GRAPH-BASED MULTI-ATTRIBUTE DECISION MAKING: IMPACT OF ROAD FENCING ON ECOLOGICAL NETWORK

Andrius Kučas

Nature Research Centre, Akademijos g. 2, 08412 Vilnius, Lithuania
E-mail: andrius@ekoi.lt

Abstract. Conservation and transport decision makers must deal with many competing criteria in order to find the optimal connectivity of habitat patches in order to maximize organisms' ability to traverse the landscape successfully. Thus, there is an increasing interest in prioritization of habitat patches by their contribution to overall landscape connectivity. Many different indices can be used to quantify structural and functional landscape connectivity. However, landscape connectivity indices alone do not clearly define conservation priorities for habitat patches. In this study priority values for each available habitat patch were calculated using multiple criteria spatial decision support techniques. As criteria for prioritization, spatial graph-based element properties (habitat patch size, number of corridors connected to a habitat patch, etc.) were characterized for each habitat patch. Graph-based connectivity rules for each habitat patch within a landscape (in conjunction with largest patch size, maximum number of corridors with a minimum length connected to a habitat patch, etc.) were defined and applied. Each criterion's importance was assessed. Criteria-based ranking of habitat patches within a graph better indicated exact critical habitat patches than connectivity index alone, especially when changes in network occur. Simulations in the case study of Lithuania showed that barriers (road fences to keep animals off the road) without prompt establishment of animal crossings may realign complexes of an ecological networks by reducing the importance of adjacent and increasing the importance of more distant patches. Such distant patches may become essential, and can sometimes be the only elements preserving the realigned ecological network.

Keywords: landscape connectivity, habitat patches, graph elements, multiple-criteria decision-making, ecological network.

1. Introduction

There is an increasing interest in considering landscape connectivity and fragmentation in landscape planning and habitat conservation. Landscape connectivity *per se* is important for various species in order to sustain viable populations (Pascual-Hortal, Saura 2006; Verboom *et al.* 2001). Since the landscape connectivity is species-specific, different organisms interact with landscape structure at different scales and in a variety of ways. Landscape connectivity may positively influence population persistence for some organisms in some situations, and negatively influence them in others (Grashof-Bokdam 1997; Johnson *et al.* 1992). Smaller habitat patches, longer and sparser corridors, increasingly isolated species are main indicators of increasing landscape fragmentation and decreasing landscape connectivity. Landscape fragmentation mainly results from the conversion of the natural area into urban areas and from the linkage of these urban areas via transport infrastructure. Meanwhile, Moser *et al.* (2007) found that landscape fragmentation can reduce landscape connectivity. Reduced landscape connectivity obstructs the movement of organisms across the landscape, potentially affecting metapopulation dynamics and gene flow (Keyghobadi *et al.* 2005). According to Brooks (2003), landscape connectivity has two components: structural (the spatial structure of a landscape and this can be described using map elements) and functional (biological component; the response of individuals to landscape features). Thus, there are many graph and non-graph based landscape connectivity indices which may be used for the prioritization of habitat patches and corridors for conservation purposes (Baranyi *et al.* 2011; Pascual-Hortal, Saura 2006; Tischendorf, Fahring 2000, 2003). Meanwhile, landscape connectivity indices alone do not clearly define conservation priorities for habitat patches. Pascual-Hortal and Saura (2006) found that many different connectivity indices have been proposed and used in this context but there is a lack of comprehensive understanding of their sensitivity to pattern structure and their behaviour to different spatial changes, which seriously limits their proper interpretation and usefulness. Meanwhile, the relative ranking of habitat patches within a landscape by their contribution to overall landscape connectivity is most

useful in the decision process. Thus, there is an increasing interest in prioritization of habitat patches by their contribution to overall landscape connectivity (Baranyi *et al.* 2011; Pascual-Hortal, Saura 2006).

