Environments. *Land* **2021**, *10*, 434. [CrossRef]
59. Pereira, J. Multi-node protection of landscape connectivity: Habitat availability and topological reachability. *Community Ecol.* **2018**, *19*, 176–185. [CrossRef]
60. Zhou, D.; Lin, Z.; Ma, S.; Qi, J.; Yan, T. Assessing an ecological security network for a rapid urbanization region in Eastern China. *Land Degrad. Dev.* **2021**, *32*, 2642–2660. [CrossRef]
61. Sun, X.; Liu, H. Optimization of wetland landscape patterns based on ecological function evaluation: A case study on the coastal wetlands of Yancheng, Jiangsu Province. *Acta Ecol. Siuica* **2010**, *5*, 1157–1166.
62. Mace, A. The Metropolitan Green Belt, changing an institution. *Prog. Plan.* **2018**, *121*, 1–28. [CrossRef]
63. Baro, F.; Bugter, R.; Gómez-Baggethun, E.; Hauck, J.; Kopperoinen, L.; Liquete, C.; Potschin, P.; Potschin, M.; Jax, K. (Eds.) Green Infrastructure, OpenNESS Ecosystem Service Reference Book (2015) EC FP7 Grant Agreement No.308428. Available online: www.openness-project.EU/library/reference-book (accessed on 1 September 2022).
64. Davies, C.; Lafortezza, R. Urban green infrastructure in Europe: Is greenspace planning and policy compliant? *Land Use Policy* **2017**, *69*, 93–101. [CrossRef]
65. Cortinovis, C.; Geneletti, D. Ecosystem services in urban plans: What is there, and what is still needed for better decisions. *Land Use Policy* **2018**, *70*, 298–312. [CrossRef]