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The Restoration Strategy of Ecological Fragmentation Structure Based on the Theory of Minimum Spanning Tree

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Abstract: Ecological restoration is one of the hot issues in ecological research. According to the energy flow relationship of biological units, one type of directed-weighted network of ecological energy flow is constructed in this paper. In this network, we consider ecological units as nodes, energy flow path between two units as directed edge between two nodes, and the effort to set up a path between units as edge weight. Due to the influence of external factors, the ecosystems are fragmented by various degrees of destruction. By using the minimum spanning tree theory, various restoration strategies under different fragmentation degree is given, in which the maximum relative energy utilization rate and stronger invulnerability are regard as the goals. The minimum spanning tree structure of the ecological energy flow has highest energy utilization rate and stronger invulnerability is proved.

Keywords: Directed-weighted network; Energy utilization rate; Invulnerability; The minimum spanning tree theory

1 Introduction

Since the middle of 1980s, with the world's population explosion, countries have hastened the development of natural resources. The destruction, loss, degradation and contamination of habitat come under observation. Due to man-made or natural factors, the original extensive and continuous distribution habitat become many isolated and unconnected patch mosaics or quads, which affects the survival of animal species [1], biodiversity [2] and ecosystem processes. It also affects the extinction threshold, distribution, interspecific interaction and abundance of animal population, and eventually lead to declination constantly or even extinction of species [3,4].

Habitat destruction influences the growth and reproduction of fora and fauna [5]. It has aroused the attention of many scholars in the early 1980s, who have carried out a lot of research on this area. Now there are a large number of studies about habitat restoration and reconstruction and study object are population [6-8]. Related papers whose study object are plant mainly discuss the genetic structure of plant population, the diffusion and germination of seed, the pollination of plants and interaction of flora and fauna [9-11]. In landscape ecology [12-14], the study of patches, the relative ecological units, and the connection between different patches mostly focus on the influence on bio-diversity [1,2]. Habitat destruction makes ecological units isolated from each other, and changes the diffusion, immigration, inherit and variation of population, then affects the breeding and migration of species [15]. On the issue of the degraded ecosystem restoration and reconstruction, the international society for ecological restoration thought that degraded ecosystem restoration is the analog of a particular ecosystem structure, function, diversity and its dynamic characteristics, and through man-made to establish a primitive ecosystem which has been appeared in the past. The main method of habitat restoration is to create paths between ecological units, such as vegetation restoration [16]. The establishment of paths is in favor of the flow of energy between biological units [17]. However, there are few researches on ecological restoration strategies under different fragmentation degree from the perspective of theory.

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This paper studies the distribution of paths between different ecological units and construct directed-weighted ecological energy flow network. To network structure with different fragmentation degrees, restore the broken paths between biological units by the using of the minimal spanning tree theory. The highest energy utilization rate of the network structure based on spanning tree theory is proven. Meanwhile the positive correlation between energy utilization rate and invulnerability is also proven. This study provide an optimal method for ecological restoration.

2 The theoretical foundation and basic concepts

2.1 The structure of ecological energy flow network

In the ecosystem, energy is transmitted and circulated through effective paths between ecological units. Therefore, the ecological units are considered as nodes in the network, the effective path between two units is considered as the edge of the network. In a network with n nodes, $V = \{v_1, v_2, \ldots, v_n\}$ denotes the set of nodes, $E = \{e_{ij}|e_{ij}$ denotes the connection between node v_i and $v_j\}$, so the network can be expressed as $G = (V, E)$. In the actual ecosystem, energy flow between two ecological units need effort expending, which is regarded as edge weight $w(e_{ij})$ in the network G. Then, the energy flow network $G = (V, E, W)$ is constructed.

