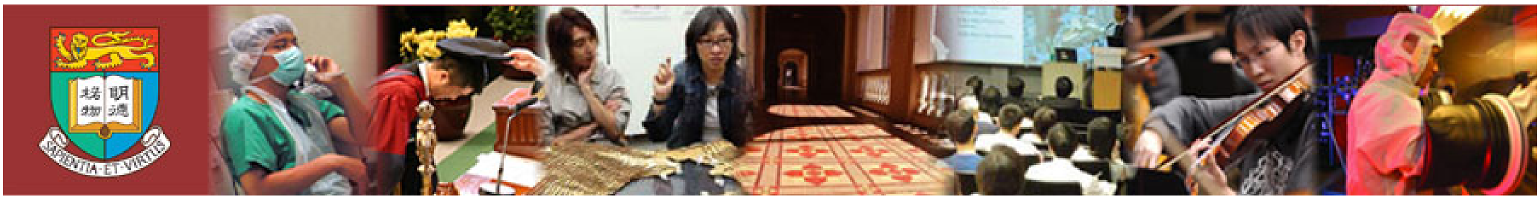


Title	Ecological Security Pattern Analysis Based on InVEST and Least-Cost Path Model: A Case Study of Dongguan Water Village
Author(s)	Lin, Q; Mao, M; Wu, J; Li, W; Yang, J
Citation	Sustainability, 2016, v. 8, p. 172:1-16
Issued Date	2016
URL	http://hdl.handle.net/10722/235397
Rights	This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License.

sustainability

MDPI

Article

Ecological Security Pattern Analysis Based on InVEST and Least-Cost Path Model: A Case Study of Dongguan Water Village

Qian Lin [1], Jiaying Mao [2], Jiansheng Wu [2,3], Weifeng Li [4,*] and Jian Yang [5,*]

[1] Ningbo Urban-Rural Planning Research Center, Ningbo 315040, China; ciaralin@126.com
[2] Key Laboratory for Urban Habitat Environmental Science and Technology, Shenzhen Graduate School, Peking University, Shenzhen 518055, China; mjysfz@sz.pku.edu.cn (J.M.); wujs@pkusz.edu.cn (J.W.)
[3] Key Laboratory for Earth Surface Processes, Ministry of Education, College of Urban and Environmental Sciences, Peking University, Beijing 100871, China
[4] Department of Urban Planning and Design, University of Hong Kong, Pokfulam, Hong Kong, China
[5] School of Urban Planning and Design, Shenzhen Graduate School, Peking University, Shenzhen 518055, China
* Correspondence: wfli@hku.hk (W.L.); yangj@pkusz.edu.cn (J.Y.); Tel.: +852-2859-2566 (W.L.); +86-755-2603-5432 (J.Y.)

Academic Editor: Vincenzo Torretta
Received: 18 November 2015; Accepted: 5 February 2016; Published: 16 February 2016

Abstract: The famous "world's factory" city, Dongguan, like many other places in China, is a typical beneficiary of China's Reform and Opening-up Policy. However, rapid urban sprawl and economic growth are at the expense of the destruction of the local environment. Therefore, it is of great importance to establish an ecological security network for sustainable development. InVEST models, effective tools to measure sensitivity and intensity of external threats to quantify habitat value, are used to calculate habitat quality of water and land. By combining structural connectivity and the Least-Cost Path model (LCP model), in which corridors are determined based on the minimum accumulative cost path between each critical point, ecological security patterns were calculated. According to the results, the northwest region of Dongguan, having a large quantity of farmlands and water and therefore many corridors and critical patches, is the most essential area in the overall security of ecological environments, which should be protected first. If developed, it should be dominated by eco-tourism and eco-agriculture. We hope that research on the ecological network, which includes critical patches and corridors formed by greenland and rivers, will lead toward better-informed proposals for local urban planning and regional sustainable development.

Keywords: InVEST models; LCP model; critical patches; corridors; network; Dongguan Water Village; ecological security

1. Introduction

Human activities are the primary cause of habitat loss, fragmentation, and degradation [1,2], which increases the pressure to further urban development [3,4]. Especially in China, since reform, rapid economic development has led to a trend of regional ecological destruction, disintegration of ecological structures, and development of ecological functional disorders in some areas [5–7]. As Forman and Collinge [8] said, "the future is not just what lies ahead; it is something that we create". In order to avoid causing irreparable ecological damage in the process of urbanization, the topic of ecological security has attracted increasing attention in urban planning [9–12].

The definition of ecological security is broad, and includes the improvement of ecosystem services [13], maintenance of ecosystem health [14], and more [15–17]. In cities, ecological security tends to focus on two aspects of security: the security of the urban environment and the security of the city's future development [18]. In other words, from the standpoint of ecology, a secure ecosystem should not only be able to maintain its structure over a certain time scale but also be resilient to stress [19,20].

The concept of an ecological security pattern is derived from the theory and methods of landscape ecology. It refers to the pattern composed by strategic landscape elements, positions, and spatial connections that are critical to the security and health of ecological processes [21]. The form of ecosystem security pattern is to exert people's subjective energy, ensure active intervention over the optimization and allocation of elements in the human–environment system, promote healthy and sustainable development of the system, and improve the condition of local ecological security [22].

Thus, compared to other identifications of critical patches and corridors, ecological security patterns are more systematic and holistic. It integrates multiple factors and can make suggestions with strong spatial characteristics to promote the harmonious development of local economy and ecosystems [23]. The foundation of the form of ecological security pattern lies in the identification of critical elements and connections. These components can exchange energy, material, and information in a fragmented landscape [24], which is the ecological security patterns' basic function. Therefore, the identification and protection of these components can increase habitat connectivity, preserve effective population size, maintain gene flow, and facilitate regular migration [25]. Until now, researchers have observed the indicators of network connection and accessibility [26] and combined graph theory and network analysis [27] to study ecological security and find methods of sustainable development, such as designing a greenway augmentation plan [28].

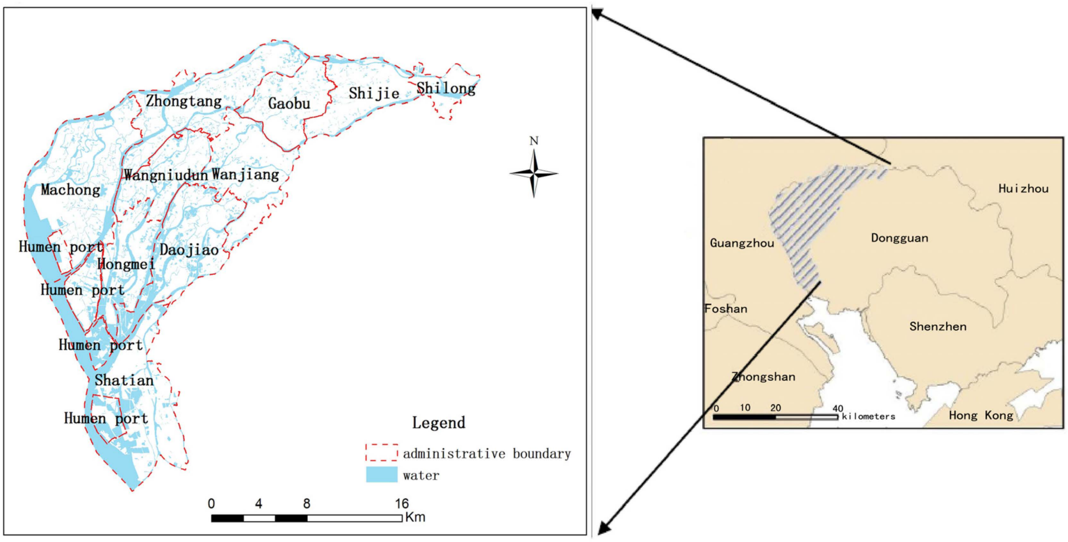
Chinese planning and implementation mostly followed a "top-down" approach, which, it has been argued [29], is necessary for establishing the ecological network to provide a scientific basis for planning. In this study, a combined model is established in which the Integrated Valuation of Environmental Services and Tradeoffs (InVEST) models are used to identify the critical patches as the source of the ecological security pattern, taking into account the dense river network, and the Least-Cost Path model (hereafter, LCP model) is used to identify corridors. Together, the two model types lead to complete ecological security patterns, which aim to improve the scientific methods of land-use planning.

