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The Functional Linkage Index: A Metric for Measuring Connectivity among Habitat Patches Using Least-Cost Distances

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ABSTRACT: Connectivity among habitat patches in fragmented landscapes is generally acknowledged as a key component in the conservation of biodiversity. This paper presents a new metric, the Functional Linkage Index, for measuring connectivity among groups of patches. The metric is based on the concept of the proximity index, but incorporates the use of least-cost distances as well as allowing for more robust measures of habitat value. It can be calculated using a publicly available tool that was developed for use in ESRI's ArcGIS® 9.2 or 9.3 software. The metric and tool can be of particular use in comparing relative changes to connectivity resulting from various development or restoration scenarios.

Keywords: Geographic Information System, GIS, connectivity, habitat, least cost distance, patch, nearest neighbor

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INTRODUCTION

Landscape connectivity has been defined as “the degree to which the landscape impedes or facilitates movement among resource patches” (Taylor et al. 1993). It is now generally accepted that landscape connectivity plays an essential role in the dispersal of organisms among habitat patches and thus the conservation of biodiversity (Tischendorf and Fahrig 2000). Connectivity can be characterized as either functional or structural; structural connectivity describes only the spatial relationships among habitat patches such as inter-patch distances and the availability of corridors, while functional connectivity measures the ability of organisms to move among patches based on the surrounding landscape (Taylor et al. 2006). Two patches may be separated by only a short distance and thus have a high structural connectivity. However, the functional connectivity of those patches will depend on the nature of the intervening distance and the dispersal characteristics and abilities of the organism being considered.

Several different metrics with varying levels of complexity have been used for the purpose of measuring connectivity (McGarigal and Marks 1995, Schumaker 1996, Moilanen and Nieminen 2002, Bender et al 2003, Calabrese and Fagan 2004, Kindlmann and Burel 2008). When considering a single patch, perhaps the simplest measure of connectivity is the distance to its nearest neighbor (a patch of the same habitat type). When considering multiple patches in the landscape, an average nearest neighbor score can be used as an indicator of connectivity for the whole group. However, although nearest neighbor distance is a commonly used connectivity metric, it appears to be a poor predictor of actual species colonization rates; the reasons being that it often ignores patches that are within a reasonable migration distance from the focal patch and that it does not explicitly factor in the size and shape of patches (Moilanen and Nieminen 2002, Bender et al 2003).

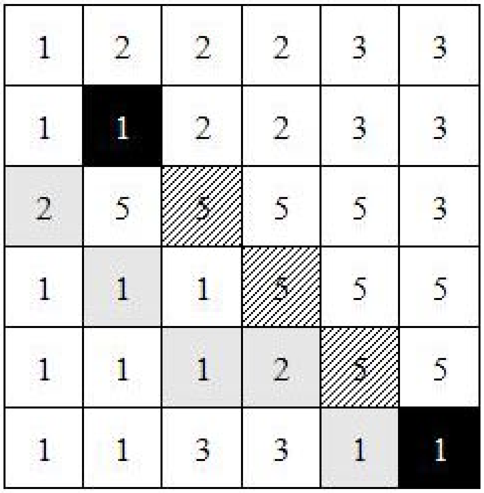
A more robust connectivity metric than a simple nearest neighbor distance is the proximity index, which is defined as the sum of the ratio between patch area and inter-patch distance for all patches within a specified buffer distance around a focal patch (Gustafson and Parker 1994, Bender et al 2003). The proximity index offers an advantage over nearest neighbor distance in that more than one other patch can be considered in relation to the focal patch, and the total area of connected patches is also factored into the equation. However, the metric is still somewhat limited in that it does not measure functional connectivity, and does not consider aspects of patch habitat quality other than patch area. Therefore, as a new alternative and potential improvement to previous methods for measuring connectivity, the “Functional Linkage Index” (FLI) is proposed. The FLI falls into the general category of connectivity metrics that are based on matrix permeability (Kindlmann and Burel 2008). It uses least-cost distances as a way of approximating functional connectivity, and also allows for more robust measurements of habitat quality. The score should be of particular use for comparing relative changes to connectivity resulting from various development or restoration scenarios within a specified study area. Because the FLI is meant to be measured in a Geographical Information System (GIS) environment, a tool for calculating the metric within ESRI’s ArcGIS 9.2 or 9.3 was also created concurrently with the development of the metric.