2.2 The shortest path with the minimum spanning tree

The spanning tree (denoted as T) is connected graph which contains the minimum number of edges in the unweighted network. For example, the spanning tree of an undirected graph with n nodes has $n-1$ edges and has no loop. Removing or adding an edge in this structure will make the new structure not meet with the definition of the spanning tree. Removing any edge will make this structure not connected. Adding an edge, there will exist ring in modified structure. The spanning three ensures that only one path between any two nodes. For a set of nodes, the structure of spanning three is not unique. For a weighted network $G = (V, E)$, $V = \{v_i\}$ is the set of nodes and $E = \{e_{ij}\}$ is the set of all the edges and $w(e_{ij})$ denotes the weight of edge e_{ij} between node v_i and v_j. Set P_{ij} is the path from node v_i to v_j in the directed-weighted graph G, which can be composed of several edges. Let $e(P_{ij})$ is the set of all the edges in this path, $W(P_{ij}) = \sum\limits_{e \in e(P_{ij})} w(e)$ is the weight of path P_{ij}, where $w(e)$ is the weight of edge e. Among the different paths between two nodes, the path with the minimum weight $P^{\star}_{ij}$ is called the shortest path from node v_i to v_j. An so on, the spanning tree with the least sum of the edge weights in all of the the multiple spanning trees is called the Minimum Spanning Tree (Minimum Spanning Tree), and denoted as MST.

2.3 The network energy utilization rate $E[G]$ and the relative energy utilization rate $E'[G]$

In the energy flow network, the longer the energy flow path is, the lower the energy utilization is gotten. In order to measure the effectiveness of energy flow between units in the disrupted ecosystem, we introduce the energy utilization E of network. Assume that the energy always flow along the shortest path between nodes. The energy utilization rate ε_{ij} between node v_i and v_j , is the reciprocal of the shortest length d_{ij} . And the energy utilization rate of the whole network G with n nodes is the average of energy utilization rate between nodes. It can be expressed as

$$E[G] = \frac{\sum\limits_{i \neq j} \varepsilon_{ij}}{n(n-1)} = \frac{1}{n(n-1)} \sum_{i \neq j} \frac{1}{d_{ij}}, \tag{1}$$

where ε_{ij} is the energy utilization rate between node v_i and v_j, $d_{ij} = w_{ik} + w_{kj}$ is the shortest length, $i, j = 1, 2, \ldots, n$ and n is the number of nodes in network G.

Define the relative energy utilization rate as the ratio of energy utilization rate and the effort for building energy flow paths. It can be expressed as

$$E'[G] = \frac{1}{n(n-1) \times \sum\limits_{i \neq j \in G} \omega_{ij}} \sum_{i \neq j \in G} \frac{1}{d_{ij}}. \tag{2}$$

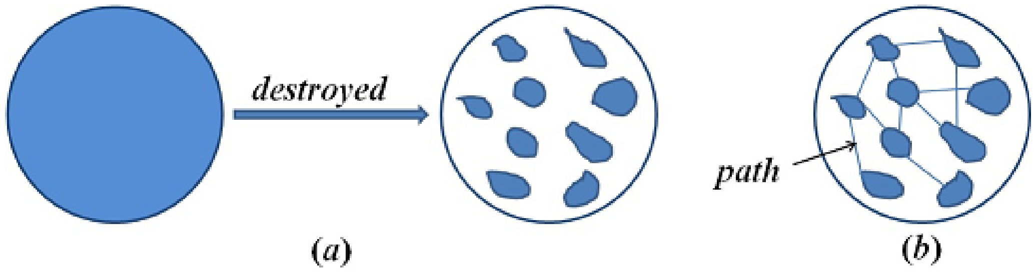

Fig. 1: (a) structure destruction; (b) restoration of paths

2.4 Anti-interference ability index

The anti-interference ability of ecosystem reflect the ability to restore under interference. It is defined similar to invulnerability, an index in network, which refers to the ability of the network to maintain or restore its performance to an acceptable level when there is a deterministic or random failure in the network. Energy flow network $G = (V, E, W)$ is a directed-weighted network. So, use the invulnerability index of the directed-weighted network as the anti-interference ability index of energy flow network.

$$F = H \times L^{-1} = \frac{\sum_{i=1}^{n} \sqrt{k_{out}(i) \times k_{in}(i)}}{n} \times \frac{1}{n(n-1)} \sum_{i \neq j} \frac{1}{d_{ij}}, \tag{3}$$

where $k_{out}(i)$, $k_{in}(i)$ are the number of energy flow paths from node v_i and into node v_i respectively.