2. Materials and Methods

2.1. Study Area

Dongguan is located in the Pearl River Delta, which is one of the most economically developed urban regions in China. Over three decades, the average economic growth rate was more than 20% (calculated based on GDP data from a local official website [30,31], which makes the "Dongguan Model", a model of economic development, known worldwide. However, in such a region, the phenomenon of industrial zones alongside residential zones and an industrial model that favors high consumption and low output cause a significant impact on land space, energy, and water.

The study area, often called the Dongguan Water Village, is located northwest of Dongguan with a total area of approximately 510 km^2, encompassing ten towns (Zhongtang, Daojiao, Wangniudun, Machong, Hongmei, Wanjiang, Shilong, Shijie, Gaobu, and Shatian) and Humen Port (Figure 1). It is an advantageous location with the necessary land for transportation between Guangzhou and Hong Kong, and it promotes local economic development.



①：Shiziyang; ②：Dongjiang North River; ③：Machong Waterway; ④：Daoyunhai Waterway;

⑤：Hongwuwo Waterway; ⑥：Chijiaokou River; ⑦：Dongjiang South River;

⑧：Zhongtang Waterway.

Figure 1. The location of the study area.

Rivers are densely distributed throughout the area, creating a complex web of waterways in the region. The main waterways are the north river of Shiziyang, the Dongjiang North River, the Machong waterway, the Daoyunhai waterway, the Hongwuwo waterway, the Chijiaokou River, the Dongjiang South River, and the Zhongtang waterway. The total area of water is approximately 63.7 km^2. In addition, the total river density is about 1.9 km/km^2.

Because of the dense river network, the study area is also an important agricultural production zone. However, in such an area, the woodlands and grasslands are distributed sparsely. In addition, the distribution of industrial and residential zones is intense and messy, which significantly affects the ecological landscape.

2.2. Methods

When we think about the future of economic development, first, we need to adhere to the ecological bottom line, to balance the economic development and ecological protection. For the purposes of this paper, taking into account the characteristics of the dense water network and the sensitive ecological system, we chose to divide the ecological landscape into two classes: blue landscape and green landscape.

These two categories encompass the landscapes that most benefit human beings. Not only can they provide a variety of raw materials and products for our survival, including food, water, oxygen, wood, and fiber, but they can also regulate climate, mitigate pollution, and provide other services such as the biodiversity conservation and disaster mitigation. In short, these two landscapes are very important for maintaining a good environment for human survival and development [32] (Table 1). Therefore, in this paper, we need to focus on these two important natural elements to construct ecological security patterns separately for each.

Table 1. The functional characteristics of the ecological landscape categories.

Class	Constituents	Functional Characteristics [18,30]
Blue Landscape	Water such as rivers, lakes, seas.	Climate regulation, cleaning environment, water supply for agriculture and industry, navigation, aquatic production, entertainment, *etc.*
Green Landscape	Urban green spaces, gardens, woodlands, *etc.*	High ecosystem service value and function, carbon sequestration, oxygen releasing, soil and water conservation, cleaning environment, noise reduction.

According to the theoretical basis of ecological security patterns, large patches with high-quality resources should be protected first. These patches, providing a large variety of ecosystem services, provide habitat for diverse species. These are known as critical patches or, within ecological security patterns, *sources*. In addition, a certain width and number of corridors are reserved for the movement of species. Therefore, when we set out to construct an ecological security pattern, identifying critical patches and corridors is the most important step in the process.

The research framework is shown in Figure 2. We integrated InVEST models and the LCP model to establish the ecological network. This approach involved (1) using InVEST models to test the biological and anthropological influences and estimate the habitat quality; (2) synthesizing the results of the habitat quality assessment and the size of the patches to identify the critical areas; (3) establishing the cost surface for each landscape according to the characteristics of blue and green landscapes; and (4) combining the cost surface results using a geographic information system (GIS)-based LCP model to identify the corridors that form the network. Each step is described in detail below. The land use data we used includes information on railways, main streets, residential streets, settlements, factories, harbors, farmlands, and more. This data was obtained from local government field survey data updated in December 2012.

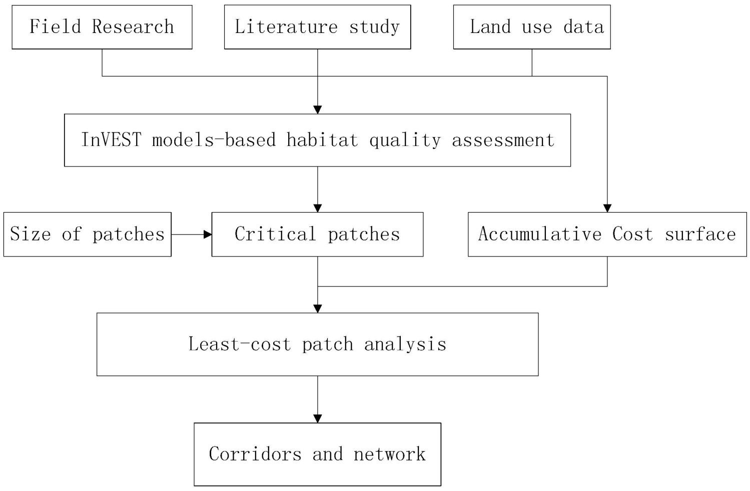


Figure 2. The research framework.

2.2.1. InVEST Model-Based Habitat Quality Estimation and Identification of Critical Patches

Critical patches with high-quality resources and large size always have better ecological service, and they play an important role in conserving biodiversity and maintaining the stability and integrity of ecosystems. In order to identify the critical patches, we realized that the patches with large size and high habitat quality were the ones that we needed to pick up as the key patches of the ecological security pattern. In this paper, we had two steps for identification of critical patches: first, through calculating the density of natural elements, we identified the distribution of large patches that consistently exhibited high density; second, we used InVEST models to assess the habitat quality of the landscape.

