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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 (separated by '-') Habitat network - Landscape graph - Carabidae - Bereg plain

Footnote Information **Electronic supplementary material** The online version of this article (doi:10.1007/s10980-009-9346-8) contains supplementary material, which is available to authorized users.

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Electronic supplementary material Below is the link to the electronic supplementary material.(DOC 81 kb)

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

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5 Béla Tóthmérész

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Introduction 38

Human pressure on natural environment is continu- 39
ously increasing, and beyond directly causing 40
extinction of species and decreasing natural habitats, 41
it leads to fragmentation of the remaining habitats 42
(Hilty et al. 2006; Haila 2002). Local populations of 43
small, isolated fragments have high extinction risk for 44
stochastic reasons (Fahrig 2003). Moreover, reduced 45
gene flow as a consequence of infrequent migration 46
leads to a loss of genetic variability (Keller and 47

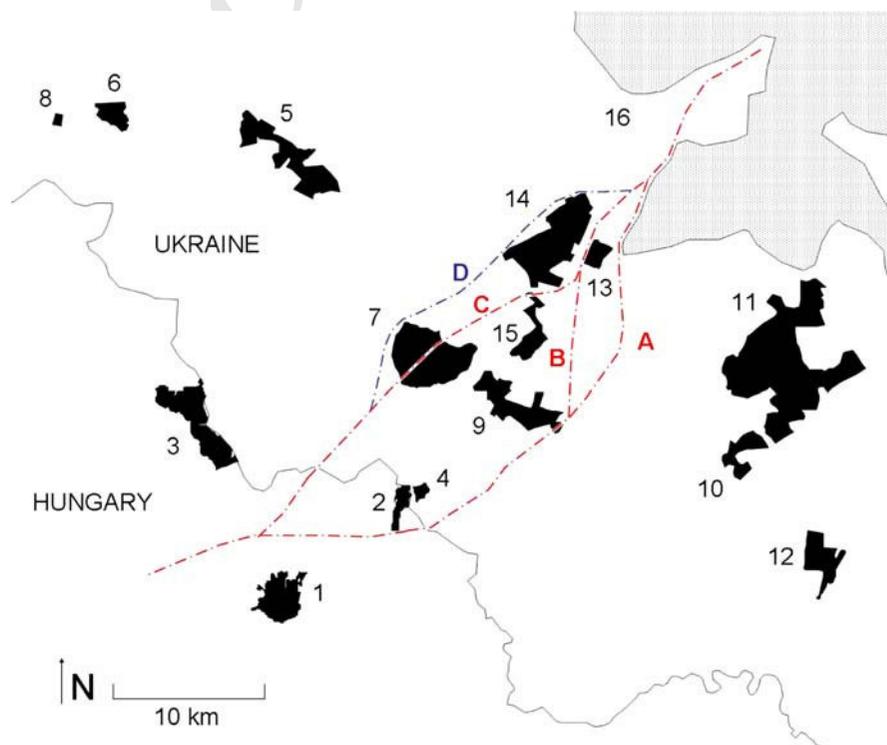
48 Largiadier 2003) in poorly connected habitat networks,
 49 which in turn increases local extinction risks (Saccheri
 50 et al. 1998). These problems most severely impact
 51 mobile high-level predators, and the cascading effects
 52 of their extinction may project single-species prob-
 53 lems to community-wide crises (Crooks and Soulé
 54 1999). Thus, landscape management should be based
 55 on network thinking and the results of realistic
 56 landscape graph models should be considered if
 57 landscape design scenarios are to be evaluated.

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

73 We focus on the landscape from the viewpoint of
 74 hill and mountain living forest carabid species
 75 (*Coleoptera: Carabidae*) inhabiting the forest patches
 76 and evaluate the effects of the three planned highway
 77 tracks on habitat connectivity. Since flightless cara-
 78 bids cannot cross highways (Koivula and Vermeulen
 79 2005; Mader et al. 1990), they are typical species
 80 being affected by road barriers. The distribution of
 81 these species is well known in the region (Magura
 82 et al. 2001; Ködöböcz and Magura 2005), so a
 83 relatively realistic landscape graph can be con-
 84 structed reflecting the quality of both patches and
 85 corridors, beyond simple network structure.

