Ecological Indicators 81 (2017) 192–200

Contents lists available at ScienceDirect

Ecological Indicators

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

Research article

Multi-node selection of patches for protecting habitat connectivity: Fragmentation versus reachability

Juliana Pereira[a,*], Ferenc Jordán[a,b]

[a] MTA Center for Ecological Research, Danube Research Institute, Budapest, Hungary
[b] Wissenschaftskolleg zu Berlin, Berlin, Germany

ARTICLE INFO

Keywords:
Conservation priorities
Ecological networks
Landscape connectivity
Multi-node graph centrality

ABSTRACT

Landscape connectivity is of major importance in biodiversity conservation, and is one of the key aspects to be taken into consideration in the spatial design of networks of protected areas. Graph-theoretical approaches are useful in modelling habitat connectivity and defining priority areas for the protection of connectivity. This prioritization can be done based on rankings of the centrality (or importance) of individual habitat patches. Moreover, the centrality of a set of *n* habitat patches can also be calculated. Importantly, the most central single patch is not necessarily a member of the most central group of *n* patches (non-nested topology). Multi-node analyses identify groups of patches that maximally complement each other in order to increase the protection of connectivity for the whole network. We apply multi-node analyses to the prioritization of habitat patches for five vulnerable bird species in Catalonia, Spain, using two different approaches to connectivity, based on fragmentation and reachability. Groups of patches based on fragmentation are usually concentrated in core areas, while reachability groups are widely spread. Fragmentation sets have higher centrality value for low-mobility species, and reachability sets for long distance dispersers. The protection of the networks against fragmentation requires fewer patches, allows for more gradual implementation and is currently better accounted for by the Natura 2000 network of protected areas, while the protection of reachability is less costly and more efficient in terms of area requirements. Our work contributes to the development of landscape graph analysis for reserve design towards multi-node approaches.

1. Introduction

In a context of limited resources for conservation action, designing systems of protected areas requires sound strategies and quantitative assessments of priorities (Cowling et al., 1999). One of the important spatial attributes that need to be taken into consideration in reserve design is habitat connectivity (Williams et al., 2005), which may be defined as the degree to which the spatial pattern of habitat patches in the landscape facilitates or impedes the movement of organisms (Taylor et al., 1993). Maintaining landscape connectivity is important because increased isolation reduces the likelihood of persistence of certain species (Margules and Pressey, 2000), since small sub-populations cut off from each other are vulnerable to the effects of inbreeding, genetic erosion, and environmental and demographic stochasticity (Lande, 1988). The Natura 2000 coordinated network of protected areas is one of the most important initiatives for habitat conservation in the European Union; one its main objectives is to achieve good ecological coherence (European Commission, 1996), which implies considerations of connectivity.

Graph-based landscape models have been applied extensively in recent years to the understanding of habitat connectivity and identification of priority areas that should be protected in order to maintain connectivity (Saura and Pascual-Hortal, 2007; Metzger et al., 2009; Vasas et al., 2009; Baranyi et al., 2011; Avon and Bergès, 2016). In conservation ecology, landscapes are usually modelled as networks consisting of nodes (habitat patches) connected by edges (functional connection between the nodes – see Bunn et al., 2000). Centrality metrics can be used to measure the positional value of each node, that is, how influential the node is in terms of its position relative to all other nodes in the network (Estrada and Bodin, 2008). For example, one very simple centrality metric is *node degree*, defined as the number of direct neighbours of the focal node (Urban et al., 2009). Several centrality metrics, as well as more complex indices based on centrality metrics, are available for habitat patch prioritization (Saura and Pascual-Hortal, 2007; Baranyi et al., 2011). In this context, the most central nodes should be prioritized for inclusion in protected area networks to ensure

Abbreviations: KP, keyplayer; KP_F, keyplayer selection based on fragmentation centrality; KP_R, keyplayer selection based on m-reach-closeness centrality (reachability)

* Corresponding author at: MTA Center for Ecological Research, Danube Research Institute, Karolina 29, 1113, Budapest, Hungary.
E-mail address: julianapereira.mailto@gmail.com (J. Pereira).

http://dx.doi.org/10.1016/j.ecolind.2017.06.002
Received 26 January 2017; Received in revised form 31 May 2017; Accepted 1 June 2017
Available online 07 June 2017
1470-160X/

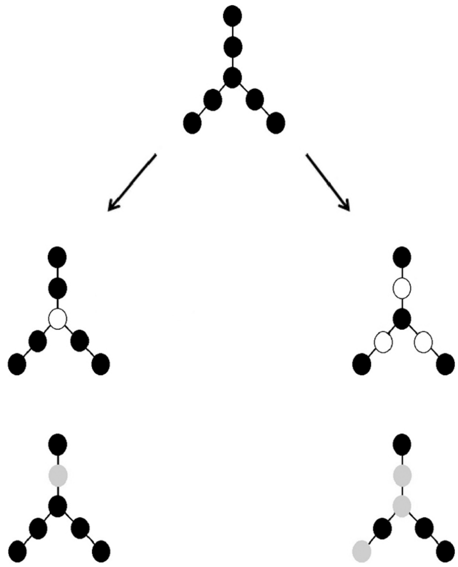

Fig. 1. Example of node prioritization with non-nested results. The centrality metric considered is fragmentation centrality. The original network is at the top. On the left, we show two candidate single-node ($n = 1$) solutions. The top-left deletion (white) results in three remaining network components, so it is more critical than the bottom-left deletion (grey) resulting in only two remaining network components. On the right, we show two candidate three-node ($n = 3$) solutions. The top-right deletion (white) results in four remaining network components, so it is more critical than the bottom-right deletion (grey) resulting in only three remaining network components. Deleting the white nodes fragments more the network, so these should be prioritized for protection in both cases. The best solution for $n = 3$ nodes (top-right) does not contain the best solution for $n = 1$ node (top-left), so the multi-node sets are non-nested. This inconsistency between solutions of different n size hinders incremental planning and implementation of protected area networks, and calls for prompt long-term planning.

the goal of habitat connectivity is achieved.