The InVEST model, Integrated Valuation of Ecosystem Services and Tradeoffs in short, is a family of tools used to value the services from nature, which are essential for sustaining and fulfilling human life [33]. This model, developed by Stanford University, the World Wildlife Fund (WWF), and The Nature Conservancy (TNC), is based on certain land-use scenarios to quantify the goods and services from nature that contribute to sustaining and fulfilling human life, which can provide scientific suggestions for decision-makers weighing the benefits and impacts of human activities.

The model "Biodiversity: Habitat Quality & Rarity", from the InVEST model set, is the tool we used to calculate the habitat quality, as it can measure sensitivity and the intensity of external threats to obtain the qualitative value of the habitat. In this model, the value of the habitat quality index represents degree of habitat fragmentation and the resistance ability of the patch to the habitat degradation caused by the disturbance of human activities. The index is designed to reveal the impact of risk factors and represent the quality of habitat. Moreover, the model assumes that if the habitat quality is good, then the biodiversity is high, which means that the concept of habitat quality is equivalent to the concept of biodiversity [34].

The habitat quality index is calculated as follows:

$$Q_{xj} = H_j[1 - (\frac{D_{xj}^2}{D_{xj}^2 + k^2})] \tag{1}$$

In this formula, Q_{xj} is the habitat quality index of grid x in land use and land cover j; D_{xj} is the habitat stress level of grid x in land use and land cover j; H_j is the habitat suitability of land use and land cover j; and k is half saturation constant.

In this study, the indexes we want to put into this model are based on the parameters of existing case studies [35–42].

The data required included the land-use data and the distribution of threat sources such as railways, main streets, residential streets, settlements, factories, harbors, and farmlands. The model also takes into account assessments of the accessibility and the weight of the threat source in order to fully depict anthropological influences.

2.2.2. LCP Model-Based Identification of Corridors

Since the travel cost of an organism's movement in a landscape is correlated with landscape connectivity [43], it is convenient to use this index to represent travel cost [44]. The distance between habitat patches is often chosen to measure travel cost based on connectivity. The most commonly used method is calculating nearest-neighbor-distance based on ordinary Euclidean distance, which equals the linear distance between two nearest habitat patches [45,46]. However, this method not only does not take into account habitat patches' shape and internal variability and ignores individual organisms' suitability for certain habitat patches and permeability of the landscape matrix [47,48]. In recent years, researchers have found that cost distance based on LCP is an effective way to make up for the deficiencies of Euclidean distance and measure the travel cost of organisms in a landscape. Cost distance based on LCP emphasizes points' spatial relativeness instead of actual distance, which is calculated based on an organism's resistance coefficient when moving through different landscape units. Greater cost distance indicates higher resistance for the organism to overcome.

LCP analysis is based on graph theory, and it uses a raster-based algorithm that weighs the minimal cost path between a source and a target cell. Cost-path represents the cost involved in moving through any particular cell in a given landscape, which can be viewed as a qualitative description of landscape pattern. Moreover, accumulative cost-path provides information on the interaction of landscape types or units, for example, the rate or speed of exchange of energy, materials, and information.

GIS based-LCP models are regarded as one of the most effective methods for calculating minimum accumulative travel costs from a source to each cell location within a raster map [49].

Therefore, in this section, we attempted to construct a landscape network similar to the ecological security patterns. Considering that geospatial changes will bring differences in the cost of movement, we used accumulative cost path models integrated in the ArcGIS platform to create the minimum cost path between each critical point as the corridors.

The first step involved selecting the location of critical patches, which have been previously identified as specific sources and destination points.

Next, we calculated the minimum accumulated cost surface over the complex resistance surface from all cells to each source point. Cost surface was used to determine least-cost routes, which revealed how the landscape facilitates or hinders movement. Coefficient of cost surface was treated as a relative value, rather than an absolute value [50]. This is because the coefficient does not represent individual moving speed through certain landscape units but stands for the individual's intent to move or its suitability to that unit [44]. Currently, the settings of cost surface and coefficient in LCP are primarily based on land cover maps [50–53].

The third step involved using selected source points and the accumulative cost surface to construct the LCP. The results represent the visualized LCP from selected locations to the closest source cell. Research has showed that the LCP is the corridor with the maximum probability of survival for the organism's movement between the source and target patches [50,51], which provides a scientific basis for the design of regional habitat corridors [53].

3. Results

3.1. The Ecological Network of the Blue Landscape

By analyzing the distribution of patches with better habitat quality calculated by InVEST models for blue landscapes (Figure 3), combined with practical investigation, we determined specific intersections of rivers that play important roles in connecting the critical patches. They are located at the intersections of the Shiziyang and Machong waterways, the Shiziyang and Daoyunhai waterways, the Hongwuwo waterway and the Dongjiang South River, the Shiziyang and the Dongjiang South River, south of the Shiziyang, and north of the Dongjiang South River (six critical patches shown in Figure 5). These with large runoff are the connection points between the main rivers.

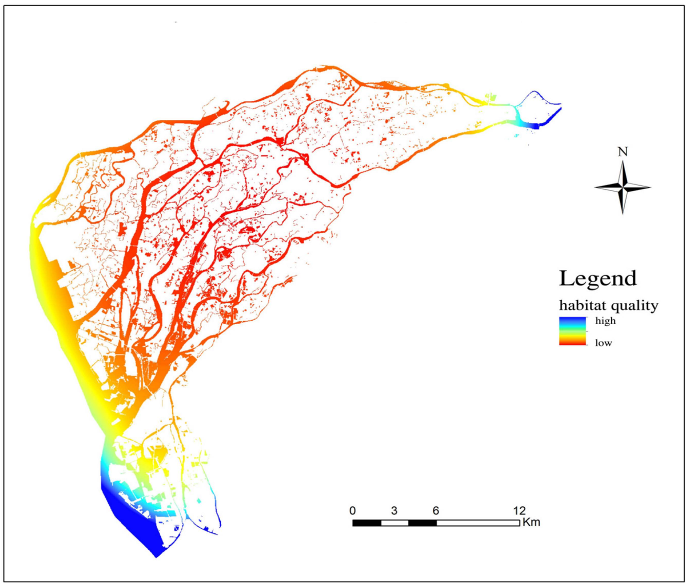


Figure 3. The habitat quality of blue landscape.

The greater the flow of water, the faster the material flow rate. Based on the area proportion of blue landscape in each 1 km^2 grid cell (Figure 4), the cost surface was constructed for spreading from the source patches. Finally, through a cost path model, the corridor and ecological security patterns were identified (Figure 5).

As shown in Figure 5, the path is mainly used to connect the Shiziyang with the Dongjiang North River and the Dongjiang South River. In addition, from the path, we know the Daoyunhai waterway, the Zhongtang waterway, and the Hongwuwo waterway play important roles in connecting those areas that should be first protected. These six rivers play a vital role in the maintenance of regional ecological stability.

