Landscape and Urban Planning 124 (2014) 140–150

Contents lists available at ScienceDirect

Landscape and Urban Planning

journal homepage: www.elsevier.com/locate/landurbplan

Research Paper

A methodological framework for the use of landscape graphs in land-use planning

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HIGHLIGHTS

- The use of landscape graphs is investigated through routine land-planning issues.
- Landscape graphs can help to identify optimal locations for increasing connectivity.
- Mitigation of a barrier effect may be guided by landscape-graph analysis.
- Diachronic analysis of graphs is useful for including landscape connectivity in impact assessment.

ARTICLE INFO

Article history:
Received 24 April 2013
Received in revised form
12 December 2013
Accepted 19 December 2013
Available online 17 January 2014

Keywords:
Functional connectivity
Decision support
Ecological network
Prioritisation
Mitigation
Impact assessment

ABSTRACT

Landscape graphs are now widely used for representing and analysing ecological networks. Although several studies have provided methodological syntheses of how to use these tools to quantify functional connectivity, it is still unclear how landscape graphs can be used for decision support in land planning. This paper outlines the different types of application that may provide relevant responses to the main questions arising in land planning about ecological networks. Three approaches are distinguished according to their objective: (1) to support prioritisation within an ecological network from a conservationist perspective; (2) to increase connectivity by identifying the best locations for adding new elements to the network, either when starting from the current state of the network or when seeking to mitigate the barrier effect engendered by a development project; (3) to assess the potential impact of a development project in terms of decreased connectivity. The computations based on connectivity metrics are explained for each of these three approaches. Then each approach is illustrated in the context of a pond network near the town of Belfort, in eastern France. The results show how the same connectivity metric used in the different approaches may serve different purposes. This emphasises the potential value of landscape graphs for the land-planning decision-support process and not just for conservation purposes (i.e. prioritisation).

1. Introduction

For several decades now biodiversity has been observed to be in decline in many parts of the world as a result of anthropogenic factors such as urban sprawl and more intensive farming (Barbault, 2001). In response to this threat, several strategies have been applied to reduce the impact of human activities on natural resources. Many countries have implemented a conservation strategy by legislating to protect areas in the form of nature reserves. However, even if methods have been developed to designate protected areas on a scientific basis (McDonnell, Possingham, Ball, & Cousins, 2002), questions have been raised about the effectiveness of conservation policies based exclusively on protected-area planning (Bishop, Philipps, & Warren, 1995). At the same time, landscape ecologists have noticed that populations living in fragmented habitats are forced to adopt specific dynamics (patchy populations or metapopulations) making them highly dependent on fluxes between their habitat patches (Hanski & Ovaslaken, 2000). Consequently, more attention has been paid to common landscapes and to connections between significant reservoirs of biodiversity (Noss & Harris, 1986). This context has highlighted landscape connectivity (Taylor, Fahrig, & With, 2006) and led to the concepts of ecological network and greenway being integrated into land-use-planning policies (Ahern, 1995; Boitani, Falcucci, Maiorano, & Rondinini, 2007). Following Ahern (1995), the term ‘ecological networks’ is used here to designate a spatial system of habitat cores connected by functional corridors rather than the set of energy fluxes within ecosystems (Fath, Scharler, Ulanowisz, & Hannon, 2007).

Since ecological networks are relevant objects to integrate into environmental management strategies (Ahern, 1995), new needs have appeared in land-use planning, reflecting the different actions

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http://dx.doi.org/10.1016/j.landurbplan.2013.12.012

likely to be taken by practitioners (Bergsten & Zetterberg, 2013). Such needs have strong geographical implications because the central question asked of landscape managers concerns space (Gurrutxaga, Lozano, & del Barrio, 2010; Theobald et al., 2000): where can one act most effectively in the field in order to maintain biodiversity? This generic question can be subdivided into three specific questions for the different approaches to ecological network planning discussed here:

(1) Where are the most vulnerable landscape patches for a given habitat or a given species? Assuming that such patches have to be protected and monitored so as to preserve functional linkages in the current ecological network, this question is one of prioritisation, i.e. of identifying the zones to be protected first (Rubio & Saura, 2012; Urban, 2002).
(2) In which locations is it appropriate to modify the ecological network, for example by implementing or restoring certain elements, so as to enhance landscape connectivity, i.e. to improve the functional relationships and the resilience of a given species? (McRae, Hall, Beier, & Theobald, 2012; Nuñez et al., 2013). Such a question also concerns the design of corridors in the adaptation strategies in response to climate change (Beier, 2012).
(3) Where are wildlife species likely to be disturbed by a change in existing land cover? How can the level of disturbance in such areas be evaluated? Such questions about environmental impact assessment arise when a specific development is planned and when one needs to anticipate its impact on biodiversity.