Most studies on graph-based habitat patch prioritization so far have focused on measuring the individual centrality of each node, ranking the nodes by centrality, and selecting as priority the highest ranked patches (Jordán, 2003; Baranyi et al., 2011; Rubio et al., 2015). However, centrality can also be calculated for sets of multiple nodes. Notably, the most central single node is not necessarily a member of the most central set of n nodes. Thus, single-node and multi-node centrality analyses may provide different and non-nested results (Fig. 1). This is frequently due to redundancies, that is, top nodes in an individual ranking may largely overlap, rather than complement each other, in their role of connecting the network (Borgatti, 2003). Multi-node analysis is used to select the optimal, non-redundant group of key nodes, potentially safeguarding the connectivity of larger parts of the network and increasing its resilience to future habitat losses (Pereira et al., 2017). However, identifying the optimal group of nodes through exhaustive testing of all possibilities may face computational limits due to the large number of combinations that may arise in a network (Rubio et al., 2015). The KeyPlayer (KP) algorithm (Borgatti, 2003; An and Liu, 2016; Pereira et al., 2017) aims to overcome the problem of exhaustive search by means of a heuristic search method, which increases processing efficiency in multi-node analysis of larger networks.

In a previous study, we compared and combined single and multi-node analysis in the selection of a fixed number of habitat patches for protection (Pereira et al., 2017). In this study, we aim to compare two multi-node methods in more detail, considering a variable number of selected patches. We perform multi-node prioritization for the habitat network of five vulnerable bird species in Catalonia, Spain. We (1) use the KP multi-node analysis algorithm (An and Liu, 2016) with two different centrality metrics: fragmentation and m-reach-closeness centrality; (2) compare the results of the two types of centrality in terms of dispersal ability of the species, predictability and area-cost for conservation management and (3) assess the coverage of optimal sets of key patches by the Natura 2000 network of protected areas.

2. Material and methods

2.1. Study area and species

Catalonia, NE Spain, is a region of approximately 32,000 km^2, comprising forested areas, agricultural land, a portion of the southern Pyrenees, the Ebro Delta wetland and about 580 km of Mediterranean coast (EEA, 2014). A high diversity of birds breeds in the varied habitats found in this region (Anton et al., 2013). Over 30% of Catalonia is covered by sites of the Natura 2000 network of protected areas.

Bird occurrence and distribution in Catalonia has been well documented in the Catalan Breeding Bird Atlas (Estrada et al., 2004). We focus our study on the five species of the atlas that have unfavourable conservation status (IUCN, 2015; Table 1). Median natal dispersal distances, required for the definition of edges in the habitat networks, were obtained from the literature for three species (Donazar et al., 1993; Elorriaga et al., 2009; Inchausti and Bretagnolle, 2005). For the remaining two species, since no information was available, we used the model by Sutherland et al. (2000), which estimates median dispersal distances based on body mass and diet type.

Table 1
The name, conservation status (NT: near-threatened, EN: endangered; IUCN, 2015), median natal dispersal distance (MND; in km), area of occurrence in Catalonia (A; in km^2), biological information and key references for the five studied bird species.

Species		IUCN	MND	A	References
Coracias garrulus	European roller	NT	8.89[a]	923.62	Avilés et al. (2000) and Kiss et al. (2016)
Insectivorous farmland bird, hole nesting, migratory, highly fragmented breeding populations, generally in decline. Dependent on traditional agriculture; uses open fields as foraging sites, and forest edges or tree lines for nesting. In the study area, restricted to small fragments in three separated regions, distant from each other relative to specie's mobility.					
Gypaetus barbatus	Bearded vulture	NT	47.10	1976.73	Bretagnolle et al. (2004), Negro and Torres (1999) and Godoy et al. (2004)
Long-lived vulture, low population densities, large home ranges, high mobility, strongly philopatric, specialist in terms of habitat. About 100 breeding pairs in the Pyrenees population, with low genetic variation and possibly suffering inbreeding depression. In the study area, restricted to a small, relatively well connected area.					
Ichthyaetus audouinii	Audouin's gull	NT	26.96[a]	554.53	Oro and Pradel (1999) and Genovart et al. (2003)
Long-lived seabird, migratory, relatively philopatric. The Ebro Delta harbours the largest population, with over 11000 pairs. Breeding habitat heterogeneity is high. In the study area, restricted to a small, relatively well connected area.					
Neophron percnopterus	Egyptian vulture	EN	20.00	1086.29	Kretzmann et al., (2003), Sarà and Vittorio (2003) and Godoy et al. (2004)
Long-lived vulture, low population densities, large home ranges, high mobility, strongly philopatric, specialist in terms of habitat. Low genetic variation and gene flow among populations. The largest population is in North Spain. In the study area, restricted to a small, relatively well connected area.					
Tetrax tetrax	Little bustard	NT	46.27	1083.79	García et al. (2007)
Farmland, ground nesting bird, highly fragmented populations. Dependent on traditional agriculture. The largest population is in the Iberian Peninsula. In the study area, restricted to a small, relatively well connected area.					

[a] MND values obtained using the model by Sutherland et al. (2000), which estimates median dispersal distances from the body mass and diet of the species.