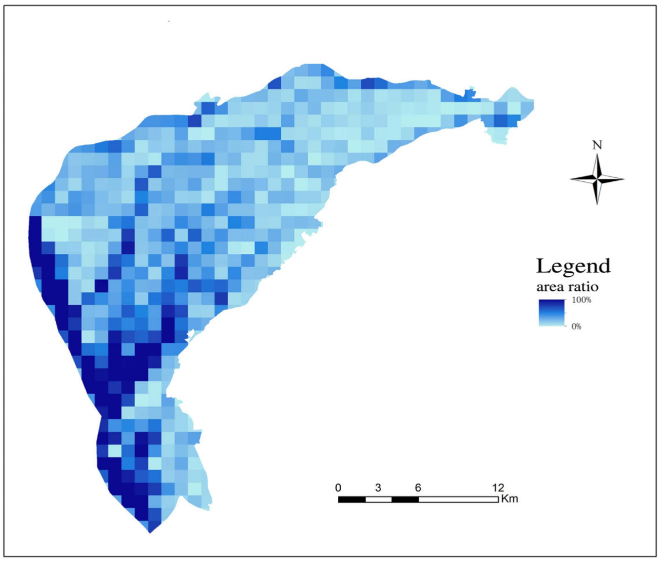
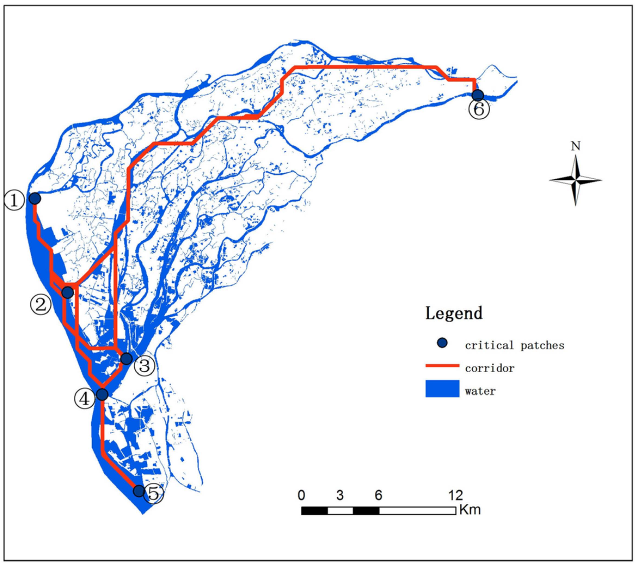


Figure 4. The proportion of blue landscape by area in a 1 km^2 grid cell.



①：Intersection of the Shiziyang and Machong waterways；
②：Intersection of the Shiziyang and Daoyunhai waterways；
③：Intersection of the Hongwuwo waterway and Dongjiang South Rivers；
④：Intersection of the Shiziyang and the Dongjiang South River；
⑤：South of Shiziyang；
⑥：North of the Dongjiang South River.

Figure 5. The ecological security patterns of blue landscape.

3.2. The Ecological Network Patterns of the Green Landscape

In order to pick the patches with the largest size, we based the choices on the density of ecological land (Figure 6), as the region with the highest value is the desired result. Figure 7 shows the results of the calculation of the habitat quality through InVEST Models. These places are surrounded by a large area of undeveloped land.

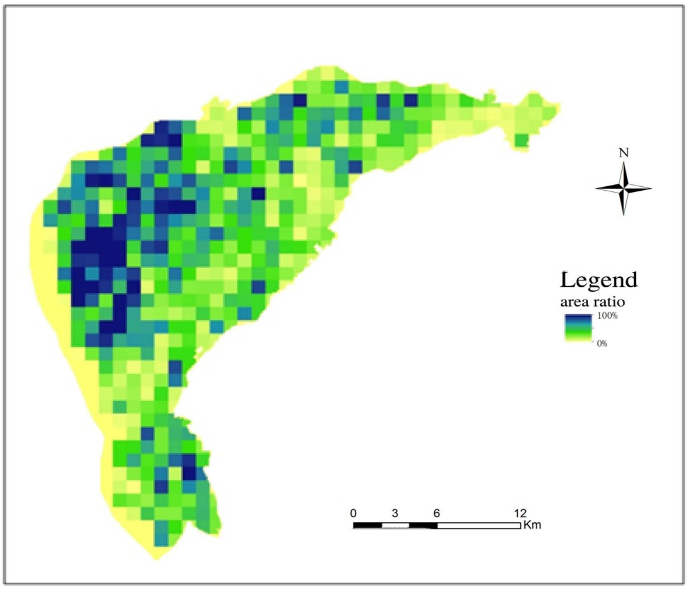


Figure 6. The area proportion of blue landscape in a 1 km^2 grid cell.

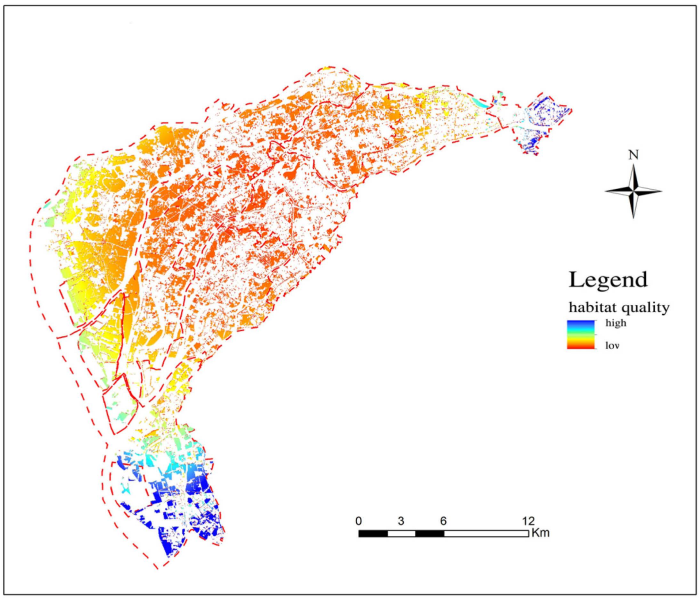


Figure 7. The habitat quality of green landscape.

Finally, combining the results of Figures 6 and 7 the critical patches were identified. The critical patches were mainly in the northwest of the study area where there is a lot of farmland. This result was also consistent with information obtained from actual interviews.

Next, we constructed a resistance surface. We took into account the different impacts on species movement caused by different land-use types. The value of the coefficient is based on existing empirical data [52–55]. Typically, if a landscape such as grass or woodland is easily passed through, the resistance coefficient is 1. A greater value represents greater difficulty in passage. As Table 2 shows, we set the coefficient between 1 and 300. Finally, after calculating the accumulative cost path, the ecological security patterns of green landscape were generated, as shown in Figure 8.

Table 2. Resistance factors and coefficients.

Resistance Factor	Resistance Coefficient
Woodland, grass	1
Agricultural land	50
Urban green spaces, gardens	70
Unused land	200
Water, construction land	300

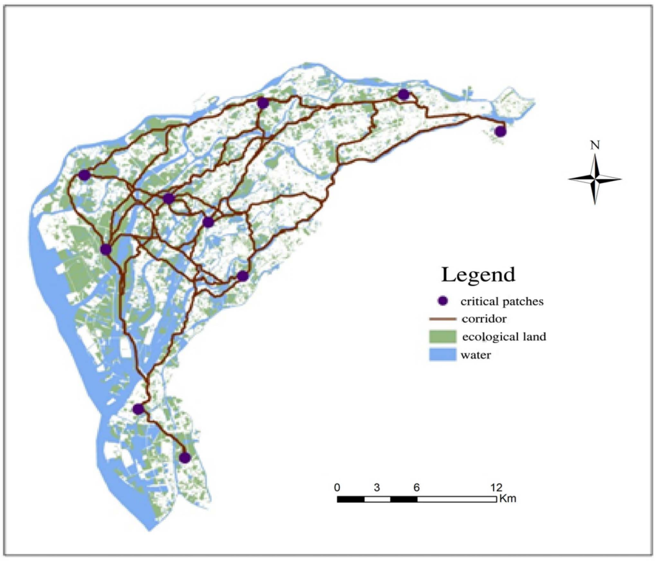


Figure 8. The ecological security patterns of green landscape.