THE FUNCTIONAL LINKAGE INDEX

Background

The simplest and most direct way to measure inter-patch distances is by using a Euclidian distance. However, measuring connectivity using the Euclidian distance between patches addresses only structural and not functional connectivity, thereby ignoring the effect of the landscape on the behavior of the migrating species (Taylor et al. 2006). Employing GIS software, functional connectivity can instead be measured through the use of least-cost distances (Bunn et al. 2000, Ray et al 2002, Adriaensen et al 2003, Compton et al 2007, Drielsma et al 2007), and various studies have shown least-cost distances to be a better measure of connectivity then Euclidian distances (Chardon et al. 2003, Coulon et al. 2004). The least-cost distance measure is identical to the ‘minimal cumulative resistance’ (MCR) concept which was originally proposed by Knaapen et al (1992) as a measure of habitat isolation. In a least-cost distance/MCR analysis, the landscape matrix between patches is viewed as a grid, with each cell in that grid having a specific resistance value or cost. Certain land cover types will be less traversable to wildlife than others, therefore cells containing these cover types will have a higher cost associated with them. The cost distance between two patches is the least accumulated cost associated with a single path (the least-cost path) between the patches (Figure 1).

FIGURE 1 A cost grid showing the least-cost path (light grey cells) as compared to the Euclidian path (hatched cells) between two focal patches (black cells). The numbers are the movement cost for traversing one linear unit within the associated cell resolution (ESRI 2007). Assuming a 10 x 10 linear unit cell resolution, the total cost distance of the Euclidian path is 226.27, while the total cost distance of the least-cost path is 102.78.



1	2	2	2	3	3
1	1	2	2	3	3
2	5	5	5	5	3
1	1	1	5	5	5
1	1	1	2	5	5
1	1	3	3	1	1

Calculation

When considering multiple patches within a landscape, a separate least-cost distance can be determined from each patch to every other patch that is within a specified dispersal or buffer distance. The dispersal distance is the theoretical maximum linear distance an organism will travel away from a patch (Figure 2). The FLI is based on a combination of the accumulated least-cost path distances, and is calculated for an individual patch (*p*) as follows:

$$F_p = \sum_i^n \left(H_p H_i\right)\cdot\left(\frac{1000}{d_i}\right)$$

F = the Functional Linkage Index

n = number of patches connected to the focal patch

H_p = habitat value of the focal patch

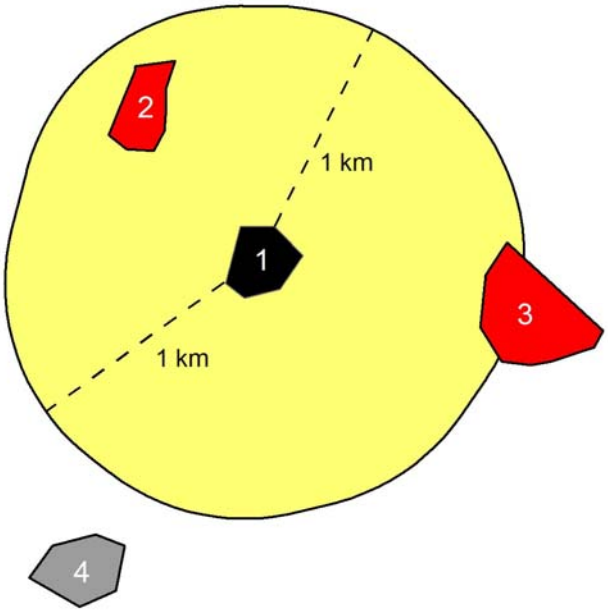
H_i = habitat value of connected patch *i*

d_i = least-cost edge-to-edge distance between the focal patch and connected patch *i*

The FLI for a group of patches is:

$$F = \sum_{p=1}^n F_p$$

FIGURE 2 An illustration of connectivity within a specified 1 km dispersal distance. Patches 2 and 3 are within the 1 km dispersal range from focal patch 1, therefore their least-cost distances to patch 1 will be used in the calculation of F_1. Patch 4 is outside of the dispersal range, therefore its least-cost distance to patch 1 will not be considered.



