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# Making graph theory operational for landscape ecological assessments, planning, and design

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ABSTRACT

Graph theory and network analysis have become established as promising ways to efficiently explore and analyze landscape or habitat connectivity. However, little attention has been paid to making these graph-theoretic approaches operational within landscape ecological assessments, planning, and design. In this paper, a set of both theoretical and practical methodological developments are presented to address this issue. In highly fragmented landscapes, many species are restricted to moving among small, scattered patches of different resources, instead of one, large patch. A life-cycle based approach is therefore introduced, in which a metapatch is constructed, spanning over these resources, scattered across the landscape. The importance of spatially explicit and geographically defined representations of the network in urban and regional planning and design is stressed, and appropriate, context-dependent visualizations of these are suggested based on experience from real-world planning cases. The study moves beyond the issue of conservation of currently important structures, and seeks to identify suitable redesigns of the landscape to improve its social–ecological qualities, or increase resilience. By introducing both a system-centric and a site-centric analysis, two conflicting perspectives can be addressed. The first answers the question "what can I do for the network", and the second, "what can the network do for me". A method for typical planning strategies within each of these perspectives is presented. To illustrate the basic principles of the proposed methods, an ecological study on the European common toad (*Bufo bufo*) in Stockholm, Sweden is presented, using the betweenness centrality index to capture important stepping-stone structures.



## 1. Introduction

Land use change represents the primary driving force in the loss of biodiversity world wide, and negative effects reach far beyond the directly impacted areas (Vitousek et al., 1997). To preserve and develop biodiversity and other ecosystem services, planning and management activities must recognize the dynamics and complex interactions within social–ecological systems, where physical planning activities are an integral part, and the physical landscape is the common point of reference. Network analysis and graph theory provide powerful tools and methods for the analysis of complex systems. The network is often represented by a graph, $G(N,L)$, consisting of a set of nodes, $N(G)$ and a set of links, $L(G)$. The link $l_{ij}$ connects nodes $i$ and $j$. When using this model in landscape ecological applications, a node typically represents a habitat patch and a link typically represents dispersal.

Recently several papers have explored graph-based models of species–habitat interactions from a landscape perspective (for a review, see Urban et al., 2009). Many of these feature analysis and visualization techniques useful in landscape ecological assessments, planning, and design. Graph theory can be used as an initial, heuristic framework for management, driven in an iterative and exploratory manner, and with very little data requirements (Bunn et al., 2000; Calabrese and Fagan, 2004). It does not require long-term population data, making it an important tool for rapid landscape-scale assessments (Urban and Keitt, 2001), but graph theory is at the same time dynamic, allowing additional knowledge to be incorporated. Despite its simplicity, a graph model based only on habitat and dispersal distance, has been shown to make predictions very similar to a spatially explicit population model (SEPM), which had nine additional life-history and behavioral parameters (Minor and Urban, 2007).

Another attractive property of network analysis is its long tradition, well developed and tested tools, as well as efficient algorithms, used in a wide variety of disciplines (e.g. Ahuja et al., 1993), many of which are used in planning. Several graph-theoretic metrics related to classical network analysis problems, such as maximum flow, connectivity, and shortest paths, have been developed over decades, and Bunn et al. (2000) as well as Urban and Keitt (2001) have proposed ecological interpretations for some of these. Some of

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the proposed graph-based metrics of functional connectivity have also been summarized and evaluated (Pascual-Hortal and Saura, 2006; Saura and Pascual-Hortal, 2007).

In addition to comparing metrics for the *overall* network for alternative planning scenarios, graph-based methods can be used to explore important *internal* structures. For example, Estrada and Bodin (2008) have used centrality indices to explore well-connected backbone structures within the network. Another approach is to evaluate the importance of each patch with respect to a particular landscape connectivity index ($I$) by removing one patch (i.e. one node) at a time, and recording the corresponding change ($\Delta I$) of the connectivity index ($I$) (Keitt et al., 1997). This has become a central technique for finding important patches, and has also been used by Urban and Keitt (2001) to find important links within the network. The patches and links contributing the most to overall connectivity can thus be found. Similar techniques have also been used to explore trade-offs between the total protected area and the overall connectivity (Rae et al., 2007; Rothley and Rae, 2005). Analyzing trade-offs between required area and some desired property is an effective technique when assessing alternative scenarios within planning.