$H = \frac{\sum_{i=1}^{n} H(i)}{n}$, the mean of $H(i), i = 1, 2, \ldots, n$, is the loop coefficient of whole network.

$H(i) = \sqrt{k_{out}(i) \times k_{in}(i)}$ is the loop coefficient of node v_i, which can quantify the level of connection between the particular ecological unit and surrounding ones.

$L^{-1} = \frac{1}{n(n-1)} \sum_{i \neq j} \frac{1}{d_{ij}}$ is the harmony shortest distance of whole network.

The index H reflects the connectivity of the whole network, and L^{-1} reflects the efficiency of the whole network. So the anti-interference ability index F, which is defined as the product of H and L^{-1}, reflects the anti-interference ability is positively related to connectivity and efficiency of the whole network.

3 Network structure restoration

3.1 Modeling

After network structure destruction, the original paths are broken. As a result, the ecological units are isolated (see as Fig. $1(a)$). Building paths between units is in favor of preserving biodiversity and improving energy flow between units (see as Fig. $1(b)$).

This paper gives the optimal plan of ecological energy flow network structure restoration, and assumes that

1. The ecosystem is divided into 20 patches after destruction, which are considered as nodes in network and marked 1 to 20. The initial network whose edge between any two points is directly connected is globally coupled network.
2. According to the difficulty of building paths between units, the edge weights are divided into three levels, which are assigned 1,2, and 4 respectively.
3. Because energy flow is mutual, directed edges can be simplified to undirected edges in the process of calculation.

3.2 Theorem and proof

For the purpose of energy utilization, the less effort is spent, the less energy is dissipated during the energy flow process, so the higher the energy utilization is. In the energy flow network, edge weight denote the effort spent during the energy

Table 1: The invulnerability indexes of structures in Fig.4

Structure number	(a)	(b)	(c)	(d)	(e)	(f)
Invulnerability index	0.4123	0.4155	0.422	0.4256	0.5249	0.4155

flow process. Getting the path with the minima weight between any two nodes, means getting the path with the minima energy-dissipation. In this paper, we use the minimum spanning tree theory to find the optimal restoration strategy for the destroyed energy flow network structure, and prove the following theory.

Theorem 1 *The network with the minimum spanning tree structure has the highest relative energy utilization rate.*

Proof. Assuming that the triangle structure (see Fig.2(a)) is a part of the network, and suppose $h > m$,$h > k$. Using the broken circle method, obtain the minimum spanning tree (see Fig.2(b)) by delete the edge with the largest weight.

According to Formula(1), we calculate the energy utilization rate E_1 and E_2 for the structures of Fig.2(a) and Fig.2(b) respectively.

$$E_1 = \frac{1}{3}(\frac{1}{m} + \frac{1}{k} + \frac{1}{h}),$$
$$E_2 = \frac{1}{3}(\frac{1}{m} + \frac{1}{k} + \frac{1}{m+k}).$$

According to formula(2), the relative energy utilization rate are

$$E_1' = \frac{1}{3(m+k+h)} \times (\frac{1}{m} + \frac{1}{k} + \frac{1}{h}),$$
$$E_2' = \frac{1}{3(m+k)} \times (\frac{1}{m} + \frac{1}{k} + \frac{1}{m+k}).$$

Then, we get

$$\begin{aligned} E_2' - E_1' &= \frac{1}{3(m+k)}(\frac{1}{m} + \frac{1}{k} + \frac{1}{m+k}) - \frac{1}{3(m+k+h)}(\frac{1}{m} + \frac{1}{k} + \frac{1}{h}) \\ &= \frac{1 + \frac{h}{m+k} + \frac{h}{m} - \frac{m}{h} + \frac{h}{k} - \frac{k}{h}}{3(m+k)(m+k+h)}. \end{aligned}$$

Because $h > m$,$h > k$,$\frac{k}{h} < 1 < \frac{h}{m}$,$\frac{m}{h} < 1 < \frac{h}{m}$,

$$E_2' - E_1' > \frac{1 + \frac{h}{m+k}}{3(m+k)(m+k+h)} = \frac{m+k+h}{3(m+k)^2(m+k+h)} = \frac{1}{3(m+k)^2} > 0,$$

so

$$E_1' < E_2'.$$

■

4 The application and main conclusions

In this paper, the energy flow network described in section 3 is demonstrated as Fig. 3.

