

Short communication

Conefor Sensinode 2.2: A software package for quantifying the importance of habitat patches for landscape connectivity

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ABSTRACT

Maintaining and restoring landscape connectivity is currently a central concern in ecology and biodiversity conservation, and there is an increasing demand of user-driven tools for integrating connectivity in landscape planning. Here we describe the new Conefor Sensinode 2.2 (CS22) software, which quantifies the importance of habitat patches for maintaining or improving functional landscape connectivity and is conceived as a tool for decision-making support in landscape planning and habitat conservation. CS22 is based on graph structures, which have been suggested to possess the greatest benefit to effort ratio for conservation problems regarding landscape connectivity. CS22 includes new connectivity metrics based on the habitat availability concept, which considers a patch itself as a space where connectivity occurs, integrating in a single measure the connected habitat area existing within the patches with the area made available by the connections between different habitat patches. These new metrics have been shown to present improved properties compared to other existing metrics and are particularly suited to the identification of critical landscape elements for connectivity. CS22 is distributed together with GIS extensions that allow for directly generating the required input files from a GIS layer. CS22 and related documentation can be freely downloaded from the World Wide Web.

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Software availability

Name of software: Conefor Sensinode 2.2.

Developers: Josep Torné and Santiago Saura.

Contact address: Santiago Saura, PlanForBio Research Group, Department of Agroforestry Engineering, ETSEA, University of Lleida, Av. Rovira Roure, 191, 25198 Lleida, Spain. E-mail: ssaura@eagrof.udl.cat.Availability and online documentation: Free download with manual and supporting material at <http://www.conefor.udl.es>. Source codes freely available by contacting the authors.

Year first available: 2007.

Hardware required: IBM compatible PC.

Software required: MS Windows (tested on Windows XP, Me and Vista).

Programming language: C++.

Compiler: Borland C++ Builder 2006.

Program size: 9 MB.

1. Introduction

Landscape connectivity facilitates the movement of organisms, genetic interchange and other ecological flows that are critical for the viability and survival of species and for the conservation of biodiversity in general (e.g. Crooks and Sanjayan, 2006). Maintaining or restoring landscape connectivity is currently a central concern in ecology and land conservation planning. In addition, connectivity is particularly crucial in the current challenge of alleviating the effects of climate change on species and ecosystems, since it may allow species to accommodate to the shifts in their natural ranges resulting from the changing environmental conditions (Opdam and Wascher, 2004). The study of connectivity is also important for the control of invasive species and diseases (e.g. Russell et al., 2006).

There is a wide consensus in the literature that connectivity is species-specific and should be measured from a functional perspective. That is, not only the spatial arrangement of the habitat (structural connectivity) but also the dispersal distances and/or the behavioral response of the focal species to the physical structure of the landscape (functional connectivity) should be taken into account (e.g. Adriaensen et al., 2003; Theobald, 2006). Although many different metrics have been proposed and used in this context, there is still a lack of tools for assessing connectivity in real-world planning problems. On the other hand, metrics and methodologies developed for landscape connectivity analysis may fail to become widespread

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in practice. This may be because they are too complex, too data intensive, not transparent enough or difficult to understand by land managers, or simply because they are not available or easy to implement in operational tools for real-world landscape planning (Sarkar et al., 2006). They may just remain as theoretical developments in the academic arena, having no real impact on actual landscape planning or on improved biodiversity conservation. More effort is required from the research community to provide end-user applications and practical recommendations for integrating connectivity considerations in landscape planning with a sound basis.

Recent comparative analyses (Pascual-Hortal and Saura, 2006; Saura and Pascual-Hortal, 2007) have shown the weaknesses of different commonly used connectivity metrics for prioritizing the most important habitat patches for the maintenance of landscape connectivity. Most of the examined metrics did not match up to all the desirable properties for decision-making, with the exception of two new landscape connectivity metrics, the integral index of connectivity and the probability of connectivity, which are based on graph structures and on the habitat availability concept (Pascual-Hortal and Saura, 2006; Saura and Pascual-Hortal, 2007). These new metrics are adequately sensitive to the loss of the different types of landscape elements and are effective in identifying the most critical habitat patches for conservation. In addition, they meet the need for the development of topoecological indices (Ricotta et al., 2000), which allow quantifying purely topological characteristics in combination with the relevant differences in the ecological characteristics of the habitat patches and links.