Therefore the objectives of this study were: (1) to define a new spatial graph element properties based calculation procedure in order to perform the relative ranking of habitat patches within a landscape by their contribution to overall structural landscape connectivity; (2) to compare the TOPSIS (technique for order preference by similarity to ideal solution) rank value reaction to a common connectivity index especially when changes in landscape occur; and (3) to validate the new calculation procedure by intersecting Lithuanian ecological networks with road fences (to keep animals off the road) in order to show how realignments of connectivity affect adjacent and distant habitat patches.

2. Functional-spatial structure of ecological network

2.1. Ecologically compensating infrastructure

Implementation of sustainable development policy is one of the most complicated tasks and challenges faced by the global community (Burinskienė, Rudzkienė 2009; Kavaliauskas 2008). Although system of ecologically compensating areas is defined as parts of the ecological infrastructure that balance disparities between the natural and anthropogenic systems (Sepp, Kaasik 2002), many different explanations have been proposed in this context and can be used as synonyms of different *ecological networks* worldwide. Whatever its scale (continental, regional, local), an ecological network consists of the following elements: *core areas* (or biocentre), *ecological* (or biological) *corridors*, *buffer* (protective) *zones* and *stepping stones* within the re-naturalisation area. Each structural element has its functions, and the whole complex makes the ecological network as a functioning system (Sepp, Kaasik 2002). Theoretical structural elements of ecologically compensating infrastructure reported by (Sepp, Kaasik 2002) can be described using graph-based elements within the *main system* (thereafter ecological network) (Fig. 1).
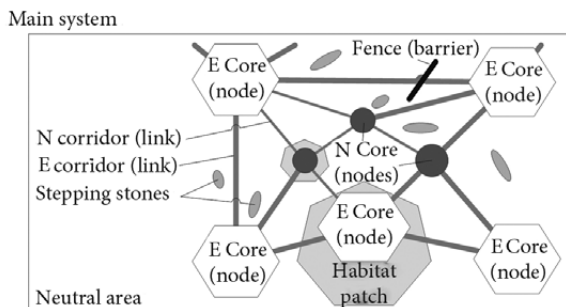
Fig. 1. Spatial graph-based structural elements of ecologically compensating infrastructure used for construction of ecological network for barrier (fence to keep animals of the road) impact analysis (E – European, N – National)

In this study, nodes represent habitat patches or core areas/center of core areas of suitable habitat surrounded by inhospitable habitat – *neutral area*. The existence of a link between each pair of habitat patches implies the potential ability of an organism to traverse between these two habitat patches, which are considered to be connected. Links may have a physical correspondence on the landscape in the form of a corridor. According to Pascual-Hortal and Saura (2006), links between habitat patches can be defined as minimum or Euclidean distances. In this study, a *component* is a region of nodes connected via links representing the structural landscape of the ecological network. An isolated node or *stepping stone* makes up a component itself. A component disconnects when a part of it, after a change in the landscape, becomes unreachable from some other part, causing an increase in the number of components in the ecological network. If disconnection creates a new component, then this link is called – *cutlink* (Pascual-Hortal, Saura 2006). If it is a link removal that causes the disconnection within a component, then this link is called *non-cutlink*. In order to prioritize habitat patches by their contribution to the overall landscape connectivity, the TOPSIS based rank values for each habitat patch in an ecological network must be delineated by assessing the following graph-based *connectivity rules*: the largest habitat patch area size, largest amount of directly connected corridors, the minimum total length of the directly connected corridors and the largest total area size of directly connected habitat patches. In this study, rank values for each available habitat patch (core areas within the ecological network) were calculated using MC-SDSS (Multiple Criteria Spatial Decision Support System) where TOPSIS method is tightly integrated within ESRI ArcGIS® mapping environment (Kučas 2010). The higher the TOPSIS based rank value (ranging from 0 to 1) for a particular habitat patch within the component, the better the overall connectivity within the component. Any barriers which appear due to increasing linkage of urban areas via transport infrastructure breaks apart the component, by increasing or decreasing TOPSIS based rank value for a particular habitat patch. This approach allows figuring out which rule under what conditions are affected.