Though deleting the edge with the largest weight in the triangle loop of the topology structure, the minimum spanning tree structures can be obtained, some of which are showed in Figs. 4((a)-(f)).

According to Theorem 1, these structures have the highest relative energy utilization rate. Though the calculation of the invulnerability, the minimum spanning tree structure with the strongest invulnerability will be chosen as the optimal restoration plan. From formula 3, the invulnerability indexes of structures in Fig.4 are gotten (see Table 1).

From Table 1, restoration plan (e) is be chosen.

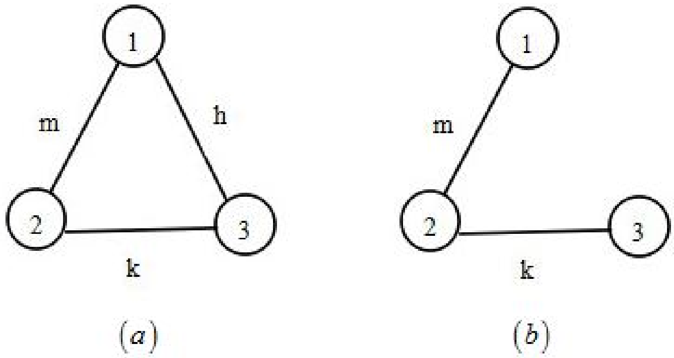

Fig. 2: (a) The triangle structure in the network (b) The minimum spanning tree of the triangle structure (a)

