Ecological Indicators 7 (2007) 481–488

ECOLOGICAL INDICATORS

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Mapping landscape corridors

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Received 11 October 2006; received in revised form 3 November 2006; accepted 6 November 2006

Abstract

Corridors are important geographic features for biological conservation and biodiversity assessment. The identification and mapping of corridors is usually based on visual interpretations of movement patterns (functional corridors) or habitat maps (structural corridors). We present a method for automated corridor mapping with morphological image processing, and demonstrate the approach with a forest map derived from satellite imagery of northern Slovakia. We show how the approach can be used to differentiate between relatively narrow ('line') and wide ('strip') structural corridors by mapping corridors at multiple scales of observation, and indicate how to map functional corridors with maps of observed or simulated organism movement. An application to environmental reporting is demonstrated by assessing structural forest corridors in relation to forest types in northern Slovakia.

Keywords: Corridors; Forest fragmentation; Spatial pattern; Morphological image processing

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1. Introduction

International biodiversity agreements require assessing indicators of connectivity and fragmentation in forested ecosystems (e.g., MPLO, 2000; Malahide, 2004) and indicators of corridors are specifically requested in tropical (ITTO, 2005) and Central American (FAO, 2001) forest assessments. Corridors are important because theoretical considerations (MacArthur and Wilson, 1967; Fahrig and Merriam, 1985) led to their emphasis in nature reserve design since Harris (1984), and because they are among the basic elements of Forman's (1995) classic description of landscape spatial structure. While

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doi:10.1016/j.ecolind.2006.11.001

detailed understanding of relationships between habitat pattern and biodiversity is elusive (Fahrig, 2003) and more research is needed on corridors in particular (Vos et al., 2002), an important principle of landscape planning for biodiversity is to maintain landscape permeability with corridors, linkages, and stepping-stones (e.g., Dale et al., 2000; Freemark et al., 2002). New indicators are needed to quantify the success or failure of land management to provide for landscape permeability.

To satisfy assessment requirements for comparability of data and indicators over large geographic regions, land-cover maps derived from remote sensing are typically used when assessing landscape patterns, and techniques are needed for accurate and repeatable identification and mapping of corridors from these data. At continental scale, it is not feasible to visually interpret corridors on detailed land-cover maps (e.g., Perault and Lomolino, 2000), or to infer corridors from observed movement patterns (e.g., Beier and Noss, 1998). Maps of simulated organism movements (Gustafson and Gardner, 1996; Hargrove et al., 2005) show places where movement is most likely but do not explicitly identify those places as corridors per se. Structural indices of patch shape such as perimeter-to-area ratio cannot reliably detect corridors because a corridor and the patches it connects are, by definition, a single patch when calculating such an index. Graph-theoretic approaches (Urban and Keitt, 2001) can analyze the importance of corridors in a network, but graph theory by itself cannot identify structural corridors as the connectors between ‘nodes’ in a network. In practice, a typical map-based assessment defines corridors in terms of a threshold patch width that is selected according to the local context (e.g., Metzger and Décamps, 1997; see review of applications by Vos et al., 2002) which requires a human interpretation and furthermore, approaches based on patch width alone might identify corridors that are not connected to anything else on the map. In summary, there is substantial support for including corridor analysis in biodiversity assessments, and there is a need for a reliable indicator of corridors and a repeatable corridor mapping technique that can be applied without human interpretation to continental-scale land-cover maps.

Here we adopt the corridor definition of Freemark et al. (2002) as a physical linkage between habitat patches within a landscape. Our interest centers on methods that assign each location on a map to one of several mutually exclusive categories including corridors. While a structural connection does not imply a functional connection (Tischendorf and Fahrig, 2000; Vos et al., 2002), some types of dispersers require a structural corridor (King and With, 2002) to locate and assess likely movement patterns. From an assessment and land management perspective a map of structural corridors is certainly useful. Allowing for corridors of different widths is an example of mapping corridors as scale-dependent objects, requiring techniques that can be applied at multiple scales of observation.