2.2. Criteria and their importance

As a criterion for habitat patch prioritization, the aggregated spatial graph element based properties were characterized for each habitat patch and each corridor within hypothetical components (Fig. 2, Table 1) in order to illustrate various real world situations.

Connections (Fig. 2) between the patches (links, represented as lines) represents length of a link (L). Nodes represented as circles of different habitat patch and represents area size (N). Noncut-link that is lost is indicated by dashed lines case (4a). It is assumed that when a patch is lost, the links (functional connections) coming from it are not lost. The represented component connectivities (Fig. 2) are the same because in all cases the amount of

habitat patches and amount of connections are the same ($N = 3$, $L = 3$), except the case (4a), ($N = 3$, $L = 2$). The represented habitat patch properties within a component: area of particular habitat patch (*NS*) and the length of particular link (*LL*) which connects two habitat patches are not the same in all cases: (1) $NS = NS$ and $LL = LL$, (2) $NS = NS$ and $LL \neq LL$, (3) $NS \neq NS$ and $LL \neq LL$, (4 and 4a) $NS \neq NS$ and $LL = LL$. Case (4a) illustrates the different reaction of a component depending on how non-cutlink change occurs. In order to demonstrate criteria importance delineation the area (e.g. ha) of a particular habitat patch (*N*) and the length (e.g. km) of a particular link (*L*) were assigned to each link and node for a particular component. Numerical values (for *N* and *L*) representing all cases (Fig. 2) are given in Table 1. In real applications such data can be easily extracted using standard GIS tools.

In order to perform ranking of habitat patches according to connectivity rules, the importance of spatial graph element based properties as a criteria and function has been defined for all components (Table 2) and further used for identification of which criteria and under what condition is more important than the other.

The importance of spatial graph element based properties was estimated by using largest *NS*, *TN*, *TA* and smallest *TL* for each habitat patch and assumed as expert questioning (Pascual-Hortal, Saura 2006; Sepp, Kaasik 2002) The ideal habitat patch within a component would be the one which best meets graph-based connectivity rules. This approach also allows adding more sophisticated ecological or species specific data (e.g. amount of nests, or amount of specific land cover data etc.) as additional criteria representing structural and functional connectivity by delineating its criterion importance and defining required function according to optimization task needs. The criteria importance calculations for all five cases were performed using the criteria importance delineation procedure as reported by (Jakimavičius, Burinskienė 2007; Kučas 2010).

After criterion importance is defined, further analysis on ranking of habitat patches within a component can be performed.

3. Multiple criteria spatial decision making methods

3.1. Prioritization of habitat patches within a component using TOPSIS

The TOPSIS method allows using importance of criteria which are delineated or in case of available importance of criterion, user-defined. For further analysis the case 3 (Fig. 2) is selected since it best describes the real world irregularity phenomena. In order to demonstrate the ranking procedure and calculation sensitivity the criterion importance (*q*) from case 3 (Table 3) will be used in assessment of all cases. The input data used for K_{BIT} calculations are: habitat patches (N_i) as alternatives, criteria (R_i) and their importance (*q*). The best alternative is with the highest K_{BIT} value. The highest TOPSIS based rank value (range from 0 to 1) means the best option and the
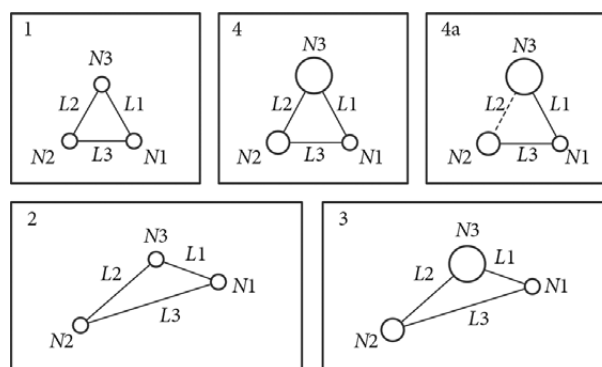

