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REPORT

Graph theory in action: evaluating planned highway tracks based on connectivity measures

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Abstract Maintaining connectivity among local populations in a fragmented landscape is crucial for the survival of many species. For isolated habitat patches, stochastic fluctuations and reduced gene flow can lead to high risk of extinction. The connectivity of the landscape is especially crucial for the carabid species living in the fragmented forests of the Bereg plain (NE Hungary and W Ukraine) because a highway will be constructed through the plain. Our purpose is to (1) evaluate the impacts of three possible highway tracks, (2) suggest a solution that is realistic with less impact on connectivity than other plans and (3) discuss how to decrease the disadvantageous effects of each track. Our results, based on a network analysis of landscape graph of patches and ecological corridors, indicate that the intended highway could have deleterious consequences on forest-living carabids. Relatively simple actions, like the establishment of stepping stones, could compensate for the loss of habitat connectivity and promote the survival of carabids, or minor modifications in one possible track could diminish its adverse effects. While many other studies would be needed for a comprehensive assessment of the biotic impact of the highway, we provide an example on the usefulness of network analysis for land use management.

Keywords Habitat network · Landscape graph · Carabidae · Bereg plain

Introduction

Human pressure on natural environment is continuously increasing, and beyond directly causing extinction of species and decreasing natural habitats, it leads to fragmentation of the remaining habitats (Hilty et al. 2006; Haila 2002). Local populations of small, isolated fragments have high extinction risk for stochastic reasons (Fahrig 2003). Moreover, reduced gene flow as a consequence of infrequent migration leads to a loss of genetic variability (Keller and

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Largiader 2003) in poorly connected habitat networks, which in turn increases local extinction risks (Saccheri et al. 1998). These problems most severely impact mobile high-level predators, and the cascading effects of their extinction may project single-species problems to community-wide crises (Crooks and Soulé 1999). Thus, landscape management should be based on network thinking and the results of realistic landscape graph models should be considered if landscape design scenarios are to be evaluated.

In the present paper, we show such an example of network analysis in action. For mostly economical reasons, a highway will be constructed through the Bereg plain (NE Hungary and W Ukraine) to connect EU member and non-member countries, using one of three proposed tracks (Fig. 1). While several economical and social aspects have been taken into consideration, the possible environmental impacts of landscape change have not been studied in a broader context. The affected area is a forest mosaic, formerly being contiguous with the Carpathian Mountains, but now behaving as sink habitat patches relying on continuous dispersal (immigration) of various forest-living animals from the Carpathians as the sole source patch (Ködöböcz and Magura 2005; Varga 1995).

We focus on the landscape from the viewpoint of hill and mountain living forest carabid species (*Coleoptera*: *Carabidae*) inhabiting the forest patches and evaluate the effects of the three planned highway tracks on habitat connectivity. Since flightless carabids cannot cross highways (Koivula and Vermeulen 2005; Mader et al. 1990), they are typical species being affected by road barriers. The distribution of these species is well known in the region (Magura et al. 2001; Ködöböcz and Magura 2005), so a relatively realistic landscape graph can be constructed reflecting the quality of both patches and corridors, beyond simple network structure.

The structure of the landscape graph (relationships of habitat patches and ecological corridors; see Urban and Keitt 2001) suggests which landscape elements are of higher conservation value, if the aim is to protect habitat connectivity and maintain migration, and so reduce local extinction risk. Previously, we examined the positional importance of existing landscape elements (patches and corridors) in maintaining connectivity and the advantages of different hypothetical landscape management solutions (Jordán et al. 2007). As an up-to-date extension, now we (1) evaluate the impacts of three planned highway