F is a unitless, relative measurement that is dependent on the nature of the cost grid and patch habitat values. *F* values from two different studies would only be comparable if the two cost grids were of the same resolution, the costs associated with each landscape type were identical, the same dispersal distances were used, and the scaling of the habitat values was the same. In the first equation, the value of “1000” was used so that *F* would generally be a number > 1; however, because of the relative nature of *F*, the selection of the value was somewhat arbitrary and could just as easily be any positive number.

Habitat values are a reflection of the quality of the habitat within a specific patch. *F* for a patch will increase if either its habitat quality or the habitat qualities of patches within the specified dispersal distance increase. The values can be scaled in any manner (although a 0.0 – 1.0 scale is suggested for simplicity), and assigned using existing information, expert opinion, determined using various index models such as those based on the Habitat Evaluation Procedure (USFWS, 1980a,b,c), or simply based on a single metric such as patch size. The effect of habitat values can also be ignored in the calculation of *F* simply by assigning all patches identical habitat values.

The calculation of *F* utilizes several simplifying assumptions. These assumptions need to be fully recognized in order to understand the limitations of the metric and to gauge the applicability of using *F* as a metric for any particular study. The major assumptions and simplifications are:

1. A least-cost path is actually representative of an organism’s movement pattern through a landscape.
2. Cost values are static in the landscape. Given the same land cover type, the cost of traversing an individual landscape cell does not increase with the distance the organism is required to travel from a source patch.
3. The issue of actual metapopulation size in individual habitat patches is not directly addressed. However, habitat values might be considered as a surrogate for population size, under the secondary assumption that a higher habitat value would correlate to a larger metapopulation.

Selecting the Cost Grid

One of the first tasks when conducting a functional connectivity analysis is the creation of the cost grid, which will vary for different species. Unless the analysis is specifically meant to target a single species, there is an issue of how best to address connectivity for the entire suite of species that utilize a particular habitat type. Perhaps the simplest way to address this issue is to create a single cost grid, based largely on best professional judgment, that is assumed to be generally representative for a number of species (i.e., urbanized areas have a greater movement cost then agricultural areas, which have a greater movement cost then forested areas, etc). Although this approach may be an acceptable method to use for screening and comparative purposes, it is also likely to produce the least accurate results. Another alternative is to use the “extended umbrella” species concept (Hurme et al 2008, Roberge and Angelstam 2004). Under this concept, the species used in the analysis would be one, among those that utilize the targeted habitat, which has some of the most demanding landscape connectivity requirements. Enhancing connectivity for this species is thus expected to improve connectivity for a number of other naturally co-occurring species which have less stringent landscape requirements. Using an umbrella species, however, requires that there is enough information concerning its dispersal preferences to create an accurate cost grid. The analysis can be made even more robust by using a focal species approach (Lambeck 1997), whereby a suite of umbrella species is used in order to reflect the connectivity requirements of different species guilds (i.e. aquatic, terrestrial, avian). Using this method however can potentially add a considerable amount of time to the analysis and requires information on the dispersal characteristics for multiple species.