Here we describe the new Conefor Sensinode 2.2 (CS22) software, which allows quantifying the importance of individual habitat patches for the maintenance of functional landscape connectivity, as well as evaluating the connectivity improvement provided by new potential habitat sites that may be added in the landscape through habitat creation or restoration. CS22 differs from other popular software for landscape pattern analysis such as Fragstats (McGarigal et al., 2002) or APACK (Mladenoff and DeZonia, 2004) in that it does not only provide descriptive values of the landscape but rather is conceived as a tool for decision support in landscape planning and habitat conservation through the identification of critical landscape elements for connectivity. CS22 complements other already existing graph-based software for the analysis of network connectivity, such as LQGraph (Fuller and Sarkar, 2006), Pajek (Batagelj and Mrvar, 1996) or UCINET (Borgatti et al., 1999), proving a valuable addition to the toolbox of conservationists and planners through the new improved habitat availability metrics and other features. CS22 can be used free of charge and directly downloaded from the World Wide Web.

2. Background

2.1. Landscape graphs

A landscape mosaic and its intricate network of functional connections are described and analysed in CS22 within the graph theory approach. The type of graph considered here is a set of nodes (or vertices) and links (or edges) such that each link connects two nodes (Fuller and Sarkar, 2006; Urban and Keitt, 2001). Nodes here represent units of suitable habitat (patches, cells, protected areas, etc.) surrounded by inhospitable habitat (non-habitat) while links symbolize the potential ability of a species to directly disperse between two nodes (e.g. through a corridor). A path is a route from one node to another through the links in the graph.

Graph structures and algorithms have been shown to be a powerful and effective way of both representing the landscape pattern as a network of functionally interconnected patches and performing complex analysis regarding landscape connectivity (Chetkiewicz et al., 2006; Jordán et al., 2003; Pascual-Hortal and

Saura, 2006, 2008; Schick and Lindley, 2007; Trembl et al., 2008; Urban and Keitt, 2001). Graphs offer the ability to identify patches that are very important to habitat connectivity and thus to long-term population persistence across the landscape (Minor and Urban, 2007). Although graph algorithms are efficient for some problems related to connectivity, it should be noted that other optimization problems remain intractable even when the landscape is represented as a graph (Garey and Johnson, 1979).

It has been suggested that graph-theoretical metrics possess the greatest benefit to effort ratio for conservation problems that require characterization of connectivity at relatively large scales (Calabrese and Fagan, 2004). These measures provide a reasonably detailed picture of potential connectivity, but have relatively modest data requirements. Some simpler metrics that only measure structural connectivity are too crude to be considered as ecologically realistic. Other more complex metrics and models that require a direct estimate of actual connectivity (through observed emigration, immigration or dispersal rates), may be more difficult to parameterize for landscape-level planning applications and are generally limited to small study areas or scientific experiments (Calabrese and Fagan, 2004). Indeed, it is important to balance metric performance with data requirements for operational landscape management, and connectivity metrics must be pragmatic and based upon data that might actually be attained on a regular basis. In addition, Minor and Urban (2007) showed that in some cases graph theory can make similar predictions to spatially explicit population models, and may provide additional insights not available from the latter. Graph theory has been considered a suitable and possibly preferable alternative to spatially explicit population models for species conservation in heterogeneous landscapes, although other methods of measuring connectivity (e.g. metapopulation capacity) may be more appropriate for specific research questions (Ovaskainen and Hanski, 2003; Minor and Urban, 2007, 2008).

2.2. Habitat availability metrics

The habitat availability concept is based on considering a patch itself as a space where connectivity occurs, integrating habitat patch area (or other patch attributes such as habitat quality) and connections between different patches in a single measure (Pascual-Hortal and Saura, 2006). This approach recognizes that for measuring connectivity in a meaningful way, the connected habitat area existing within the patches themselves (intrapatch connectivity) has to be considered together with the area made available by the connections between habitat patches (interpatch connectivity). For a habitat being easily available for an animal or population, it should be both abundant and well connected. Therefore, habitat availability for a species may be low if habitat patches are poorly connected, but also if the habitat is highly scarce even if the patches are highly connected, as quantified through metrics like the integral index of connectivity or the probability of connectivity (Saura and Pascual-Hortal, 2007). This is different from the strict and traditional way of measuring connectivity that only takes into account the connectivity among different patches (and not within them). It has been suggested that landscape connectivity should be considered within the wider concept of habitat availability in order to be successfully integrated in landscape conservation planning applications (Pascual-Hortal and Saura, 2006).