In this paper, we present an approach to identify and map corridors as physical links between relatively large patches containing ‘core’ conditions (Freemark et al., 2002) on land-cover maps. The technique is based on morphological image processing (Soille, 2003) and is an extension of an earlier application (Vogt et al., 2006) that identified ‘core,’ ‘edge,’ ‘perforated,’ and ‘patch’ features on land-cover maps. The approach satisfies the assessment requirements of feasibility and repeatability when using continental-scale land-cover maps and it can be implemented at multiple scales of observation as we will demonstrate by differentiating between relatively wide (‘strip’) corridors and relatively narrow (‘line’) corridors (Forman and Godron, 1986). We illustrate how indicators derived from the methods can be used in a regional assessment of forest patterns in Slovakia in relation to forest cover types and anthropogenic activity in that region.

2. Methods

Matheron (1967) and colleagues introduced morphological image processing almost four decades ago but only recently have the techniques been used in landscape ecology applications. Metzger and Décamps (1997) defined a corridor as a strip of land that differed from the adjacent land on both sides. They used the two morphological operations known as ‘dilation’ and ‘erosion’ (see below) to illustrate a landscape-level habitat connectivity index called ‘interior habitat percolation degree’ as a measure of connectivity, ‘stepping-stones,’ and corridors in highly fragmented landscapes, or in landscapes that contain linear habitats. In contrast, our interest centers on the pixel-level mapping of corridors as the physical connections between habitat patches that are large enough to contain interior habitat (Freemark et al., 2002). For this purpose, we extend techniques presented earlier (Vogt et al., 2006) and use an additional morphological operation known as 'skeletonization' (see below). The geometric nature of this technique allows the processing of any binary raster map and we use a forest map as an example. In the interest of stimulating the application of this technique we provide only short, verbal descriptions of the algorithm and refer the reader to Soille (2003) for a comprehensive, formal treatment of mathematical morphology.

The fundamental morphological operations are called erosion and dilation. The erosion operator shrinks regions of forest while the dilation operator expands them. The extent and direction of these changes are defined by the structuring element (SE), a region of pixels of predefined size and shape (analogous to a window in image convolution). We define E as the 8-neighborhood, F as the 4-neighborhood, and connectivity for adjacent pixels in cardinal directions (F). A size parameter n is used to increase the size of the SE, symbolized by nE or nF (Fig. 1).

The algorithm also applies the concept of skeletonization (Calabi and Hartnett, 1968), a process which iteratively removes the boundary pixels of a region to its line representation. Here, we use a special type called anchored skeletonization (Ranwez and Soille, 2002) where a predefined set of pixels cannot be removed. A classification algorithm can now be defined by a sequence of logical operations combining the result of a series of morphological operations with specific SEs.

We consider nine classes of forest pattern which are illustrated on a hypothetical forest map in Fig. 2 and listed below with a short thematic description and a brief note on the algorithmic implementation in parenthesis. Classes 5–9 are derived after building the skeleton of the forest mask without the patches and using the core as the anchor set.

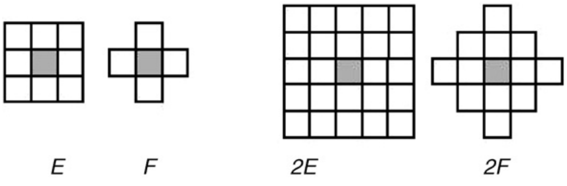

Fig. 1. The two types of structuring elements E and F displayed for a size parameter of $n = 1$ (left) and $n = 2$ (right). Squares represent the pixels belonging to the structuring element with the center pixel highlighted in grey.

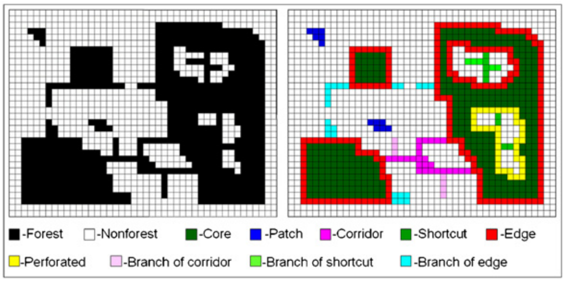

Fig. 2. Hypothetical forest map and the classification result showing nine classes for forested pixels.