GIS Tool

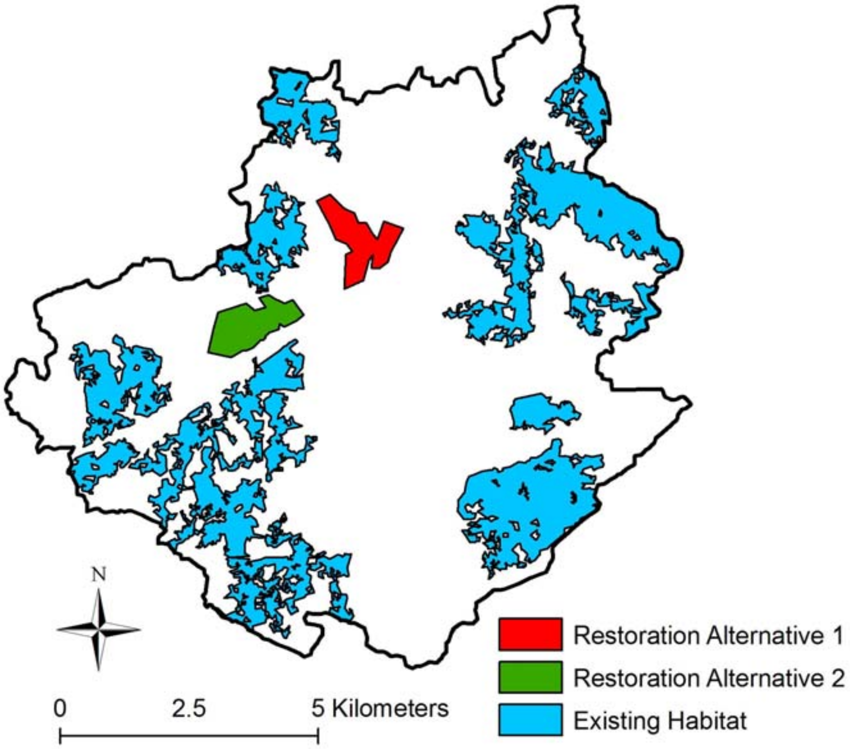
An ArcGIS® 9.2 and 9.3 tool has been developed specifically to calculate *C.* The tool was written as a script in the Python programming language, and runs out of the ArcGIS Toolbox application. It calculates *C* for individual patches and summarizes the results across one or more study areas. The code utilizes the ArcGIS Spatial Analyst "Cost Distance" function to compute the least-cost distances from every cell in the landscape to the source patch. The "Zonal Statistics" feature is then utilized to determine the minimum least cost path from each destination patch to the source patch. The user required inputs into the tool include a shapefile of the habitat patches to be analyzed with habitat values assigned to each of the patches, a cost grid, and a dispersal distance. The tool is available for download at http://el.erdc.usace.army.mil/emrrp/gis.html.

EXAMPLE APPLICATION

One potential application of the connectivity score is in comparing the increases in connectivity resulting from alternative habitat restoration locations. To use a hypothetical example, suppose that two potential locations have been identified by a non-profit group for habitat restoration within a watershed (Figure 3). Both proposed locations are of similar size and will provide similar on-site habitat value once restored. However, there are enough funds available to purchase and restore only one of these land parcels. Information on how each of these patches will contribute to connectivity within the watershed can be used to help identify which of these parcels should be targeted.

This example is meant to illustrate just one possible application for the Functional Linkage Index. This type of analysis could be conducted for many other possible scenarios which entail activities that result in an addition or loss of patches, changes in patch habitat value, or changes in the surrounding land cover.

FIGURE 3 The location of two alternative restoration locations within a watershed.



METHODS

A land cover based cost grid (Figure 4) was created using a selected area from the 2001 National Land Cover Database (NLCD) (Homer et al 2002), which has a 30 m x 30 m cell resolution. The NLCD was reclassified by assigning a cost to each specific land cover (Table 1). The costs were based on values used by Nikolakaki (2004) for the redstart (*Phoenicurous phoenicurous*), an umbrella species of migratory woodland bird found in England which prefers mature, deciduous forest. These cost values were selected purely for demonstrative purposes and to illustrate how values may be derived from the published literature.

Existing habitat patches were defined as contiguous areas of deciduous forest that were greater than 50 ha in size, per the habitat requirements of *P. phoenicurous* (Nikolakaki 2004). The study watershed contained 12 habitat patches, ranging from approximately 60 to 524 ha (155 to 1357 acres) in size. For simplicity, the two largest existing habitat patches were assigned habitat values of 1.0 (on a 0 – 1.0 scale), and the remaining habitats were randomly assigned habitat values ranging from 0.3 – 0.9. The two potential restoration sites were both 121 ha (313 acres), and were overlaid over existing agricultural land and forested areas that were not large enough to qualify as suitable habitat. The restoration sites were arbitrarily assigned post-restoration habitat values of 0.6.

FIGURE 4 The land cover cost grid used for the calculation of the functional linkage indices.