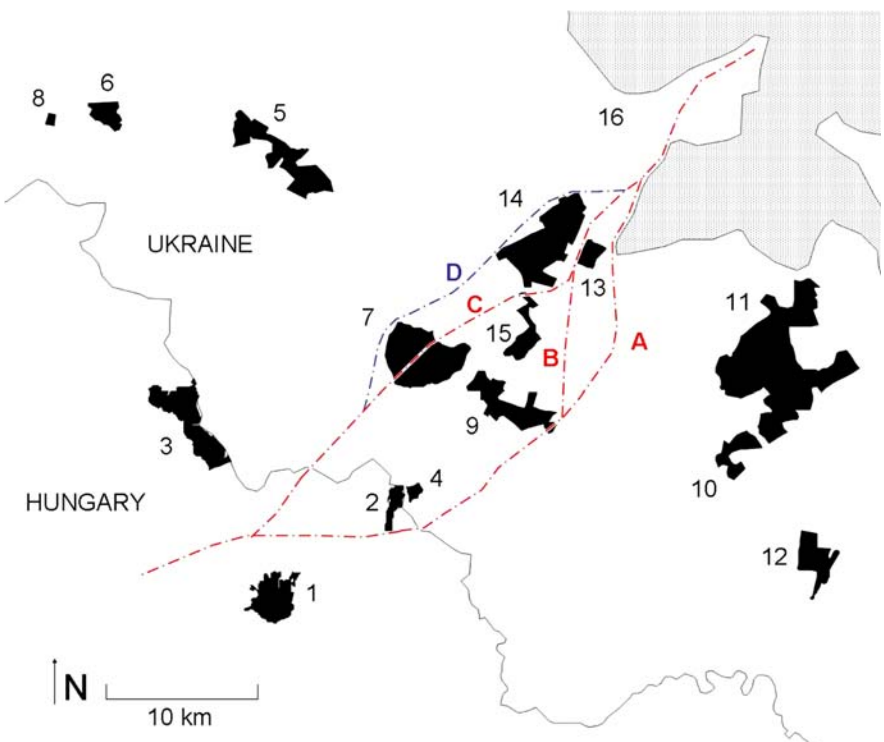

Fig. 1 Symbolised forest patchwork of the studied location (Bereg Plain, NE Hungary and W Ukraine). Forest patches are numbered (Name of forest patches: *1* Bockerek, *2* Déda H, *3* Lónya; *4* Déda U, *5* Dobrony, *6* Peres, *7* Rafajna, *8* Téglás, *9* Gút, *10* Alsóremete, *11* Beregújfalu, *12* Puskino, *13* Munkács, *14* Alsókerepec, *15* Gát, *16* Carpathians). In this source-sink metapopulation system, patch 16 can be regarded as a huge source, while all of the other patches are sinks. Thus, for the survival of local populations, connectedness to the Carpathian Mountains (16 *dotted patch*) is essential. *A*, *B* and *C* mark the planned highway tracks, while *D* marks our proposed solution

tracks (A, B and C; Fig. 1); (2) suggest a new solution (D) that is realistic and much less disadvantageous for habitat connectivity than the others (D, Fig. 1); and (3) discuss how to decrease the impacts of each track by establishing stepping stones.

Methods

Species

We studied hill and mountain living carabid species inhabiting forests only (Magura et al. 2001; Lövei et al. 2006): *Carabus intricatus* Linnaeus, 1761, *Cychrus caraboides* (Linnaeus, 1758), *Leistus piceus* Frölich, 1799, *Abax parallelus* (Duftschmid, 1812), *Cymindis cingulata* Dejean, 1825, *Carabus arcensis carpathus* Born, 1902, *Pterostichus melas* (Creutzer, 1799) and *Molops piceus* (Panzer, 1793). We analysed the composite habitat network for all of these carabid species since their habitat choice (i.e., old-growth deciduous forest patches) and landscape use are very similar.