3. Program description

3.1. Graphs and connection models in CS22

CS22 implements undirected and weighted graphs, in which attributes can be attached both to habitat nodes and links. Two different connection models can be used within CS22, the binary

and the probabilistic connection model (Saura and Pascual-Hortal, 2007), which affects the way links are characterized and the graph implementation itself. In the binary model two nodes are just either connected or not, with no intermediate modulation of the strength or feasibility of the connection between two patches, and no attribute is attached to the links in the graph. In the probabilistic model, there is a certain probability of direct dispersal between each two patches, as an estimation of the strength, frequency or feasibility of that direct movement by the analysed organisms; the landscape is modeled by default as a complete graph (a link existing between every two nodes) with the probability of dispersal being the attribute of the link. Depending on the type of information available for a particular analysis and the purposes of the application, one or other connection model may be used. Nevertheless, the binary model may present some limitations compared to the richer probabilistic model for various applications (Bodin and Norberg, 2007; Saura and Pascual-Hortal, 2007). When dealing with large datasets the probabilistic connection approach may be too time-consuming if the landscape is modeled as a complete graph; therefore, CS22 includes the possibility to specify a minimum probability value so that only those links with a probability of dispersal above that value are created in the graph structure. This can largely reduce the total required processing time in very big and sparsely connected landscapes.

3.2. Input data

CS22 quantifies functional connectivity, requiring as an input the information necessary for quantifying both the structural (spatial arrangement of habitat patches) and the functional (dispersal abilities of the analysed species) aspects of connectivity (Fig. 1). The information required by CS22 consists of two input text files (the node file and the connection file) and some other user-specific settings, all of them shown in a simple interface in the main screen of the software.

The node file contains a list of the habitat nodes existing in the landscape and their attributes. The node attribute is the characteristic of the node that is considered relevant for the analysis, such as habitat area, habitat quality, quality-weighted area or some other attributes where appropriate (e.g. population density, core area, carrying capacity, habitat suitability, etc.).

The connection file contains the information necessary for characterizing the connections between every two nodes in the landscape, and may be entered in three ways: as a distance file, as a probability file, or as a link file. The distance file is the most common way for standard users, with the connection file reporting the distance between every two nodes, which may be Euclidean (straight-line) or effective (least-cost) distances by considering the different movement abilities and mortality risk of a species through different land cover types (e.g. Adriaensen et al., 2003; Theobald, 2006). CS22 allows entering the connection file as a partial file (only including those pairs of nodes that are directly connected to some degree, the rest being considered as completely unconnected). In the binary connection model, a link between two nodes is assigned to those nodes that are separated by a distance not exceeding the threshold dispersal distance specified by the user. In the probabilistic connection model, CS22 automatically computes the probabilities of dispersal between every two nodes as a decreasing exponential function of the distance between them (e.g. Saura and Pascual-Hortal, 2007; Urban and Keitt, 2001) matching the probability of dispersal for a certain distance specified by the user. The user may also compute these direct dispersal probabilities in a different way externally to CS22 or measure them directly through actual movement patterns monitoring or mark-release-recapture methods, and provide them as an input probability file already calculated to CS22.

3.3. Connectivity metrics implemented in CS22

CS22 includes the following nine graph-based connectivity metrics, the first six based on the binary connection model and the other three based on the probabilistic one:

- number of links;
- number of components, where a component is a set of nodes for which a path exists between every pair of nodes;
- Harary index, computed from the number of links in the shortest path (topological distance) between every pair of nodes;
- class coincidence probability, defined as the probability that two randomly chosen points within the habitat belong to the same component. It is a generalization of the degree of coherence by Jaeger (2000);
- landscape coincidence probability, defined in a similar way to the previous metric but when the two random points can fall anywhere within the landscape (either in habitat or non-habitat areas);
- integral index of connectivity, a habitat availability metric that combines the attributes of the nodes (e.g. patch area) with the number of links in the shortest path between every pair of nodes;
- flux, calculated as the sum of the probabilities of direct dispersal between every pair of nodes (Urban and Keitt, 2001);
- area-weighted flux, similar to the previous metric but with the dispersal probabilities multiplied by the area of the nodes;
- probability of connectivity, a habitat availability metric that combines the attributes of the nodes with the maximum product probability of all the possible paths between every pair of nodes.