1. Core: core forest pixels are the inner part of a forested region, beyond a certain distance to forest boundary (erosion of the forest mask).
2. Patch: patch forest pixels are forest regions that are too small to contain core forest (all isolated components which disappear during the erosion used in step 1). Note that this definition is different from the classical definition of 'patch' as a connected cluster of pixels.
3. Perforated: perforated forest pixels are the transition zone between core forest and a nonforest patch (dilation of nonforest patch).
4. Edge: edge forest pixels are the transition zone between core forest and core nonforest (subtracting the union of core and perforated from the dilation of the core).
5. Corridor: corridor forest pixels are without core forest and connect at least two different core forest regions (skeleton branches connecting different dilated core regions).
6. Shortcut: shortcut forest pixels are a corridor which connects to the same core forest region (skeleton branches connecting at both ends to the same dilated core region).
7. Branch of corridor: branch of corridor forest pixels are without core forest and connect at one end only to corridor (skeleton branches connecting at one end to corridor).
8. Branch of shortcut: branch of shortcut forest pixels are without core forest and connect at one end only

to shortcut (skeleton branches connecting at one end to shortcut).

9. Branch of edge: branch of edge forest pixels are without core forest and connect at one end only to edge (skeleton branches connecting at one end to edge).

The nine classes cover a wide range of forest spatial patterns which are of interest in biodiversity assessments. For example, core forest represents unfragmented habitat that is potentially suitable for interior forest species, while patch forests are isolated forest fragments where organisms are less likely to communicate with organisms outside the fragment. Forest edge is more likely to host invasive species and edge-dependent species, and 'interior edge' (perforated forest) is of interest because it introduces edge effects deeper into otherwise core forest. Corridors and shortcuts characterize potential movement pathways, and as relatively narrow features they may be vulnerable to future fragmentation and conversion to patch. The different type of branches may represent stubs upon which forest restoration can build new corridors between regions of core forest. They can also be linked to the search time or number of movement steps for an individual species to find a new core habitat. Some classes could be combined for specific applications. For example, the classes representing corridors, shortcuts and three types of branches are all 'connecting' features, of which the branches could be viewed as 'broken connections.'

3. Applications

The first application illustrates the classification technique in northern Slovakia between the Tatra and Low Tatra mountains (49.1°N, 19.8°E). We used the CORINE Land Cover 2000 (CLC) vector data which identifies 44 land cover classes with the scale of 1:100,000, a minimum mapping unit of 25 ha, and the minimum width of a linear feature equal to 100 m (Perdigao and Annoni, 1997; I&CLC, 2000; Nunes de Lima, 2005; CORINE, 2000). To preserve a high level of spatial detail the original vector data was rasterized with a resolution of 25 m (0.0625 ha per pixel). The classes 'broad-leaved forest', 'coniferous forest', 'mixed forest', and 'transitional woodland shrub' were combined to build the binary forest map and the classification was conducted using $n = 13$ to illustrate the technique (Fig. 3).

Allowing for some differences caused by the minimum mapping unit size in CLC and the time of data acquisition, the spatial features detected by morphological image processing of the CLC map correspond well with patterns that are visually apparent in the satellite image. For example, the southern part of the longest corridor is interrupted by a motorway that separates "patch" from "branch of edge" forest. The latter forest terminates in a small region of "core" forest at its northern tip, beyond which "corridor" forest connects to other "core" forest regions. The nonforest area contains a variety of landscape elements such as urban and agricultural areas, water bodies, and infrastructure such as railways, motorways, airport runways, and power lines. This example illustrates the potential benefit of incorporating additional GIS information in the interpretation of the classification results.