Area and the construction of habitat network

We analysed a previously developed landscape graph (Jordán et al. 2007) representing the network of forest patches and ecological corridors in Bereg plain (NE Hungary and W Ukraine; Fig. 2). Patch and corridor quality have been weighted from 1 to 4 (Supplement 1; methodology was taken from Jordán et al. 2003). Weight reflects local population size for patches (values 1, 2, 3 and 4 correspond to a yearly average of 0–10, 11–100, 101–1,000 and more than 1,001 trapped individuals) and is marked as LPS_i for patch *i*. For corridors, it describes permeability (for corridor *j*, $p_j = 1, 2, 3$ or 4) and was estimated based on the species-specific traits of carabids.

Now we focus on the harmful effects of the planned highway tracks and explore a possible compensation. For the latter purpose, we studied the effects that the insertion of 18 hypothetical green corridors (Supplement 2) would have on connectivity. Green corridors are a series of forest patches with a size of 50 m × 50 m and distances from one another of not more than 1 km. These forest patches could serve as stepping stones for carabids (Jopp and Reuter 2005).

Network analysis

Previously (Jordán et al. 2007), we examined the landscape graph for the Bereg Plain using various indices. In this paper we focus on indices applicable to source-sink metapopulation with one source patch, as most likely a continuous immigration to the habitat patches is needed and does happen from the Carpathian Mountains (Ködöböcz and Magura 2005; Varga 1995). The hill and mountain living forest carabid species are able to disperse from the Carpathians to the lowland forests. Historically large, forested areas are now reduced to small isolated forest fragments separated by agricultural areas. So, the metapopulation of these carabid species depends on the dispersal of individuals from the source areas in the Carpathians (Magura et al. 2001; Jordán et al. 2007). Based on the efficiency at which carabids are able to use corridors, two different indices might be employed.

Core: total population size connected to the source habitat

If carabids can migrate without significant problems between habitat patches, distances from the Carpathians do not matter and we may be interested only in the contiguity with the Carpathians (patch 16). In this scenario, contiguity may be key to survival, while isolated local populations probably become extinct. This was measured by the core index (C_{source}) that describes the total population size connected to the source habitat. It is calculated as the sum of LPS_i values of all *i* patches (see network construction) which are connected to the Carpathians (patch 16).

Reachability from the source habitat

If migration is not ideal but the contiguity with the source habitat (patch 16) is still of high interest, a slightly modified version of the distance-weighted reachability measure (Borgatti 2003; $R_{16}^{D;\text{tgr}}$) can be used. Each patch's population size is weighted according to the topological distance from the Carpathians as well as the estimated permeability of corridors (reflected in link weights). The weight is given as the topographical distance from patch 16 and calculated as