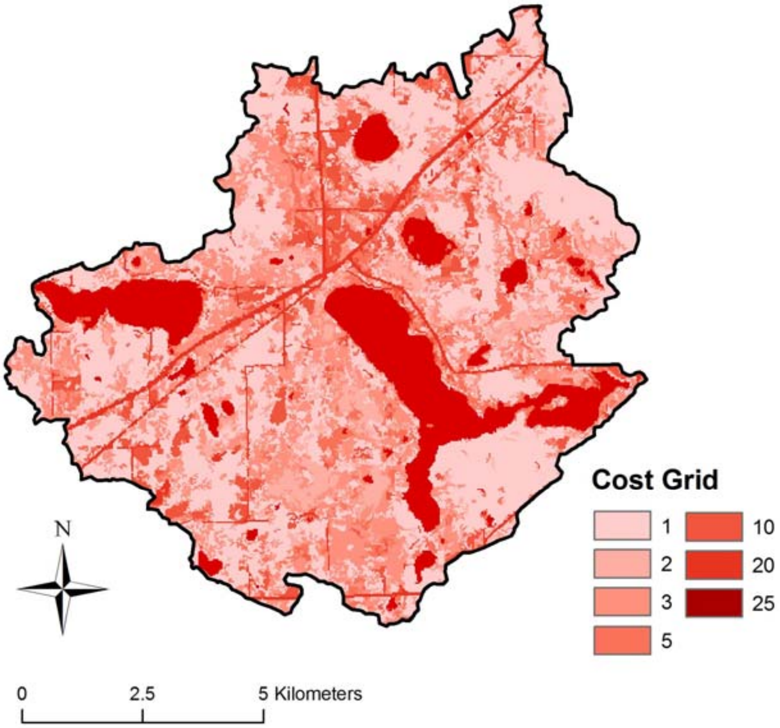


TABLE 1 The Costs Used for Each NLCD Land Cover Class

NLCD Class	Landscape Cost Value
Deciduous Forest	1
Mixed Forest	2
Woody Wetlands	2
Evergreen Forest	3
Barren Land	5
Shrub/Scrub	5
Grassland Herbaceous	5
Herbaceous Wetlands	5
Pasture/Hay	10
Cultivated Crops	10
Developed, Open Space	20
Developed, Low Intensity	20
Open Water	25

RESULTS

Using the created cost-grid and specifying a 3 km (1.9 mi) dispersal distance (Nikolakaki 2004), *F* was first calculated for the watershed without either of the restoration alternatives, and then for the watershed with each of the restoration alternatives separately. The results are shown in Table 2. Based on this analysis, alternative 2 will provide more connectivity in the watershed than alternative 1.

F for the watershed is equal to the sum of *F* for each of the individual patches within the watershed. In addition to measuring the change in *F* for the watershed, the change in *F* was also measured for each of the individual patches for both restoration alternatives. Figure 5 shows the *F* scores for each of the individual patches in the no restoration scenario. Figure 6 (page 35) shows the changes in *F* for each existing patch resulting from restoration alternative 1, while Figure 7 (page 35) shows the changes resulting from restoration alternative 2. As can be seen in these figures, *F* for a patch can change even though its nearest neighbor distance remains the same.

TABLE 2 Watershed Functional Linkage Index and Percent Increase in the Score due to Restoration for the Three Example Scenarios

Plan	Functional Linkage Index (*F*)	Percent Increase in *F*
Without Restoration	81.2	-
Restoration Alternative 1	83.6	3.0
Restoration Alternative 2	90.2	11.1

FIGURE 5 *F* scores for individual patches under baseline conditions.

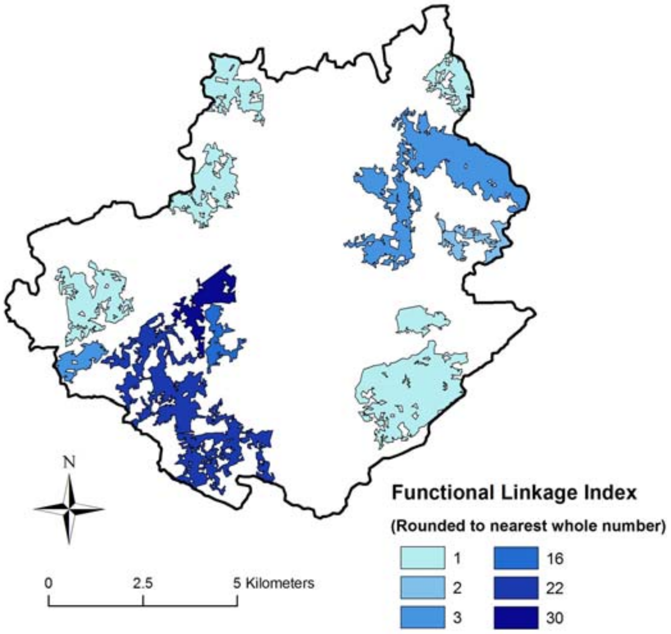


FIGURE 6 The changes in *F* to existing habitat patches due to restoration alternative 1.