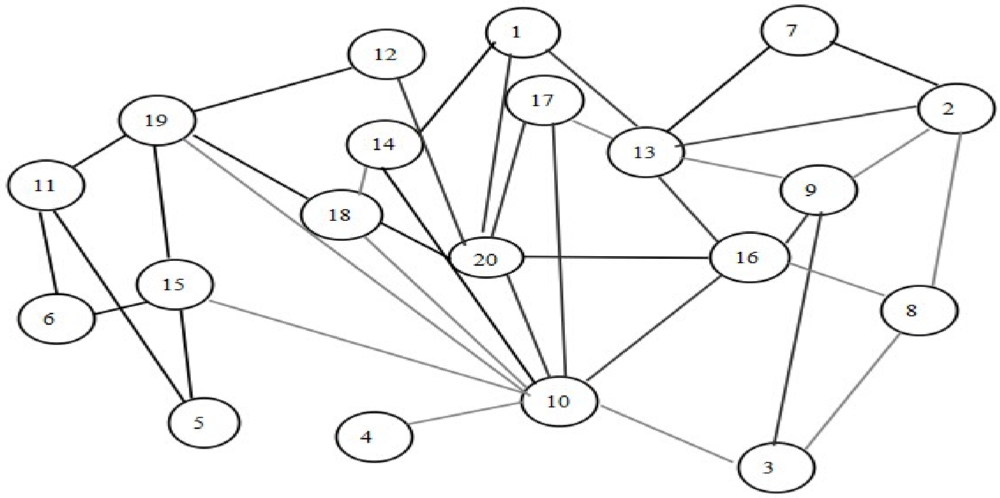

Fig. 3: Structure of the energy flow network structure

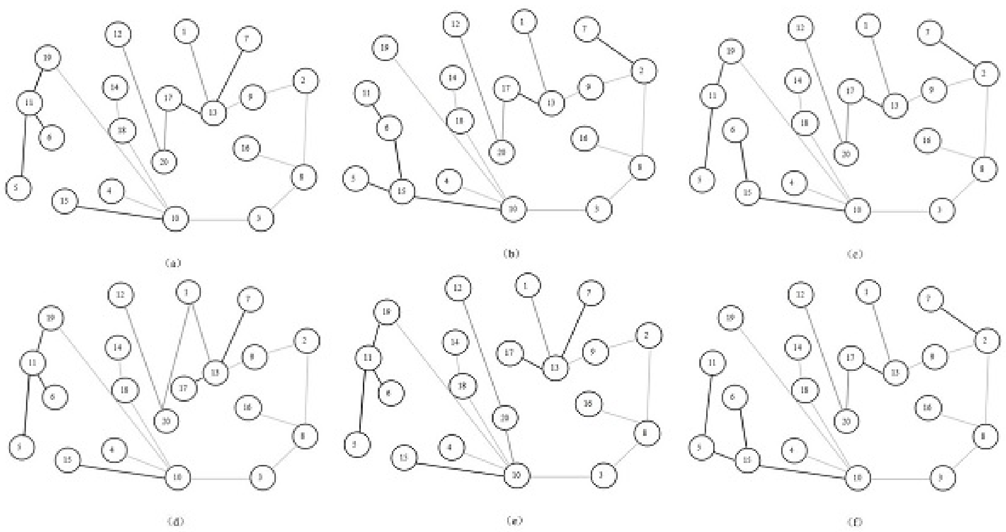

Fig. 4: The minimum spanning tree structures of Fig.3

5 Conclusion

Using the proposed approach, the restoration with the highest relative energy utilization rate and strongest invulnerability plan can be found. Although the schemes and measures proposed in this paper can't solve all the problems in the restoration of the degraded network structure, but it can increase the connection level between ecological units by less effort spending under the premise of the highest energy utilization rate, avoiding the loss of species caused by destruction.

References

[1] Z.J. Wu, Y.M. Li. Effects of habitat fragmentation on survival of animal populations. *Acta Ecologica Sinica*, 23(2003): 2424–2435.

[2] F. Yang, D.H. He. Effects of habitat fragmentation on biodiversity. *ECOLOGIC SCIENCE*, 25(2006): 564–567.

[3] C. Philippe, F. Burel. The role of spatio-temporal patch connectivity at the landscape level: an example in a bird distribution. *Landscape Urban Planning*, 38(1997): 37–43.

[4] A. Andrews. Fragmentation of habitat by roads and utility corridors:a review. *Austral Zool*, 23(1990): 130–141.

[5] L.J. Pan et.al. Synchronization for complex networks with Markov switching via matrix measure approach. *Applied Mathematical Modelling*, 39(2015): 5636–5649.

[6] J. Wu, Z.M. Liu. Effect of habitat fragmentation on biodiversity: A review (in Chinese). 2014.

[7] P. Galbusera et.al. Genetic equilibrium despite habitat fragmentation in an Afrotropical bird. *Molecular Ecology*, 13(2004): 1409–1421.

[8] T.O. Bickel et.al. Influence of habitat fragmentation on the genetic variability in leaf litter ant populations in tropical rainforests of Sabah. *Biodiversity and Conservation*, 15(2006): 157–175.

[9] S.A. Bael et.al. Bird diversity in cacao farms and forest fragments of western Panama. *Biodiversity Conservation*, 16(2007): 2245–2256.

[10] D.L. Thomas et.al. Length of docked tail and the incidence of rectal prolapse in lambs. *Journal of Animal Science*, 81(2003): 2725–2732.

[11] K. Henle et.al. Christian Wissel Species Survival in Fragmented Landscapes: Where are We Now? *Biodiversity and Conservation*, 13(2004): 1–8.

[12] K. M. Alofs, N. L. Fowler. Habitat fragmentation caused by woody plant encroachment inhibits the spread of an invasive grass. *Journal of Applied Ecology*, 47(2010): 338-347.

[13] H.S. Xiao et.al. Evaluation on the Forest Lands- cape Stability of Liuxi River National Forest Park. *Journal of Central South University of Forestry and Technology*, 27(2007): 88-92.

[14] C.F. Fu, G. Zhang. Analysis on stability factors of forest lands- cape at Liuxihe River. *Jour of Fujian Forestry Sci and Tech*, 35(2008): 176-180.

[15] W. Fu et.al. A review on ecological connectivity in landscape ecology. *Acta Ecologica Sinica*, 29(2009): 6174-6182.

[16] G.S. Jiang et.al. Patch scale structure of red deer winter habitat fragmentation factors using GeoStatistics method. *Journal of Beijing Forestry University*, 28(2006): 95-100.

[17] G.Z. Shen et.al. Structure and dynamics of subalpine forests in giant panda habitat. *Acta Ecologica Sinica*, 24(2004): 1294-1299.