As shown in Figure 8, the critical patches are mainly located in Machong, Zhongtang, Wangniudun, Hongmei, and Daojiao, in the northwest of the study area. Large amounts of paddy, water, and wetland, which have a high value of ecosystem services, are widely distributed in the area, which is the most attractive region in Dongguan. Therefore, complying with the principles of ecological protection, the strategies of eco-agriculture and eco-tourism development can be adopted. As shown in Figure 7, corridors are made up by the Dongjiang North River, the Chijiaokou River, the Dongjiang South River, the Dongguan Waterway, and large amounts of undeveloped land in Machong.

3.3. Identification of Ecologically Fragile Areas Impacted by Human Activities

In order to analyze the status of ecological networks, especially the implications caused by human activities, we calculated the developed area that falls within the scope of the ecological network. Considering corridors should have a certain width, we set the limit at 100 m for simplification. Then, we created a 100 m by 100 m grid. After calculating the proportion of construction zone in each square of the grid, we set 50% as the dividing line; that is, if the developed area is larger than 50%, there has been serious interference by humans. As shown in Figure 9, 32.6% of all sections of the blue landscape ecological network had construction over ⩾50% of their area. Development was mainly distributed in the northeast of the study area, around Dongjiang North River, which is the main tributary of Dongjiang River and the most important river of our study area. In the green landscape ecological network (Figure 10), 41.5% of the squares had construction over more than 50% of their area mainly distributed in the east and middle of the study area.

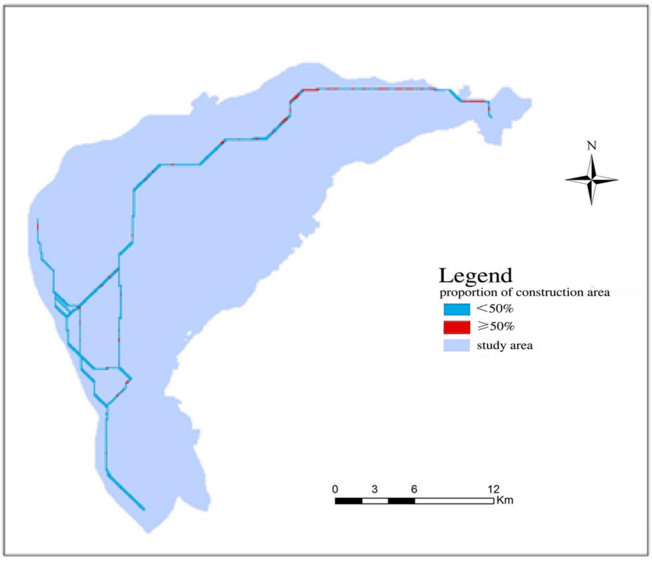


Figure 9. The proportion of construction area falling within the scope of the blue landscape ecological network.

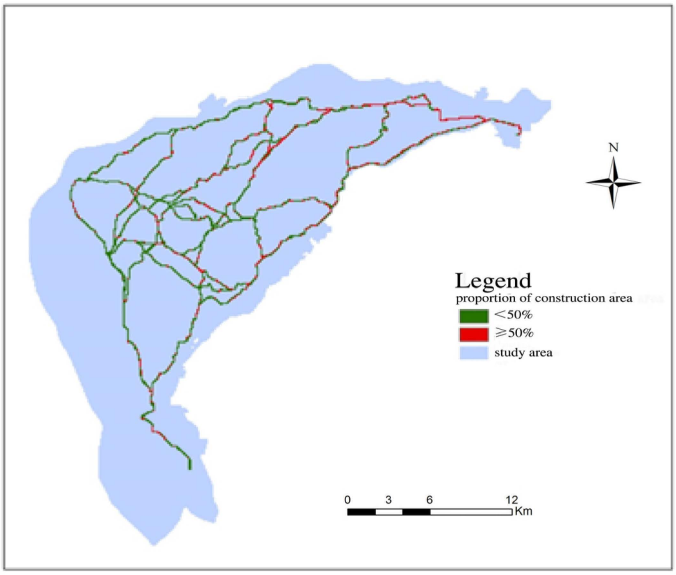


Figure 10. The proportion of construction area falling within the scope of the green landscape ecological network.

3.4. Design and Suggestions for the Balance of Ecological Protection and Urban Development

When performing city planning or urban generation, the components of ecological networks, such as critical patches and corridors, should be protected first. A reasonable approach is relying on water networks to develop eco-tourism and agro-tourism in order to achieve balance between economic development and ecological protection. Important actions include establishing greenways, parks, and other ecological "stepping stones" [24], as well as limiting the development of industries around the ecological network. Appropriate measures, such as industry transformation and movement of settlements, should be taken, especially in the northeast of the study area with a more developed industry and more settlements that have caused a serious impact on ecological security. Therefore, in this last section, we designed corridors based on the ecological network developed in this study that can be developed to form sightseeing routes (Figure 11) to promote ecological protection. As Figure 11 demonstrates, based on the distribution of the river, we designed nine routes. Route 1, located in Shiziyang, connects points 1, 2, and 3. As for the development of this route, it has the potential for port development, it can be used to connect to the outside world, and it should be focused on protection in the process. Points 5, 6, 7, 9, and 11 are concentrated in abundant wetland sources, which can be developed into wetland parks designed for protection and sightseeing. In addition, points 6, 8, 10, and 12 aggregate large amounts of cultivated land resources, which can be developed for sightseeing and ecological agriculture. Routes 2, 3, 4, and 5 represent blue corridors, which are based on the river network, and they connect to the critical points that attract tourists. Routes 6, 7, 8, and 9 are comprised of farmland, wetland, and urban green space and can be transformed into greenway. The routes from 1 through 9 not only ensure the movement of species and the flow of energy, but they also connect to tourist locations that are ecological landscape corridors full of local characteristics.