A second application of the method is targeted to detect corridor types defined by Forman and Godron (1986) as relatively thin corridors that do or do not contain interior habitat, that is, 'strip' and 'line' corridors, respectively. These can be identified by conducting multiple analyses with different values of the size parameter n because n directly corresponds to the width in pixels of all classes but core. With an increase in n, the perforated and edge regions become larger at the expense of the core regions, some physically connected regions turn into branch of edge, and narrow core forest regions become corridor. However, the maximum spatial information content at the pixel level is maintained for all n as evidenced by the single pixel marked as patch in the center of the example in Fig. 4.

Corridors of different widths can be subdivided into line and strip corridors by comparison of the two analyses with different size parameter. For example, a pixel labeled as core in a small n analysis and corridor in a large n analysis is a part of a relatively wide strip corridor. The specific definitions of wide and narrow depend on the context but the analysis and interpretation would be the same for other choices.

In the final application, we illustrate a regional assessment of forest patterns by investigating the relationships between forest pattern class and land

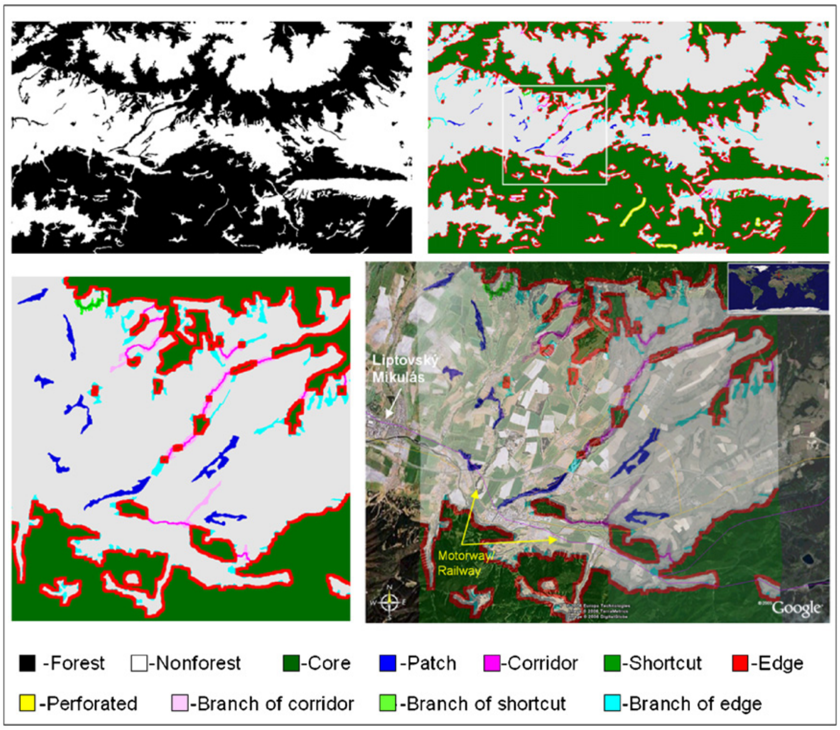

Fig. 3. Forest mask of north-central Slovakia derived from the CORINE land cover map (top left) and the resulting classification (top right) with a sub-region highlighted in white for detailed interpretation (bottom left) and overlaid on a satellite land cover map (bottom right) (© 2006 Europa Technologies, Image © 2006 TerraMetrics, Image © 2006 DigitalGlobe, © 2005 Google^{TM} Earth).

cover type. Using the data shown in Fig. 3, a summary was prepared by geographic overlay to cross-tabulate forest according to pattern class and CLC forest type (Table 1).

Relative frequency of forest class within a pattern class is calculated as the ratio of the CLC forest class proportion in a specific pattern class and CLC forest class proportion in the total forest area. For example, the relative frequency of the core mixed forest case is calculated from the area statistics in Table 1 as: (8334/106,923)/(9780/139,326) = 1.11. Relative frequency values larger than 1.0 indicate over-representation of the CLC forest class within the respective pattern class.