All of them are landscape-level metrics for which higher values indicate improved connectivity, with the exception of the number of components, which behaves in the opposite way. Further details on these metrics can be found in Pascual-Hortal and Saura (2006) and Saura and Pascual-Hortal (2007). Users may select one or more of these metrics for analysis. CS22 allows simultaneous processing of both types of metrics (binary and probabilistic) from the same set of input data. However, the use of the integral index of connectivity (for the binary connections model) and the probability of connectivity (for the probabilistic connection model), both recently developed as habitat availability metrics, is especially recommended, since they have been shown to present improved properties for prioritizing landscape elements by their contribution to landscape connectivity (Pascual-Hortal and Saura, 2006, 2007; Saura and Pascual-Hortal, 2007). The main graph algorithms used by CS22 to calculate these connectivity metrics are the BFS (bread first search), DFS (depth first search) and Dijkstra's algorithms (e.g. Jungnickel, 2008).

3.4. GIS extensions linked to CS22

Although the connectivity analysis is performed by CS22 (Fig. 1), users will need a GIS to prepare the information required by CS22 and to visualize and further process the results provided by CS22. To facilitate the integration with common GIS, CS22 is distributed together with two free GIS extensions developed by Jeff Jennens ("ID Within Distance: Conefor" for ArcView 3.x and "Conefor Inputs" for ArcGis 9.x) that allow easily generating from any GIS layer the node and connection files (the latter as a Euclidean distance file) directly in the format required by CS22. Effective (least-cost) distances can be calculated through other software tools external to CS22, such as the free PathMatrix extension for