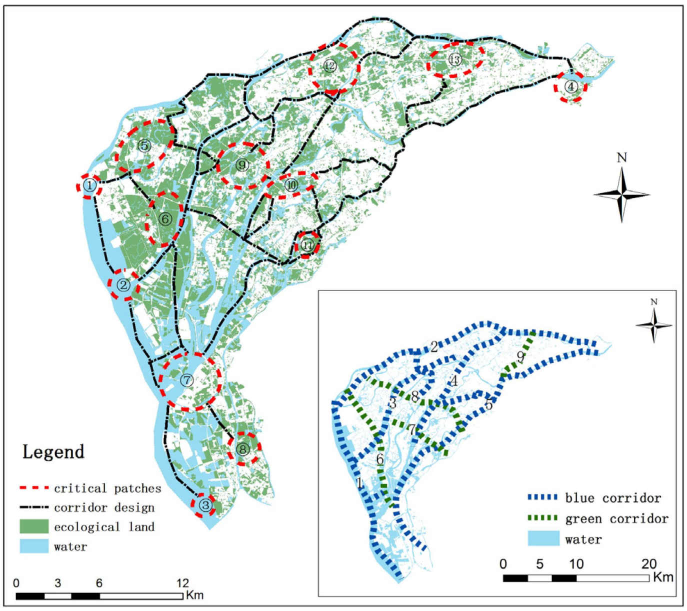


Figure 11. A network design for the balance of ecological protection and urban development.

4. Discussion

4.1. Advantage of the Method

Whether the landscape is homogeneous or not, the importance of each element in the landscape is not the same for all ecological processes. Some points and spatial connections play key roles in the control of ecological processes at the landscape level. These elements, which form the ecological security pattern as described in this paper, represent existing or potential ecological infrastructure. In a limited landscape with significant heterogeneity, these elements—the key points and spatial connections—can be identified by experience. However, in several cases, similar to our case study, these elements cannot be directly recognized empirically. In this scenario, quantitative methods such as the InVEST and LCP model we used to construct ecological security patterns for our study area are necessary to help the local government to take actions for the ecological protection and urban construction [21].

The models we used also have been proved to be generalizable and can be used in other areas of research. The combination of these two models can greatly assist us to improve the accuracy of analysis to obtain a quantitative result. For example, many researchers have used these models for their case studies respectively.

As for the InVEST models, we used this to assess the habitat quality of the landscape. Compared with other models, the InVEST model requires less time spent on data import and produces a large output of data. This model can simplify the explanation of many complex problems, by using GIS to quantify ecosystem services and using maps to show an intuitive and visual assessment. The InVEST model has therefore been successfully applied in the ecosystem assessment of Hawaii, Tanzania, California, Indonesia and other regions of China [34–42].

As for the LCP model, the least cost path is the corridor with the maximum probability of survival for an organism moving between the source and target patches [50,51]. Currently, this model is often used to predict the results caused by landscape changes. For example, Singleton [56] used this model to investigate the effects of expressway construction on the landscape permeability of four large mammals (*Canis lupus*, *Gulogulo*, *Lynx canadensis*, and *Ursus arctos*) in British Columbia and Idaho. Epps [53] established an LCP model for diffusion of *Oviscanadensis nelsoni*. Jihong Li [57] also used this model to construct functional division for the panda nature reserve in the old town of Shanxi.

4.2. Evaluation of the Results

The hypothesis of this study is based on the results of Kongjian Yu [58]. We supposed that there is some potential landscape pattern formed by a number of points and the relationship between them. Furthermore, such a pattern has a key role in maintaining and controlling ecological processes. Thus, based on this hypothesis, we believed that the identification of these elements to construct a reasonable ecological security pattern could provide some help for local ecological protection and restoration.

Because of insufficient data, we cannot perform quantitative dynamic simulation and evaluation. However, because of the rationality of our approach, after discussion with the local authorities, there is a high degree of certainty that our results are reasonable. Specifically, in the ecological security patterns, the key corridors cover the important rivers and patches with high quality in our study area. According to the actual field survey, in the identified areas, local species are quite active. Now, based on the report "Dongguan city of freshwater and estuarine fish color map", completed in 2011 by two local agencies—the Fisheries Research Institute of Dongguan and Dongguan Fisheries Technology Promotion Center Station—the number of fish species has dropped from 134 in 1983 to 98. Our results, especially the construction of the ecological security pattern, have a significant and practical value in maintaining and restoring natural ecosystems.

In addition, as Figures 9 and 10 show, we found that many areas, especially in the north and east of our study area, around the Dongjiang North River, have been affected by human activities frequently. These, mostly in the range of the Dongjiang River, are the main areas needing urgent ecological restoration. Another report, "Investigation report on the establishment of Dongguan city water supply safety guarantee system", completed by the Dongguan Water Affairs Bureau in 2012, also confirmed that the water quality of the Dongjiang River has declined year by year and piecewise from upstream to downstream. More importantly, from our ecological security perspective, we offer overall consideration to all natural resources, including water systems and green space, to propose an all-inclusive strategy for ecological protection. Thus, we attempt to meet the challenge identified in the report "Dongguan city of freshwater and estuarine fish color map" by providing comprehensive advice for mitigation of phenomena such as habitat destruction, over-exploitation, and pollution.

4.3. Prospects

Because of data limitation, we currently cannot construct multi-scale ecological security patterns. We hope that in the future, our study area can range from the entire Pearl River Basin to the smallest river basin. We believe that after breaking the boundaries of administrative jurisdiction, the multi-scale ecological security patterns can help us more clearly find the importance of each corridor and patch and propose a further educated policy.

5. Conclusions

Our study area "Dongguan Water Village", a brooky area with strong ecological sensitivity, has been subjected to obvious human interference. In this paper, using the InVEST models and a GIS-based LCP model, we constructed the blue and green landscape ecological security patterns for the Dongguan Water Village, which is very important as the basis for the implementation of urban planning or urban development.

Results of model calculations show the important corridors and patches of this area, which should be protected first in the future. These elements are the main rivers, wetlands, and green spaces in the region: the rivers, including Dongjiang North River, Chijiaokou River, Dongguan Waterway, Daoyunhai Waterway, Zhongtang Waterway, and Hongwuwo Waterway, are the main tributaries of the Dongjiang River, playing important roles in the migration of species and the flow of energy; and in the north and west part of the study area, there are a wide range of critical patches, which are made up of paddy, water, wetland and farmland, with high value of ecosystem services. In addition, according to the identified corridors and critical patches, the reasonable ecological security patterns are designed for the balance of ecological protection and urban development. Such places, including nine routes and thirteen patches, should be protected first and, if developed, should be dominated by eco-tourism and eco-agriculture. Particularly, Machong and Daojiao have abundant wetlands, which are superior tourist resources. In addition, the northern and eastern regions, which are greatly disturbed by human beings, should be the main areas of ecological restoration in the future.

Because of insufficient data, we cannot perform quantitative dynamic simulation and evaluation. However, after referring to the on-the-ground investigation and the discussion with the local authorities and experts, our results have proved to be consistent with the actual local needs and to have profound implications for the sustainable development of this region. We are also convinced that, in the future with the increase of data, we can use the same methods to do multi-scale research and in-depth discussion that can help us to make further detailed recommendations.

Acknowledgments: This research is financially supported by the National Natural Science Foundation of China (41330747).

Author Contributions: Conceived and designed the experiments: Qian Lin, Jiansheng Wu, Weifeng Li, Jian Yang; Performed the experiments: Qian Lin, Jiansheng Wu; Analyzed the data: Qian Lin, Jiansheng Wu; Contributed reagents/materials/analysis tools: Qian Lin, Jiaying Mao, Jiansheng Wu; Wrote the paper: Qian Lin, Weifeng Li, Jiansheng Wu, Jian Yang; Paper revision and Language correction: Qian Lin, Weifeng Li, Jiansheng Wu, Jiaying Mao.