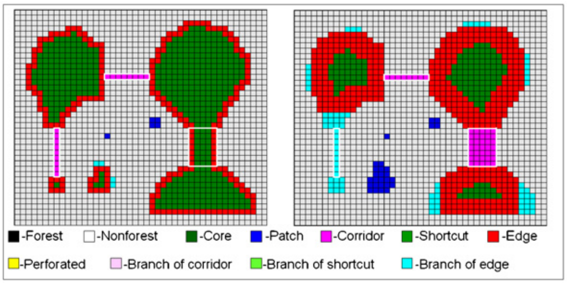

Fig. 4. Detecting line and strip corridors using classifications from two analysis with a size parameter of $n = 1$ (left) and $n = 3$ (right). Corridors from both scales are outlined in white. The strip corridor in the right panel is composed of edge and core in the left panel.

The study area contains approximately 139,000 ha of forest, dominated by coniferous forest (81.40%) with lesser amounts of transitional woodland shrub (10.63%), mixed forest (7.02%), and broadleaved forest (0.95%). The pattern analysis indicates that this forest area is mostly core (76.74%) with lesser amounts of edge (17.46%), branch of edge (4.00%), and other pattern classes (<1% each). The hypothesis of no association between pattern class and CLC forest class (performed using the cross-tabulated pixel counts) was rejected by the Pearson χ^2 test ($p < 0.0001$) which indicates that interpretations of the summary statistics are warranted.

Because the study area is dominated by the CLC coniferous forest class, it is logical that most of the

Table 1
Cross-tabulation of forest area by pattern class and CLC class in the Slovakia study site

Pattern class	CLC forest class				Pattern class total [ha]	Pattern class [% of forest area]
	Broad-leaved forest[a]	Coniferous forest[a]	Mixed forest[a]	Transitional woodland shrub[a]		
Core	1013 (0.99)	86,492 (0.99)	8334 (1.11)	11,084 (0.98)	106,923	76.74
Patch	83 (13.03)	367 (0.67)	73 (1.56)	145 (2.04)	668	0.48
Perforated	0 (0.00)	601 (1.12)	18 (0.39)	42 (0.60)	661	0.47
Edge	109 (0.47)	20,693 (1.04)	1022 (0.60)	2,506 (0.97)	24,330	17.46
Corridor	0 (0.00)	173 (0.84)	29 (1.63)	52 (1.93)	254	0.18
Shortcut	0 (0.00)	96 (1.01)	3 (0.37)	18 (1.45)	117	0.08
Branch of corridor	37 (6.55)	344 (0.71)	62 (1.49)	149 (2.37)	592	0.42
Branch of shortcut	0 (0.00)	178 (1.05)	4 (0.27)	27 (1.22)	209	0.15
Branch of edge	87 (1.64)	4,472 (0.99)	235 (0.60)	783 (1.32)	5,577	4.00
Forest class total [ha]	1329	113,416	9780	14,806	139,326	100.00
Forest class [% of forest area]	0.95	81.40	7.02	10.63	100.00	

Numbers in parentheses are the row percentages.

[a] Area in hectares (relative frequency of forest class within a pattern class).

area of each pattern class is associated with that CLC class. Because forest classes are not equally abundant, it is also informative to examine their proportional representation in different pattern classes. The most striking example of over-representation is the patch broadleaved forest for which the relative frequency value is 13.03, indicating a much higher likelihood for an isolated fragment of forest to be broadleaved in comparison to other forest types. These isolated patches tend to occur in association with agricultural lands in the lower part of the study area.

The corridor, shortcut, and branch classes exhibit many examples of over- and under-representation. Because these classes generally indicate relatively narrow features on the landscape, it is of interest that the transitional woodland shrub type is over-represented in all corridor classes. The implication is that temporary disturbances (e.g., forest harvest) are over-represented in corridors, which in turn implies that historical land management has not been oriented towards the preservation of corridors. Furthermore, the mixed forest type is over-represented in two of the corridor pattern classes, which together with the results for the transitional woodland shrub type indicates that corridor-like features are disproportionately associated with the low elevation forest classes, reflecting the gross distributions of different forest classes in the study region. The broadleaved forest type is not represented at all in the corridor class but at the same time it is over-represented in two of the "branch" classes. The interpretation is that the broadleaved forest type does not tend to form connections between core forest regions but instead appears as branches from corridors formed by other forest types. Finally, it is interesting that the dominant forest type (coniferous) in the study region is under-represented in the class corridor because it indicates that corridors between core regions of coniferous forest are of a different forest type. This might call into question the sustainable management of critical features like corridors based on overall forest patterns, and suggests that a more detailed assessment of corridors in this region could consider each forest type separately.