86 The structure of the landscape graph (relationships
 87 of habitat patches and ecological corridors; see Urban
 88 and Keitt 2001) suggests which landscape elements
 89 are of higher conservation value, if the aim is to
 90 protect habitat connectivity and maintain migration,
 91 and so reduce local extinction risk. Previously, we
 92 examined the positional importance of existing
 93 landscape elements (patches and corridors) in main-
 94 taining connectivity and the advantages of different
 95 hypothetical landscape management solutions (Jor-
 96 dán et al. 2007). As an up-to-date extension, now we
 97 (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 Beregújfalú, 12 Puskinó, 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



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

103 Methods

104 Species

105 We studied hill and mountain living carabid species
 106 inhabiting forests only (Magura et al. 2001; Lövei
 107 et al. 2006): *Carabus intricatus* Linnaeus, 1761,
 108 *Cychrus caraboides* (Linnaeus, 1758), *Leistus piceus*
 109 Frölich, 1799, *Abax parallelus* (Duftschmid, 1812),
 110 *Cymindis cingulata* Dejean, 1825, *Carabus arcensis*
 111 *carpathus* Born, 1902, *Pterostichus melas* (Creutzer,
 112 1799) and *Molops piceus* (Panzer, 1793). We ana-
 113 lysed the composite habitat network for all of these
 114 carabid species since their habitat choice (i.e., old-
 115 growth deciduous forest patches) and landscape use
 116 are very similar.

117 Area and the construction of habitat network

118 We analysed a previously developed landscape graph
 119 (Jordán et al. 2007) representing the network of forest
 120 patches and ecological corridors in Bereg plain (NE
 121 Hungary and W Ukraine; Fig. 2). Patch and corridor
 122 quality have been weighted from 1 to 4 (Supplement
 123 1). Weight reflects local population size for patches
 124 (values 1, 2, 3 and 4 correspond to a yearly average of
 125 0–10, 11–100, 101–1,000 and more than 1,001
 126 trapped individuals) and is marked as LPS_i for patch
 127 i . For corridors, it describes permeability (for corridor
 128 j , $p_j = 1, 2, 3$ or 4) and was estimated based on the
 129 species-specific traits of carabids.

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

Network analysis

140
 141 Previously (Jordán et al. 2007), we examined the
 142 landscape graph for the Bereg Plain using various
 143 indices. In this paper we focus on indices applicable
 144 to source-sink metapopulation with one source
 145 patch, as most likely a continuous immigration to
 146 the habitat patches is needed and does happen from
 147 the Carpathian Mountains (Ködöböcz and Magura
 148 2005; Varga 1995). The hill and mountain living
 149 forest carabid species are able to disperse from the
 150 Carpathians to the lowland forests. Historically
 151 large, forested areas are now reduced to small
 152 isolated forest fragments separated by agricultural
 153 areas. So, the metapopulation of these carabid
 154 species depends on the dispersal of individuals from
 155 the source areas in the Carpathians (Magura et al.
 156 2001; Jordán et al. 2007). Based on the efficiency at
 157 which carabids are able to use corridors, two
 158 different indices might be employed.