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

References

1. Johnson, E.A.; Klemens, M.W. *Nature in Fragments: The Legacy of Sprawl*; Columbia University Press: New York, NY, USA, 2005; p. 400.
2. Van Calster, H.; Vandenberghe, R.; Ruysen, M.; Verheyen, K.; Hermy, M.; Decocq, G. Unexpectedly high 20th century floristic losses in a rural landscape in northern France. *J. Ecol.* **2008**, *96*, 927–936. [CrossRef]
3. Foley, J.A.; DeFries, R.; Asner, G.P.; Barford, C.; Bonan, G.; Carpenter, S.R.; Chapin, F.S.; Coe, M.T.; Daily, G.C.; Gibbs, H.K.; *et al.* Global consequences of land use. *Science* **2005**, *309*, 570–574. [CrossRef] [PubMed]
4. Xiang, W.N.; Stuber, R.M.B.; Meng, X. Meeting critical challenges and striving for urban sustainability in China. *Landsc. Urban Plan.* **2011**, *100*, 418–420. [CrossRef]
5. Qu, G.P. Strategic points and countermeasures of ecological safety in China. *Environ. Prot.* **2002**, *8*, 3–5. (In Chinese)
6. Yang, Y.Y.; Zhang, S.W.; Wang, D.Y.; Yang, J.C.; Xing, X.S. Spatiotemporal changes of farming-pastoral ecotone in Northern China, 1954–2005: A case study in Zhenlai County, Jilin Province. *Sustainability* **2015**, *7*, 1–22. [CrossRef]

7. Cen, X.T.; Wu, C.F.; Xing, X.S.; Fang, M.; Garang, Z.; Wu, Y.Z. Coupling intensive land use and landscape ecological security for urban sustainability: An integrated socioeconomic data and spatial metrics analysis in Hangzhou city. *Sustainability* **2015**, *7*, 1459–1482. [CrossRef]
8. Forman, R.T.T.; Collinge, S.K. Nature conserved in changing landscapes with and without spatial planning. *Landsc. Urban Plan.* **1997**, *37*, 129–135. [CrossRef]
9. Gong, J.Z.; Liu, Y.S.; Xia, B.C.; Zhao, G.W. Urban ecological security assessment and forecasting, based on a cellular automata model: A case study of Guangzhou, China. *Ecol. Model.* **2009**, *220*, 3612–3620. [CrossRef]
10. Li, Y.F.; Sun, X.; Zhu, X.D.; Cao, H.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]
11. Zhou, K.H.; Liu, Y.L.; Tan, R.H.; Song, Y. Urban dynamics, landscape ecological security, and policy implications: A case study from the Wuhan area of central China. *Cities* **2014**, *41*, 141–153. [CrossRef]
12. Peng, J.; Zong, M.L.; Hu, Y.N.; Liu, Y.X.; Wu, J.S. Assessing landscape ecological risk in a mining city: A case study in Liaoyuan city, China. *Sustainability* **2015**, *7*, 8312–8334. [CrossRef]
13. Zuo, W.; Zhou, H.Z.; Wang, Q. Conceptual framework for selection of anindicator system for assessment of regional ecological safety. *Soil* **2003**, *1*, 2–7. (In Chinese)
14. Kong, H.M.; Zhao, J.Z.; Ji, L.Z.; Lu, Z.H.; Deng, H.B.; Ma, K.M.; Zhang, P. Assessment method of ecological health. *Chin. J. Appl. Ecol.* **2002**, *13*, 486–490. (In Chinese)
15. Xiao, D.N.; Chen, W.B.; Guo, F.L. On the basic concepts and contents of ecological security. *Chin. J. Appl. Ecol.* **2002**, *13*, 354–358. (In Chinese)
16. Zhao, Y.Z.; Zou, X.Y.; Cheng, H.; Jia, H.K.; Wu, Y.Q.; Wang, G.Y.; Zhang, C.L.; Gao, S.Y. Assessing the ecological security of the Tibetan plateau: Methodology and a case study for Lhaze County. *J. Environ. Manag.* **2006**, *80*, 120–131. [CrossRef] [PubMed]
17. Gao, Y.; Wu, Z.F.; Lou, Q.S.; Huang, H.M.; Cheng, J.; Chen, Z.L. Landscape ecological security assessment based on projection pursuit in Pearl River Delta. *Environ. Monit. Assess.* **2012**, *184*, 2307–2319. [CrossRef] [PubMed]
18. Chang, H.; Li, Z.; Wang, R.; Wang, Y.; Li, F.; Xiong, X. Study on Network Analysis for Urban Ecological Security Pattern in Changzhou City. *Acta Sci. Nat. Univ. Pekin.* **2009**, *45*, 728–736.
19. Guo, X.; Yang, J.; Mao, X. Primary studies on urban ecosystem health assessment. *China Environ. Sci.* **2002**, *22*, 525–529. (In Chinese)
20. Xie, H.; Li, B. A Study on Indices System and Assessment Criterion of Ecological Security for City. *J. Beijing Norm. Univ.* **2004**, *40*, 705–710. (In Chinese)
21. Yu, K.; Wang, S.; Li, D. The function of ecological security patterns as an urban growth framework in Beijing. *Acta Ecol. Sin.* **2009**, *29*, 1189–1204. (In Chinese)
22. Liu, Y.; Meng, J.; Zhu, L. Progress in the research on regional ecological security pattern. *Acta Ecol. Sin.* **2010**, *30*, 6980–6989. (In Chinese)
23. Ma, K.; Fu, B.; Li, X.; Guang, W. The regional pattern for ecological security: The concept and theoretical basis. *Acta Ecol. Sin.* **2004**, *24*, 761–768. (In Chinese)
24. Chang, H.; Li, F.; Li, Z.G.; Wang, R.S.; Wang, Y.L. Urban landscape pattern design from the viewpoint of networks: A case study of Changzhou city in Southeast China. *Ecol. Complex.* **2011**, *8*, 51–59. [CrossRef]
25. Jepsen, J.U.; Baveco, J.M.; Topping, C.J.; Verboom, J.; Vos, C.C. Evaluating the effect of corridors and landscape heterogeneity on dispersal probability: A comparison of three spatially explicit modelling approaches. *Ecol. Model.* **2005**, *181*, 445–459. [CrossRef]
26. Xiong, J.X. Superior strategies and analysis on integrity of urban eco-network construction regions around lake-take ChangDe city of west DongTing lake region as an example. *Econ. Geogr.* **2008**, *28*, 752–756. (In Chinese)
27. Zetterberg, A.; Mörtberg, U.M.; Balfors, B. Making graph theory operational for landscape ecological assessments, planning, and design. *Landsc. Urban Plan.* **2010**, *95*, 181–191. [CrossRef]
28. Zhang, L.Q.; Wang, H.Z. Planning an ecological network of Xiamen Island (China) using landscape metrics and network analysis. *Landsc. Urban Plan.* **2006**, *78*, 449–456. [CrossRef]
29. Yu, K.J.; Li, D.H.; Li, N.Y. The evolution of Greenways in China. *Landsc. Urban Plan.* **2006**, *76*, 223–239. [CrossRef]
30. Dongguan Statistical Bureau. Statistical yearbook 2014 of Dongguan. Available online: http://tjj.dg.gov.cn/website/flaArticle/art_show.html?code=nj2014&fcount=2 (accessed on 16 February 2016). (In Chinese)