All these issues facing land-use planners are problematic because ecological networks are spatial patterns that do not necessarily correspond to spatially explicit elements in the landscape. Consequently, answering the questions above involves a methodological approach specifically designed for modelling ecological networks and functional connectivity. Landscape ecologists quantify connectivity by various methods such as individual-based movement models (Grimm & Railsback, 2005), least-cost analysis (Adriaensen et al., 2003), circuit theory (McRae, Dickson, Keitt, & Shah, 2008; McRae et al., 2012), centrality analyses (Rudnick et al., 2012) or landscape graphs (Urban & Keitt, 2001). Calabrese and Fagan (2004) have reported that these methods differ in their capacity to characterise the ecological processes and in the amount of input data and adjustments they require. Graph-theoretical methods provide an interesting compromise for both those criteria. The great advantage of landscape graphs over other possible ways of modelling functional connectivity is that they can easily be applied on a broad spatial scale. Experiments have shown that landscape graphs can provide similar results to individual simulations (Lookingbill, Gardner, Ferrari, & Keller, 2010; Minor & Urban, 2007), confirming their capacity to represent ecological processes. This useful compromise between methodological simplicity and ecological relevance makes landscape graphs suitable for land planning, which is usually concerned with broad spatial scales (Urban, Minor, Treml, & Schick, 2009).

A series of original works introducing graph theory to the landscape-ecology community (Bunn, Urban, & Keitt, 2000; Keitt, Urban, & Milne, 1997; Urban & Keitt, 2001) has provided a basis which has been expanded substantially in recent years. Some recent reviews of landscape graphs have covered the whole approach and the ecological issues raised by these methods (Dale & Fortin, 2010; Galpern, Manseau, & Fall, 2011; Urban et al., 2009) while others have focused on connectivity computations by listing and comparing the available metrics (Baranyi, Saura, Podani, & Jordán, 2011; Laita, Kotiaho, & Mönkkönen, 2011; Rayfield, Fortin, & Fall, 2011). Nonetheless, although many researchers (e.g. Pereira, Segurado, & Neves, 2011) have claimed that landscape graphs can be readily applied to land-use planning, there has not yet been any synthesis of the operational applications of these methods.

Beginning with the questions above about the major needs of land-use planners, we propose an overview of the operational use of landscape graphs. The aim is to clarify the main ways of applying these methods, by moving one step beyond the qualitative and visual use of network mapping and by making use of systematic methods as much as possible. A case study from eastern France will illustrate these applications, by focusing on a pond network in a landscape much changed by human activity.

2. Methods

We propose a global framework for combining the needs arising in land-use planning with applications of landscape graphs (Section 2.1). This methodological framework encompasses current research in this domain, especially the background to landscape graph construction (Section 2.2). From this foundation, we provide details about the specific implementations of landscape graphs in each type of application (Sections 2.3–2.5). A final part examines the question of the spatial scale on which landscape connectivity should be considered (2.6).

2.1. Global framework

The operational goal assigned to graph-based methods involves specifying how the decision-support process might benefit from the use of landscape graphs. The questions set out above likely to be asked of land-use planners lead us to list three main purposes: prioritisation, modification of the ecological network and impact assessment. These purposes concern different fields of application and result in specific approaches which differ in their temporal dimensions. In case 1, support for prioritisation is a static approach in which the landscape is considered solely in its current state. An important point in such an application is how best to define protected areas and conservation measures. For the second purpose, the landscape graph is used as a template for designing new elements capable of modifying the functional properties of the network, which raises concrete questions about landscape management. The approach is prospective, in the sense of potential developments the analysis may suggest. Two cases are distinguished depending on the context: case 2 is about the improvement of the current ecological network whereas case 3 is a mitigation approach for a disruptive element. Then in case 4, the potential impact assessment of a given land cover change implies a diachronic approach between an initial state and a modified state of the ecological network. This type of application relates to environmental impact assessment.

2.2. Background: graph construction

The common background to most graph-based approaches to ecological networks is first the definition of a landscape map, which may be either a straightforward land-cover map or the result of a more complicated combination of several factors such as land cover, slope, topographic aspect or climatic variables. On this map, a specific category is defined as the preferential habitat of one or more target species. These habitat patches are the nodes of the landscape graph and the links represent functional connections between nodes. Most of the links are generated if the cost of movement between two nodes is less than a given value, which varies with the species. The spatial metric used to measure the cost of movement may be the Euclidean distance but it is more often based on least-cost distances, allowing the user to take into account the resistance value of each landscape category and to include barrier