Fig. 2. Different cases illustrating four types of habitat patch connectivity and one case illustrating change corresponding to the loss of non-cutlink or corridor

Table 1. Input data. Area of particular habitat patch (*N*) and the length of particular link (*L*) for all cases

Node/Link	Case No.				
	1	2	3	4	4a
N1	1	1	1	1	1
N2	1	1	2	2	2
N3	1	1	3	3	3
L1	1	1	1	1	1
L2	1	2	2	1	1
L3	1	3	3	1	1

Table 2. Importance of criteria

No.	Criteria description	Function
R1	Area size (*NS*) of particular habitat patch (hereafter *N*). Hereafter *NS*	Maximize
R2	Total amount (*TN*) of links (hereafter *L*) connected to a particular habitat patch (*N*). Hereafter *TN*	Maximize
R3	Total length (*TL*) of links (*L*) connected to particular habitat patch (*N*). Hereafter *TL**	Minimize
R4	Total area (*TA*) of habitat patches which are connected (adjacent) to particular habitat patch (*N*) via links (*L*). Hereafter *TA*	Maximize

Note: * – the length of particular link (*L*) which connects two habitat patches (*N*) – hereafter *LL* used only for *TL* calculation.

Table 3. The criteria importance calculation results for all cases (rank within a particular case)

Case	Criteria			
	R1	R2	R3	R4
1	0.250 (1)	0.250 (1)	0.250 (1)	0.250 (1)
2	0.245 (2)	0.245 (2)	0.264 (1)	0.245 (2)
3	0.265 (1)	0.231 (4)	0.253 (2)	0.251 (3)
4	0.269 (1)	0.237 (3)	0.237 (3)	0.256 (2)
4a	0.249 (2)	0.249 (2)	0.228 (3)	0.274 (1)

"strongest" habitat patch in the component. The alternatives can then be prioritized according to their rank value in descending order.

Habitat patches which have the highest ranks within priority row (1) make components more compact. The habitat patches with the lowest rank (priority row ‑ 3) assigned – rarefies the component. The ranking of habitat patches within particular components for all cases are presented in Table 4 and Fig. 3.
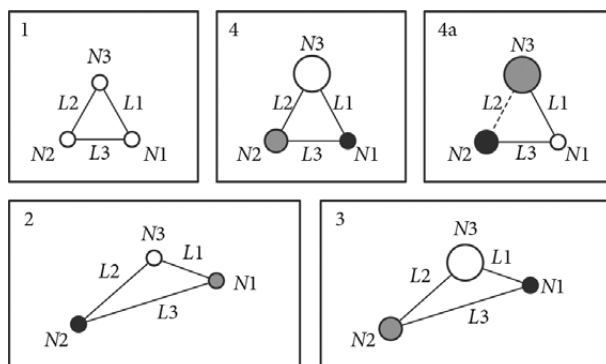
Habitat patches that have highest rank within priority row (1) within a component are indicated in white color, medium (2) – in gray and lowest (3) – in black (Table 4, Fig. 3). Habitat patches with a higher rank can be considered more important: its loss affects more seriously the connectivity of the whole component. The habitat patch (N1) case 4a shows that it may be important for connectivity of the whole component, but it does not mean that it is so. From an ecological point of view there are many findings in different studies concluding that small and distant habitat patches are usually not occupied and appear less important (Baranyi *et al.* 2011). Meanwhile, if the size of a habitat patch (case 4a, N1) is big enough in order to maintain the population of a certain species, as well as enabling movement to assure gene flow, then such a habitat patch may preserve whole component connectivity in case of loss of non-cutlink (L2), case 4a.