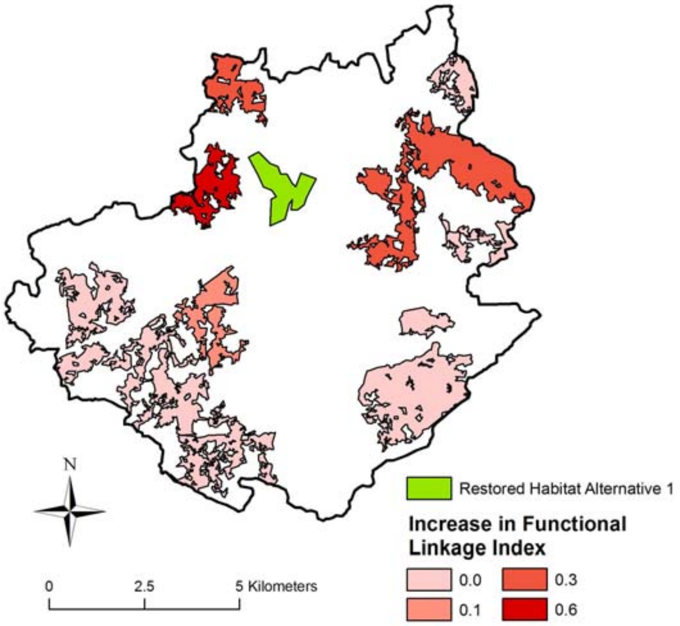
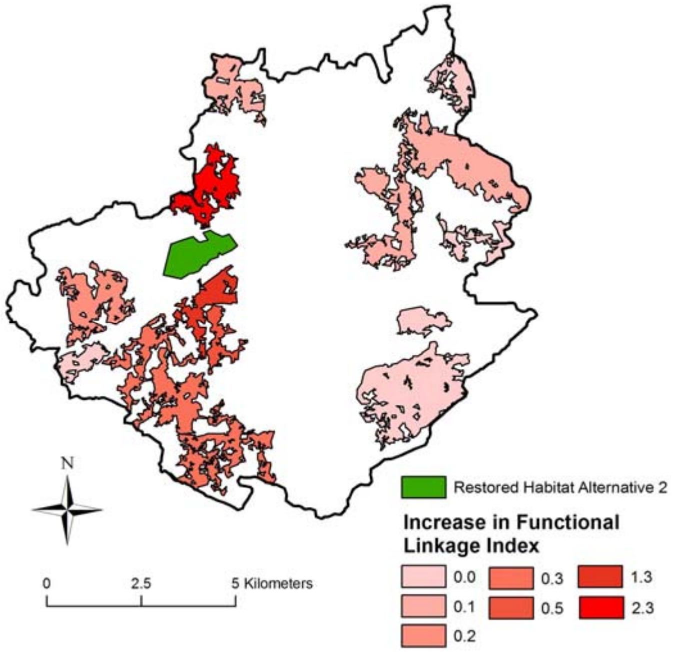


FIGURE 7 The changes in *F* to existing habitat patches due to restoration alternative 2.



DEALING WITH ISSUES OF HABITAT FRAGMENTATION

The Functional Linkage Index is measured in such a way that, all else being equal, it will increase as the number of suitable habitat patches in the landscape increases, and vice versa. This makes sense in some analyses, in that connectivity should decrease when existing patches are lost through development, and connectivity should increase when new patches are gained through restoration efforts. On the other hand, it can be counterintuitive when the number of patches are increased by land development projects (via fragmentation of existing patches) or lost through restoration (via combining several smaller patches into a single larger patch).