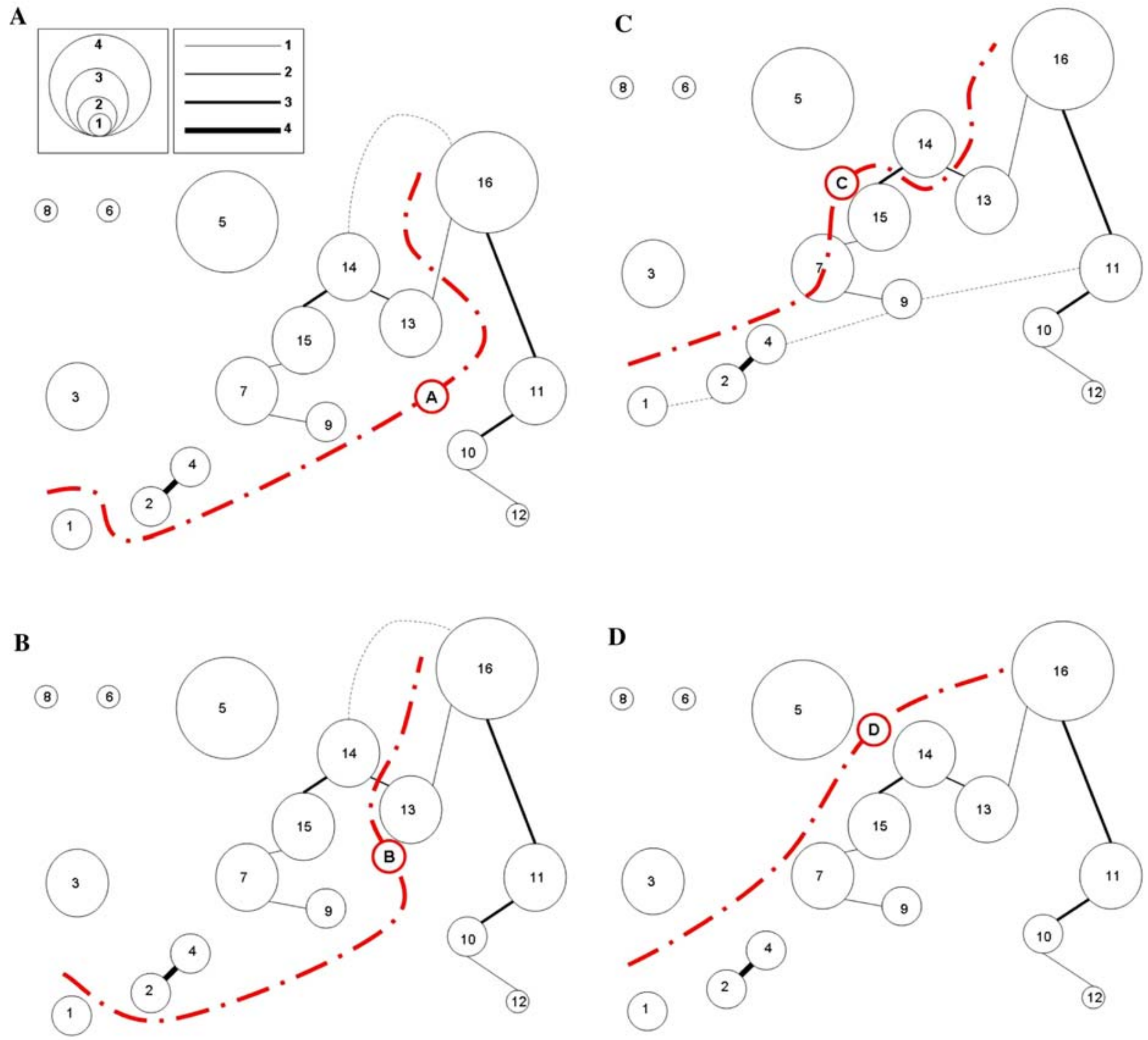

Fig. 2 Landscape graph of the studied area showing the topological arrangement of landscape elements and the highway tracks. Nodes represent patches and links represent corridors. Quality values of landscape elements are illustrated by node size and link width, according to the *top left insets*. *Wide*, *striped lines* mark highway tracks and *narrow*, *striped lines* mark *green* corridors whose establishment would restore the original connectivity. Note that this abstract "topological map" follows spatial relationships only roughly. Figures A, B, C and D correspond to the respective tracks

$$d_{\mathrm{tgr};16,i} = \sum_j \left(5 - p_j\right),$$

where the shortest path from patch 16 to node i contains j links with p_j permeability. Reachability is calculated as:

$$R_{16}^{D;\mathrm{tgr}} = \sum_i \frac{\mathrm{LPS}_i}{d_{\mathrm{tgr};16,i}},$$

where LPS_i is the local population size in patch i. We also note that this is an unnormalised version of the reachability index, since the normalised one would give contraintuitive results, i.e., deleting isolated nodes is advantageous (for more details, see Jordán et al. 2007).

The greatest advantage of the proposed connectivity measures is that they account for the explicit spatial pattern of habitats, which is essential in case of a source-sink system. The calculation assumes that the habitat and the matrix stand apart; whenever this assumption is fulfilled, such measures provide a readily available method to study habitat connectivity.