3.2. Connectivity of components

If habitat patches are discrete, then Lindenmayer and Fischer (2006) considered that connectivity within a component could be quantified as a function of a number of connections between those habitat patches, relative to the maximum number of potential connections. Thus, if there are direct links between all habitat patches (N) within a component, there will be $N(N–1)/2$ such links (Lindenmayer, Fischer 2006). Then, connectivity index (C) of patches and links within a component can be calculated as follows:

$$C = \frac{2L}{N(N-1)}, \qquad (1)$$

where L – the number of links; N – the number of patches. A fully connected component with complete levels of landscape connectivity would have a value of 1, and a component that has no connectivity would have a value of 0. In cases (Fig. 3, cases 1, 2, 3, 4) the landscape connectivity index $C = 1$. This means that these components are homogeneous. In case 4a, the connectivity index $C = 0.67$. Case 4a illustrates the habitat patch (N1) rank change from lowest (case 4) to highest (case 4a) corresponding to the loss of non-cutlink. Using only the connectivity index, it is impossible to delineate such particular change. Components with more dispersed and less linked habitat patches have lower connectivity.

4. Simulation of criteria based ranking of habitat patches

4.1. Study site and calculations

This study considers how TOPSIS rank value reacts to the different types of change that can occur in the landscape and how ranks differ in predicting which habitat patches (based on criterion importance delineation) are more important for the maintenance of overall component condition. To compare and evaluate the performance of connectivity rules under real graph-based conditions, the Lithuanian structural ecological network (further – ecological network) was prepared using the ecologically compensating infrastructure concept (Fig. 1) and presented in Fig. 4. The Ecological networks in the Baltic countries are a constituent part of the Pan-European ecological network. Therefore its main structural elements and their functions are the same as those in the Pan-European network. In this study, the ecological network (Fig. 4) is limited to graph-based network analysis only. It is presumed that all habitat patches are similar, since no particular ecological or species specific data are added during the preparation of the network. This means that habitat patch sizes and amount of links may differ for particular species and do not represent the real condition of the Lithuanian ecological network. In this context, the validity of the full-fledged Lithuanian ecological network is not questioned. Nevertheless, since the ecological network is a coherent system of natural or semi-natural landscape elements configured and managed with the objective of maintaining or restoring ecological functions as a means of conserving biodiversity, the methods and workflows proposed in this study allow the use of more sophisticated ecological or species oriented data as criteria.

Table 4. Results of habitat patch ranking. TOPSIS (priority row within particular case)

Case	Habitat patches		
	N1	N2	N3
1	n/a (1)	n/a (1)	n/a (1)
2	0.500 (2)	0.000 (3)	1.000 (1)
3	0.353 (3)	0.426 (2)	0.691 (1)
4	0.334 (3)	0.500 (2)	0.666 (1)
4a	0.551 (1)	0.356 (3)	0.449 (2)

Fig. 3. Different cases illustrating three types of habitat patch ranking according TOPSIS

European level core areas (represented as nodes) in a component are indicated in black colour, national level core areas – in grey, stepping stones – in white. European and national level corridors represented in grey lines, existing road fences in black lines. Finally, the patch area illustrates real boundaries of core areas represented in polygons (Fig. 4). The base data are defined based on data from the Nature Research Centre, State Science Research Institute. The road barriers – fencing data are defined based on data of Lithuanian Road Administration under the Ministry of Transport and Communications. The ecological network consists of one main component, 82 core areas containing all core areas except 9 components as standalone stepping stones and 176 corridors. Connectivity index $C = 0.05$. Connections between the core areas – corridors indicated as lines. These lines represent corridors of national and European importance. Nodes represented as circles indicate core areas and represent area size. All areas are coded with unique letters and numbers (Note: E – European level, N – national level and J – stepping stone) as recognized by national and European institutions (Sepp, Kaasik 2002). After data were prepared, the first assessment of core area ranking was performed in order to define the condition of the present ecological network. The TOPSIS method was used for calculations. The results are presented in a map showing ranking values for each core area and illustrates the overall component condition. The higher the TOPSIS (range from 0.119 to 0.737) values the larger the circle on the map (Fig. 5). The criterion importance (q) calculation results for the ecological network: $NS = 0.301$, $TN = 0.145$, $TA = 0.264$, $TL = 0.290$ ($W = 0.016$). So, the most important criteria for assessment were length of connected corridors TL and size of core area NS. This means that change in NS and TL may affect all components more than change of TN and TA.