Core: total population size connected to the source habitat

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

Reachability from the source habitat

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

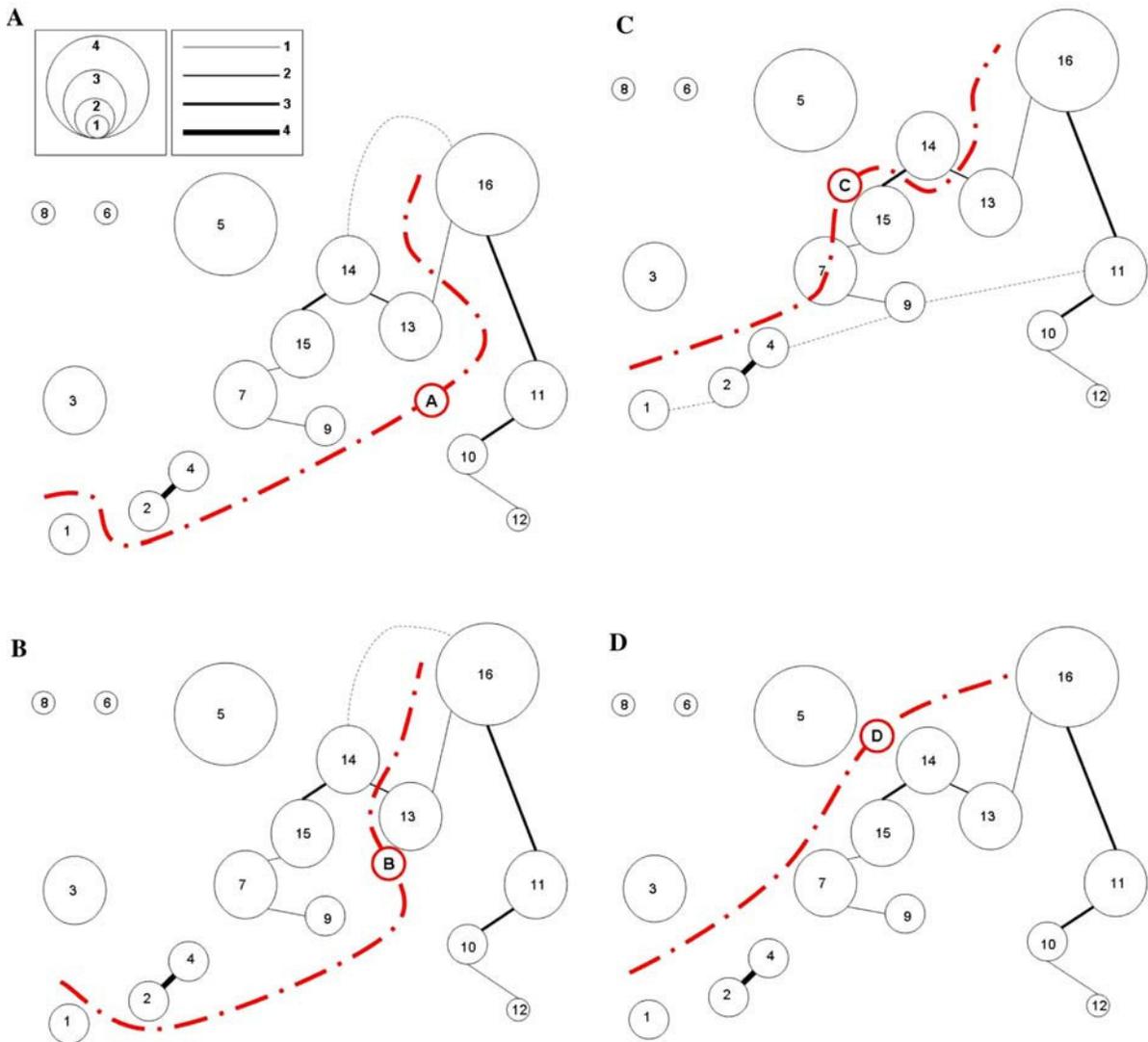


Fig. 2 Landscape graph of the studied area showing the topological arrangement of landscape elements and the highway tracks. Nodes represent patches and links represent corridors. Quality values of landscape elements are illustrated by node size and link width, according to the *top left insets*.