Although graph theory has been proposed as an efficient way to explore and analyze landscape connectivity, little attention has been paid to making graph-theoretic approaches operational (i.e. being in operation) within ecological assessments, planning, and design. In this paper a set of methodological developments, both theoretical and practical, are presented to address this issue:

- In highly fragmented landscapes, such as urbanizing regions, many species are restricted to moving among small, scattered patches of different resources instead of one, large, contiguous habitat patch. These patches are not captured with the traditional ways of constructing patches by finding contiguous regions of some selected land use classes. Here, a life-cycle based approach is therefore introduced, in which a *metapatch* can be constructed spanning over different kinds of life-cycle resources scattered across the fragmented landscape. This metapatch also has the potential to capture issues related to scaling in that it always has to be defined with respect to a temporal scale related to a specified part of the life-cycle. Shorter time frames are then nested spatially within longer time frames.
- The importance of spatially explicit and geographically defined representations of the network in urban and regional planning and design are stressed, and appropriate, context-dependent visualizations of these are suggested. This, in combination with network analysis and graph theory, allows the planner to study the details of a *local site* in a relevant planning context while bringing *systemic* or *regional* properties into the planning and decision making process.
- The study moves one step beyond the issue of conservation of *currently* important structures, and seeks to identify suitable redesigns of the landscape with *improvement potential*. In order to systematically address conflicts between local and regional perspectives on improvement, a system-centric and a site-centric analyses are introduced. The first answers the question “what can I do for the network”, and the second, “what can the network do for me”. A method for a typical planning issue within each of these two perspectives is presented. The system-centric analysis illustrates how the spatial redundancy in the network can be increased, which is argued to improve the resilience of the entire system with respect to node/link removal. The site-centric perspective aims at finding areas with the potential of mitigating the exposure or isolation of *locally* important sites.

To illustrate the basic principles of working with the proposed methods, the paper is framed around an ecological study on the European common toad (*Bufo bufo*) in Stockholm, Sweden. The network analysis in the study uses the betweenness centrality index (Freeman, 1979) in order to capture important stepping-stone structures (Bodin and Norberg, 2007; Minor and Urban, 2007). By only calculating least-cost-distances of the links within the selected threshold distances, a fairly large network could be analyzed with 22 428 potential reproduction patches grouped into 1361 separate annual home-range patches connected by 4372 dispersal links. Despite there being very few habitat patches in the highly urbanized municipality of Stockholm, the regionally most important network path with respect to betweenness centrality, consisting of several small but critical stepping-stones, turned out to pass through this region. A redesign of the landscape also managed to restore a dispersal link into a locally important site.

## 2. Methods

The methods presented in this paper are of two main types. A set of landscape ecological, theoretical methods and concepts are introduced which have been developed to better meet the requirements in fragmented landscapes. The other type pertains to process related methods and visual representations that are considered important in order to make graph-theoretic approaches operational in practice.

### 2.1. Terminology

In this paper, the term network is used as short for ecological network, and defined in a general manner as a complex, multi-species network representation of a set of ecosystems, interacting with the landscape and linked through functional relations between the organisms of the ecosystem (sensu Opdam et al., 2006). In the ecological study of the European common toad, the network is reduced to a single-species habitat network. The terms patch and node are conceptually the same within this network but node is here used when referring to general network theory and patch is used when referring to a spatially explicit, geographically defined part of the network, with a physical realization in the landscape. The same reasoning holds for the terms connectivity zone and link. Connectivity zone is introduced as a general term defining a spatially explicit area corresponding to the *functional* link between two patches, and is used instead of the often used term corridor in order to avoid confusion with the *structural* corridors used in greenway planning (Fig. 1).

### 2.2. The spatial aspects of urban or regional planning, and design

Urban and regional planning are commonly referred to as physical planning (or spatial planning). An important aspect of physical planning with respect to this paper is that it refers to planning with a spatially explicit, geographically defined component. The general idea is to plan the *spatial* configuration of land use and activities in

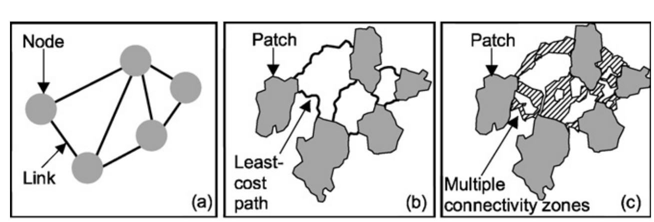


**Fig. 1.** Three representations of networks. (a) A traditional representation of a network, but with suitable spatially explicit locations of the nodes and links. (b) A “patch-link” representation showing the physical extent of the patches and the least-cost path (LCP). (c) The physical extent of both the patches and connectivity zones. Note the multiple connectivity zones between patches.