The highest values were assigned to larger core areas E2, E1, N16, E28 and E4. The lowest values were assigned to core areas N14, N25, E16 which are smallest and less connected. In this study E16 is of a European importance which received overall lowest rank. Highest ranked are N16, E28 and E4. However, different standardization/ weighting techniques may lead to different results (Coutinho-Rodrigues *et al.* 2011). TOPSIS based ranking shows stepping stones as important, because it represents the full component. Since the TOPSIS method is more accurate on parameter sensitivity, the results show larger distance between low and high rank values assigned to core areas. In general the central and northern parts of the ecological network (within a main component of the ecological network) have core areas with lower ranks ("weaker" movement opportunities) assigned and eastern, southern, western parts with higher ("stronger") movement opportunities) ranks. The central and northern parts of the ecological network show that core areas are smallest in size and connected with other adjacent small core areas via the longest corridors. Meanwhile, these parts of Lithuania are more fragmented (regarding forests), and mainly used for agricultural purposes (Kučas 2010).

4.2. Impact of road fences as barriers on realignment of core areas

Road barriers without prompt establishment of animal crossings or conduction of chemical repellents (Balčiauskas, Jasulionis 2012) may prevent animals' movement across the structural landscape. For further analysis and method validation the graphical data of road fences were added to the present ecological network and 36 corridors which were intersected were removed. Removal of a corridor is not the only option, and in other cases corridor weights may be assigned and assessed via particular core areas. In the real world such situations may occur when the proper animal crossings are not available or established in inexact places. Reassessment using the same input data (Fig. 5) with road fencing affected corridors was performed. The criterion importance calculation results for an ecological network affected by road fencing: $NS = 0.305$ (increased), $TN = 0.164$ (increased), $TA = 0.240$ (decreased), $TL = 0.291$(increased) ($W = 0.016$). Loss of non-cutlink affected the total area (TA) of habitat patches which are connected (adjacent) to a particular habitat patch (N) via links (L). TOPSIS (range from 0.175 to 0.826) rank values for particular habitat patches increased, but the network was rarefied because the connectivity index decreased $C = 0.04$ (before $C = 0.05$). This meant
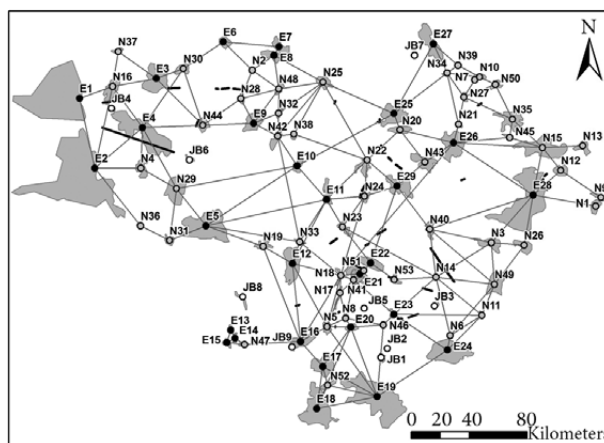

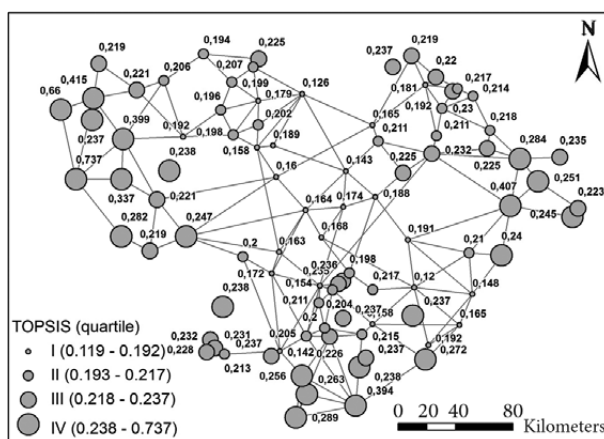**Fig. 4.** Input data prepared based on ecologically compensating infrastructure concept

Fig. 5. TOPSIS based ranking of core areas within ecological network

that habitat patches which became less connected became more important in the context of the whole component. The lowest values were assigned to core areas N25, E16, N42 which are the smallest and least connected. In this case E16, as a core area of European importance, received the overall lowest rank as before.