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

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

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

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

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

194 The greatest advantage of the proposed connec-
 195 tivity measures is that they account for the explicit

196 spatial pattern of habitats, which is essential in
 197 case of a source-sink system. The calculation
 198 assumes that the habitat and the matrix stand apart;
 199 whenever this assumption is fulfilled, such measures
 200 provide a readily available method to study habitat
 201 connectivity.

202 Results and discussion

203 We quantitatively evaluated and compared the three
 204 proposed tracks for a future highway crossing the
 205 Bereg plain. The planned highway tracks are among
 206 the worst possibilities for the fragmented forest
 207 habitat network of carabids. According to our results,
 208 all three planned highway tracks (A, B, C) disrupt
 209 forest connectivity (track A is the worst; Fig. 3).
 210 However, we propose a fourth track that (1) crosses
 211 no inhabited area, (2) cuts no presently used corridor
 212 of ground beetles, (3) crosses no river or railway
 213 (probably more economical to build) and (4) is not

214 longer than the other planned ones. It is only slightly
 215 different from track C, but provides an example for
 216 possible tracks that do not seem to have negative
 217 effect on the connectivity of forest fragments, at least
 218 for ground beetles.

219 The negative effects of track A or B could be fully
 220 compensated (at least by the means of calculated
 221 connectivity) by building a green corridor of six
 222 forest patches between Alsókerepec forest (patch 14)
 223 and the Carpathian Mountains [patch 16] (Fig. 2).
 224 Habitat connectivity in these cases is even slightly
 225 better than originally (Fig. 3). If track C is built,
 226 compensation needs three new corridors containing
 227 17 stepping stones (between patches 4–9, 9–11 and
 228 1–2).

229 To summarise, in the already highly fragmented
 230 forest patches of Bereg plain, the intended highway
 231 could have deleterious consequences on the hill and
 232 mountain living carabids. However, relatively simple
 233 actions like the establishment of green corridors
 234 (series of small, artificial forest patches that can serve
 235 as stepping stones between habitat patches) could
 236 compensate for the loss of habitat connectivity and
 237 promote the survival of carabids. We caution that no
 238 network analysis and no ground beetle study can tell
 239 the whole truth; for example, what is good for forest
 240 living animals may well be bad for meadow organ-
 241 isms. However, we emphasise that carabids are a vital
 242 component of the soil fauna, because they are
 243 trophically high, mobile predators on the ground,
 244 more sensitive to fragmentation and exert a consid-
 245 erably large community effect (Lövei and Sunderland
 246 1996).

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

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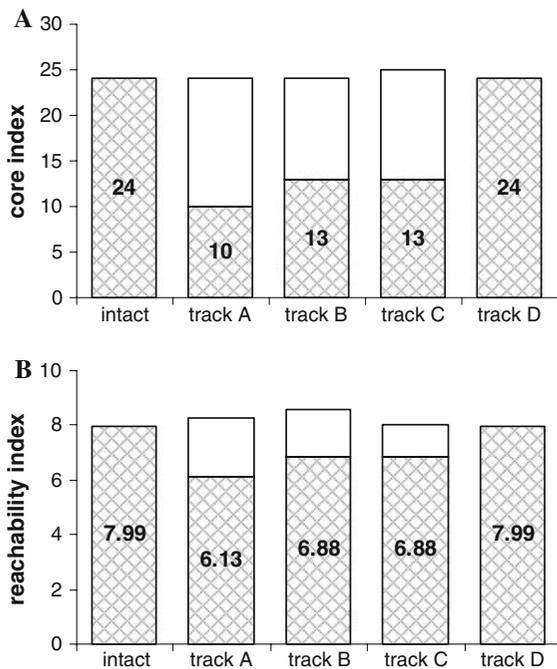


Fig. 3 Comparison of the intact situation, three planned highway tracks (tracks A, B and C) and our proposed solution (track D), based on two network indices of connectivity. **a** Connectivity evaluated by the core index (C_{source}). **b** Connectivity evaluated by the reachability index ($R_{16}^{D_{tgr}}$).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

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