31. Dongguan Statistical Bureau Statistical yearbook 1978–1990 of Dongguan. Available online: http://tjj.dg.gov.cn/website/web/scan/PDF/1978-1990TJNJ.pdf (accessed on 16 February 2016). (In Chinese)
32. Millennium Ecosystem Assessment. Ecosystems and human well-being: A framework for assessment. In *Report of the Conceptual Framework Working Group of the Millennium Ecosystem Assessment*; Island Press: Washington, DC, USA, 2003.
33. Sharp, R.; Tallis, H.T.; Ricketts, T.; Guerry, A.D.; Wood, S.A.; Chaplin-Kramer, R.; Nelson, E.; Ennaanay, D.; Wolny, S.; Olwero, N.; *et al.* InVEST +VERSION+ User's Guide. Available online: http://data.naturalcapitalproject.org/nightly-build/invest-users-guide/html/ (accessed on 16 February 2016).
34. He, J.; Liu, J.; Yu, K.; Zhang, L.; Li, X.; Wang, D. Evaluation of change in the ecological quality for Minjiang River Basin based on the InVEST Biodiversity model. *China Sci. Pap.* **2015**, *10*, 1782–1788. (In Chinese)
35. Pan, T.; Wu, S.; Dai, E.; Liu, Y. Spatiotemporal variation of water source supply service in Three Rivers source area of China based on InVEST model. *Chin. J. Appl. Ecol.* **2013**, *24*, 183–189. (In Chinese)
36. Wu, J. *Integrated Assessment of Ecosystem in Hainan Bamen Bay based on CA-Markov and InVEST Models*; Hainan University: Haikou, China, 2012. (In Chinese)
37. Bai, Y.; Zheng, H.; Zhuang, C.; Ouyang, Z.; Xu, W. Ecosystem services valuation and its regulation in Baiyangdian Basin: Based on InVEST model. *Acta Ecol. Sin.* **2013**, *33*, 711–717. (In Chinese)
38. Wang, Y.; Sun, Y.; Lian, J.; Li, Y. Study on wetland ecological assessment of Honghe nature reserve. *J. Cap. Norm. Univ.* **2011**, *32*, 73–76. (In Chinese)
39. Sun, Y.; Zhang, J. The ecological evaluation for north branch of Changjiang Estuary Wetland Nature Reserve. *Wetl. Sci. Manag.* **2011**, *7*, 25–28. (In Chinese)
40. Nelson, E.; Mendoza, G.; Regetz, J.; Polasky, S.; Tallis, H.; Cameron, D.R. Modeling multiple ecosystem services, biodiversity conservation, commodity production, and tradeoffs at landscape scales. *Front. Ecol. Environ.* **2009**, *7*, 4–11. [CrossRef]
41. Theobalda, D.M.; Crools, K.R.; Norman, J.B. Assessing effects of land use on landscape connectivity: Loss and fragmentation of western U.S. *For. Ecol. Appl.* **2011**, *21*, 2445–2458. [CrossRef]
42. Petrosillo, I.; Zaccarelli, N.; Semerarn, T.; Zurlini, G. The effectiveness of different conservation policies on the security of natural capital. *Landsc. Urban Plan.* **2009**, *89*, 49–56. [CrossRef]
43. Bélisle, M. Measuring landscape connectivity: The challenge of behavioral landscape ecology. *Ecology* **2005**, *86*, 1988–1995. [CrossRef]
44. Calabrese, J.M.; Fagan, W.F. Acomparison-shopper's guide to connectivity metrics. *Front. Ecol. Environ.* **2004**, *2*, 529–536. [CrossRef]
45. Moílanen, A.; Nieminen, M. Simple connectivity measures in spatial ecology. *Ecology* **2002**, *83*, 1131–1145. [CrossRef]
46. Bunn, A.G.; Urban, D.L.; Keitt, T.H. Landscape connectivity: A conservation application of graph theory. *J. Environ. Manag.* **2000**, *29*, 265–278. [CrossRef]
47. Taylor, P.D.; Merriam, G. Connectivity is a vital element of landscape structure. *Okios* **1993**, *68*, 571–573. [CrossRef]
48. Wu, C.; Zhou, Z.X.; Wang, P.C.; Xiao, W.F.; Teng, M.J.; Peng, L. Evaluation of landscape connectivity based on least-cost model. *Chin. J. Appl. Ecol.* **2009**, *20*, 2042–2048. (In Chinese)
49. Foltête, J.C.; Berthier, K.; Cosson, J.F. Cost distance defined by a topological function of landscape. *Ecol. Model.* **2008**, *210*, 104–114. [CrossRef]
50. Chardon, J.P.; Adriaensen, F.; Matthysen, E. Incorporating landscape elements into a connectivity measure: A case study for the Speckled wood butterfly (Parargeaegeria L.). *Landsc. Ecol.* **2003**, *18*, 561–573. [CrossRef]
51. Adriaensen, F.; Chardon, J.P.; de Blust, G.; Adriaensen, F.; Chardon, J.P.; Blust, G.D.; Swinnen, E.; Villalba, S.; Gulinck, H. The application of 'least-cost' modelling as a functional landscape model. *Landsc. Urban Plan.* **2003**, *64*, 233–247. [CrossRef]
52. Sutcliffe, O.L.; Bakkestuen, V.; Fry, G.; Stabbetorp, O.E. Modelling the benefits of farmland restoration: Methodology and application to butterfly movement. *Landsc. Urban Plan.* **2003**, *63*, 15–31. [CrossRef]
53. Epps, C.W.; Wehausen, J.D.; Bleich, V.C.; Torres, S.G.; Brashares, J.S. Optimizing dispersal and corridor models using landscape genetics. *J. Appl. Ecol.* **2007**, *44*, 714–724. [CrossRef]
54. Verbeylen, G.; Bruyn, D.L.; Adriaensen, F.; Matthysen, E. Does matrix resistance influence red squirrel (Sciurusvulganis L. 1758) distribution in an urban landscape? *Landsc. Ecol.* **2003**, *18*, 791–805. [CrossRef]

55. Sun, D.F.; Dawson, R.; Li, H.; Wei, R.; Li, B. A landscape connectivity index for assessing desertification: A case study of Minqin County. *China. Landsc. Ecol.* **2007**, *22*, 531–543. (In Chinese). [CrossRef]
56. Singleton, P.H.; Gaines, W.L.; Lehmkuhl, J.F. Landscape Permeability for Large Carnivores in Washington: A Geographic Information System Weighted-distance and Least-cost Corridor Assessment. Available online: http://rewilding.org/Singletonl.pdf (accessed on 15 October 2008).
57. Li, J.H.; Liu, X.H. Research of the nature reserve zonation based on the least-cost distance model. *J. Nat. Res.* **2006**, *21*, 219–224. (In Chinese)
58. Yu, K.J. Landscape Ecological Security Patterns in Biological Conservation. *Acta Ecol. Sin.* **1999**, *19*, 8–15. (In Chinese)