In the case of fragmentation through development, this issue is somewhat addressed through the use of habitat values and the cost matrix. In these situations, overall landscape connectivity may still decrease even though the number of patches increases. This decrease in connectivity can result because the new patch fragments will generally have a lower habitat value associated with them, and the cost distance between them will usually be high due to the increased costs of movement in the surrounding landscape. However, if the development project still shows an increase in connectivity over pre-development conditions, the values assigned to the cost matrix may need to be re-evaluated, with higher costs assigned to developed areas. Another alternative in this situation is to divide *F* by the total number of patches, and use that value as the comparison metric for pre- and post-project conditions.

The alternative situation, one in which restoration results in the total number of patches decreasing, can be handled in a different manner. In this case, the original set of pre-restoration patches should be used as the input in both pre- and post-project analysis. However, in the post project analysis the habitat values of the affected patches can be changed to reflect what the value would be in the larger, post-restoration patch that they are now part of. Also, the post-restoration cost matrix should be changed so that the cells being restored are assigned a cost value of 1. This process is illustrated in Figure 8.

CONCLUSIONS

The Functional Linkage Index presented in this technical note can be used as a way for measuring and comparing functional connectivity among groups of habitat patches. The accompanying GIS tool can be used as an easy and automated way for calculating the index, and can potentially be utilized in analyses of project alternatives in a wide variety of land development or restoration plans, as well as an assessment of existing conditions. Although the Functional Linkage Index represents a potential improvement over many currently used measures of connectivity, it has still yet to be compared against real world species dispersal data. Therefore, further research should be undertaken in order to validate the results of the tool's application.

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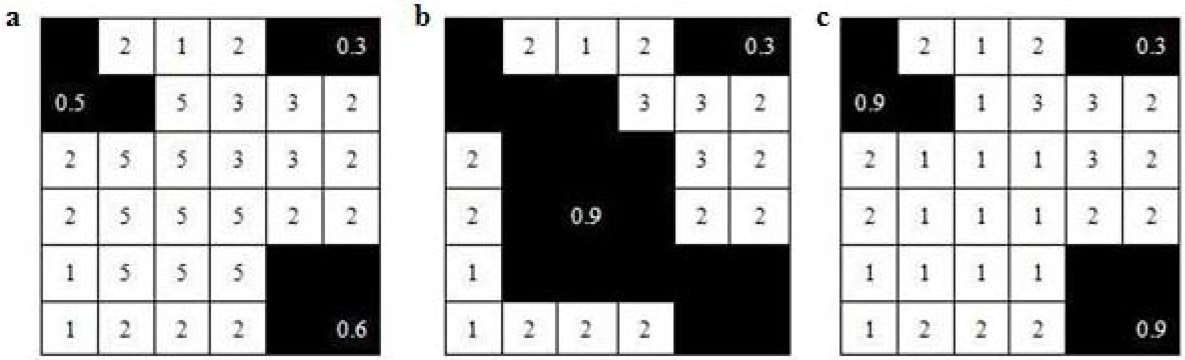
FIGURE 8 An illustration of how to conduct the Functional Linkage Index analysis when, due to the combination of existing patches, the total number of patches in the landscape decreases. Grid (a) shows the landscape pre-restoration, where the black areas are existing habitat patches. The numbers in the black areas are the habitat value of the patch; the other numbers are the cell movement costs. Grid (b) shows the landscape after areas have been restored. Two of the patches have been joined to form one larger patch, which now has a higher habitat value. Grid (c) shows how the inputs for the post-restoration analysis should look. The patches are the same as in grid (a), however, the habitat value of the larger patch in grid (b) is now utilized. Also, the cost grid is changed so that the cells that would be encompassed by the new patch area now have a cost of 1.



a

■	2	1	2	■	0.3
0.5	■	5	3	3	2
2	5	5	3	3	2
2	5	5	5	2	2
1	5	5	5	■	■
1	2	2	2	■	0.6

b

■	2	1	2	■	0.3
■	■	■	3	3	2
2	■	■	■	3	2
2	■	0.9	■	2	2
1	■	■	■	■	■
1	2	2	2	■	■

c

■	2	1	2	■	0.3
0.9	■	1	3	3	2
2	1	1	1	3	2
2	1	1	1	2	2
1	1	1	1	■	■
1	2	2	2	■	0.9

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