From other maps (not shown here), it is clear that most of the corridors are associated with riparian vegetation along streams, suggesting that additional insight could be gained by extending the geographic analysis to cross-tabulate corridors in relation to stream location. The results for the branch classes suggest that the efficiency of corridor creation and restoration may be greatest in the broadleaved and transitional woodland shrub types because these types already have a disproportionate area of stubs upon which to build connections to other forest areas. Finally, the analysis of multi-temporal data would allow the assessment of trends in corridor areas as they are created or eliminated over time.

As is the case for any assessment, these results depend on assumptions such as the CLC types chosen to be treated as forest and the spatial and thematic detail of the input data. For example, transitional woodland shrub could be treated as nonforest in a second analysis, and the differences would provide information to assess where, in relation to corridors and other features, the temporary disturbances had occurred. Also important are the choices made during the analysis such as the size parameters selected for the classification. Because patterns are mapped at the pixel level, it is possible to aggregate the results according to different administrative or ecological units for different assessments. In choosing size parameters for the classification, it is probably better to choose several because the way that results change over scale is usually more informative than the answer obtained at any one scale.

4. Summary

Landscape indicators of corridors and other connecting features are required for biodiversity assessments but the available indicators can be ambiguous and difficult to implement over large areas. We presented a method to identify nine types of landscape spatial pattern including corridors as physical connections between large forest regions. While a structural connection does not imply a functional connection, knowledge of structural corridors is certainly valuable in biodiversity assessments. In many cases, however, interest centers on corridors as defined by the movements of organisms, and application of corridor mapping requires preparation of a suitable movement map for a corridor analysis. With sparse data (e.g., from radio telemetry tracking of individuals), grid cells can be marked as used or not, and corridors can be mapped on the resulting binary map. With dense data (e.g., from tracking many individuals over a long time period, or from movement simulations), the probability of grid cell usage can be converted to a binary map by setting a threshold probability value. In these cases, the morphological image analysis will identify not only corridors but also the spatially dense concentrations of movement (core) that might represent ‘home range.’ Indeed, many types of binary maps can be analyzed by morphological image processing, and the resulting pattern classes could be combined or interpreted in different ways to address other research or assessment questions.

The choice of indicators used in biodiversity assessments must recognize that biodiversity is inherently a multiple-scale concept that depends on other types of patterns in addition to corridors. For this reason, a premium should be placed on methods that can perform multi-scale analyses and that can identify not only corridors but also other types of spatial patterns at the same time. Our interest centers on regional to continental scale forest biodiversity assessments for which the new method provides two types of information. First, in addition to tabular summaries of forest pattern indicators, a map of patterns is a powerful communication device to increase the awareness of spatial pattern in policy formulation, implementation, and monitoring. Second, because patterns are mapped at the pixel level, the status and trends of forest patterns can be assessed by interpreting them in relation to other geographically explicit information such as land development.

Many ecologists will be interested in relating forest patterns at multiple scales to site- and species-specific information such as the distribution and movement of organisms, particularly for species demonstrating sensitivity to habitat features such as structural corridors. Accurate and repeatable corridor mapping may help to understand the roles of corridors in ecology. Consistent mapping and analysis of corridors over very large regions and across many observation scales will allow ecologists to better address the concept of corridors in biological conservation studies and policies.

Acknowledgements

The research described in this article was performed as a part of the Collaboration Agreement (No. 22832-2005-06 S0SC ISP) between the European Commission, Joint Research Centre, Institute for Environment and Sustainability and the United States Department of Agriculture, Forest Service. KR acknowledges support from the Strategic Planning and Resource Assessment Staff, USDA Forest Service.

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