Results and discussion

We quantitatively evaluated and compared the three proposed tracks for a future highway crossing the Bereg plain. The planned highway tracks are among the worst possibilities for the fragmented forest habitat network of carabids. According to our results, all three planned highway tracks (A, B, C) disrupt forest connectivity (track A is the worst; Fig. 3). However, we propose a fourth track that (1) crosses no inhabited area, (2) cuts no presently used corridor of ground beetles, (3) crosses no river or railway (probably more economical to build) and (4) is not longer than the other planned ones. It is only slightly different from track C, but provides an example for possible tracks that do not seem to have negative effect on the connectivity of forest fragments, at least for ground beetles.

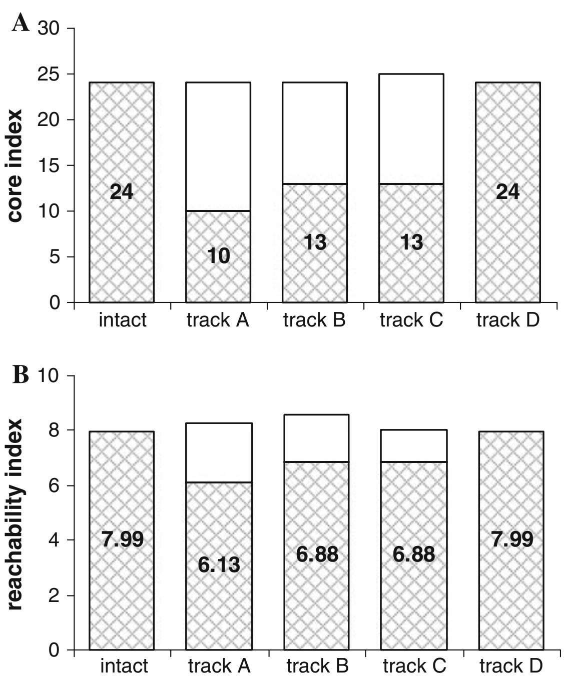

Fig. 3 Comparison of the intact situation, three planned highway tracks (tracks A, B and C) and our proposed solution (track D), based on two network indices of connectivity. **a** Connectivity evaluated by the core index (C_{source}). **b** Connectivity evaluated by the reachability index ($R_{16}^{D;\text{tgr}}$). *White bars* indicate connectivity after the establishment of the proposed stepping stones

The negative effects of track A or B could be fully compensated (at least by the means of calculated connectivity) by building a green corridor of six forest patches between Alsókerepec forest (patch 14) and the Carpathian Mountains [patch 16] (Fig. 2). Habitat connectivity in these cases is even slightly better than originally (Fig. 3). If track C is built, compensation needs three new corridors containing 17 stepping stones (between patches 4–9, 9–11 and 1–2).

To summarise, in the already highly fragmented forest patches of Bereg plain, the intended highway could have deleterious consequences on the hill and mountain living carabids. However, relatively simple actions like the establishment of green corridors (series of small, artificial forest patches that can serve as stepping stones between habitat patches) could compensate for the loss of habitat connectivity and promote the survival of carabids. We caution that no network analysis and no ground beetle study can tell the whole truth; for example, what is good for forest living animals may well be bad for meadow organisms. However, we emphasise that carabids are a vital component of the soil fauna, because they are trophically high, mobile predators on the ground, more sensitive to fragmentation and exert a considerably large community effect (Lövei and Sunderland 1996).

We believe that network analysis is a considerably powerful method in case of problems like this. As highways and other linear structures are known to be a major factor of fragmentation, infrastructure development projects should account for such environmental impacts (Geneletti 2004), which is a challenge without a well-developed ecological toolkit. Thus, conservation practice now calls for robust and easy-to-use methods to assess fragmentation, and the method proposed here can become a tool of decision-making. Accordingly, our main goal with this paper was to illustrate the usefulness of network analysis in questions of land use management.

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