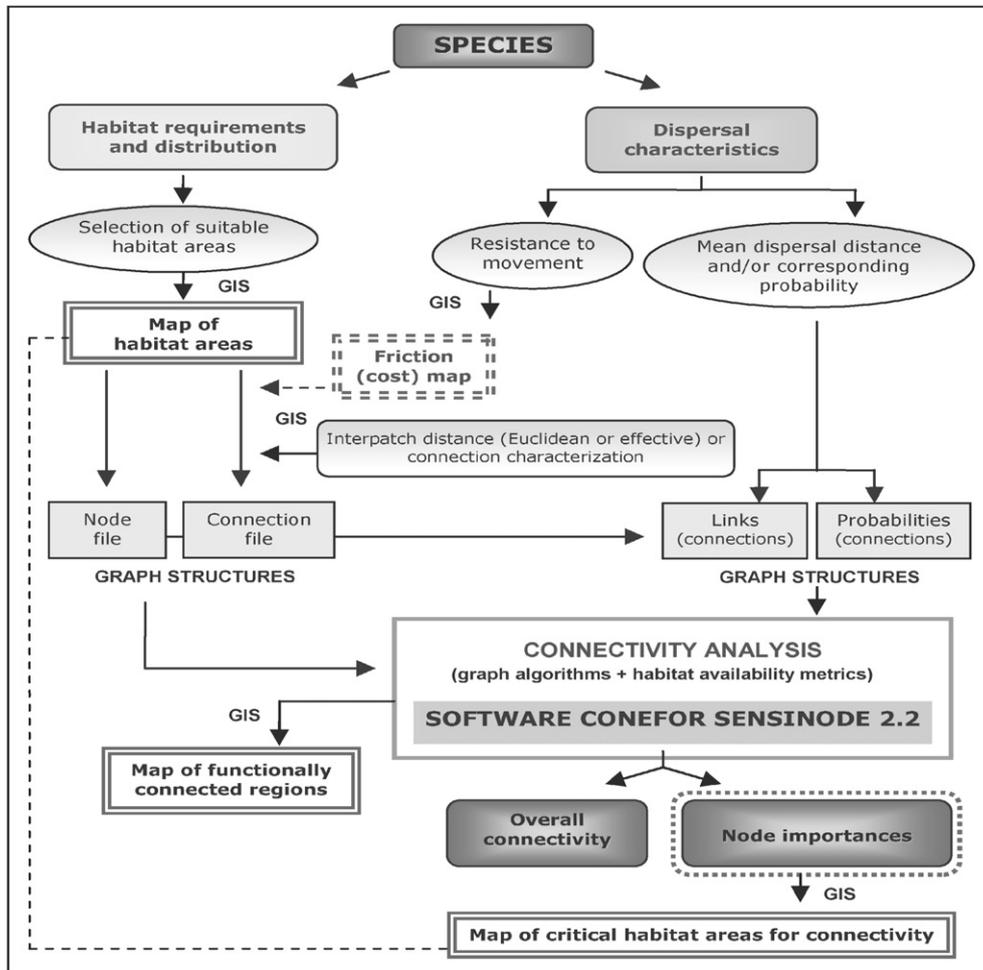


Fig. 1. Schematic outline of the methodology for the analysis of landscape connectivity through the Conefor Sensinode 2.2 software.

ArcView 3.x (<http://cmpg.unibe.ch/software/pathmatrix/>, accessed April 2008), or the cost distance tools in ArcGIS 9.x.

3.5. Results

The main result provided by CS22 is the importance of each individual node (e.g. habitat patch) for maintaining overall landscape connectivity according to the different metrics, calculated as the percentage of variation in the metric value occurring when that node is removed from the landscape graph. This allows ranking habitat patches by their contribution to landscape connectivity (patches prioritization), which provides objective criteria for the selection of the most critical habitat areas for landscape conservation planning purposes. CS22 also allows including in the analysis potential new habitat areas (nodes) that currently do not exist but that may be added in the landscape through habitat creation or restoration. In this case, CS22 will also compute the individual contribution of these potential new nodes to the improvement of landscape connectivity. This is different from the approach adopted in LQGraph (Fuller and Sarkar, 2006), which builds a minimum spanning tree of new nodes to be conserved in order to augment the connectivity between the already existing network of protected areas through least-cost paths in the landscape.

Other results provide complementary information on the landscape and its degree of connectivity, such as the overall values of the different connectivity metrics, the component to which each habitat node belongs, the probabilities of direct dispersal and the

maximum product probabilities between every two nodes. The results provided by CS22 can be saved in standard text or DBF files, which facilitates further post-processing and directly joining the results in a GIS layer.

3.6. Processing capabilities

CS22 is a powerful software package for analysing connectivity that allows processing landscapes comprising thousands of nodes. Any standard computer is usable for most of the applications of CS22. The processing time required to complete the analysis will depend not only on the computer characteristics but also on the landscape configuration and scale of analysis (determining the number of nodes differentiated in the landscape), the dispersal distances of the analysed species (determining the number of links between the nodes, with more links for larger dispersal distances) and the selected connectivity metrics. For a standard PC (e.g. 3 GHz CPU, 1 GB RAM) the maximum number of nodes that may be processed in a reasonable time (less than 24 h) will typically be about 20,000 for most of the binary metrics, about 10,000 for the flux, area-weighted flux, Harary index and integral index of connectivity, and about 3000 for the probability of connectivity.

4. Conclusions and further development

The need for maintaining ecological fluxes in the landscape and the natural dispersal routes for the movement and survival of

wildlife species call for a more integrated management of the land in which connectivity considerations should be necessarily incorporated. CS22 and the methodology in which it is based (graph structures, habitat availability concept, and the new improved metrics) may be a helpful decision support tool for integrating connectivity in landscape planning. It presents several improved characteristics compared to other approaches available for analysing connectivity, and at the same time it is conceived as a user-driven application that is easy to understand by land managers and conservation planners. The software has already been successfully applied to identify critical habitat patches for the maintenance of overall landscape connectivity. It has provided valuable guidelines for orienting forest management and focusing conservation efforts and further analyses directly on those areas that are most valuable due to their attributes and specific network location within the landscape mosaic (Saura and Pascual-Hortal, 2007; Pascual-Hortal and Saura, 2008).

Further development of the software may include: (1) a specific evaluation of the importance for connectivity of individual corridors and links in the landscape (and not only of the habitat nodes as currently implemented); (2) a better integration with the most common GIS and geospatial data formats; (3) a separated quantification of the different ways in which the loss of a habitat patch may affect the habitat availability and connectivity of the landscape; (4) improved processing capabilities to allow the analysis of landscapes with even larger sets of nodes and links; and (5) the implementation of directed graphs to extend the application of the software to cases involving asymmetric dispersal, such as fish population dynamics in river networks or topography or wind-driven connectivity (e.g. Schick and Lindley, 2007).

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