The map (Fig. 6) shows change impact to overall component compactness via core areas and shows change of TOPSIS based rank before and after road fencing data introduction to analysis. The overall TOPSIS based rank decrease (range from –0.086 as large black dots, and from –0.084 to –0.041 as small black dots) and increase (range from 0.041 to 0.066 as small white dots, and from 0.067 to 0.106 as large white dots) of ranks are presented in Fig. 6.

Black (with negative sign) and white (with positive sign) dots indicate the decrease or increase (respectively) of core area rank within an overall ecological network. Larger circles indicate larger change. Thick black lines represent the fences. Thin black dashed lines represent the fencing affected corridors, and thin grey lines – corridors not affected by fences (Fig. 6). The results show that barriers (fences to keep animals off the road) without prompt establishment of animal crossings may realign complexes of an ecological network by reducing the importance of adjacent and increasing importance of distant core areas. As an example, in the western part of the ecological network, some adjacent core areas such as E4 and N4 received lower ranks after road fencing data were introduced to analysis. Some distant areas such as N44, E5 or even N19 received lower ranks as well. From an ecological point of view, core areas in which ranks decreased break apart the whole component and these areas are the most sensitive in the whole ecological network. If N4, N29, E5, E4 and N16 lose their importance, then areas with increased ranks (E1, E2, N36, N37, E3 and N31) may compensate for the loss of resources. Core areas E1, E2, N36 and N31 which are connected via corridors may become more attractive to animals from N4, N29, E5, E4 and the entropy of these areas should be artificially increased. Meanwhile, the core area N16 is most sensitive to potential road fencing and it is the first candidate to disconnect the north-west and south-west parts of the component. N16 has the highest negative rank change
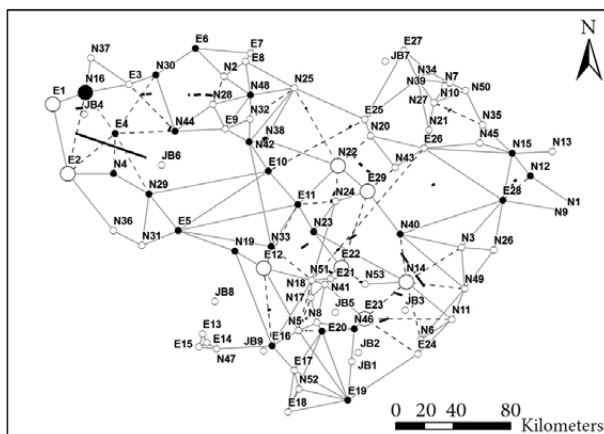
and it may be a signal that this core area may lose its attractiveness for animals to traverse through. Though, if no proper alternative animal crossings for the road fences that intersect corridors (N29-E4, N4-E4, E2-E4, E2-N16, E4-N16, E4-N30, E3-N44 and E44-N44) are established, it may be presumed that N16 is the most important as well as the most sensitive core area within the ecological network. Other parts of the ecological network, such as E29, N22 and E12 in the central part of the ecological network after realignment, may become the most important target area for animals to congregate to, because some adjacent areas may lose their attractiveness. Some distant migration corridors may potentially be affected by inappropriate road fencing and cause avoidance or forced inaccessibility of adjacent core areas.

These are only a few result interpretations which may lead to more precise assessment of ecological networks in order to define which spatial graph element based criteria and under what conditions are important for animals to traverse landscape successfully. The ranking procedure of ecologically sensitive areas may be introduced to similar domain analysis in the context of future assessments, such as species specific habitat monitoring (Juškaitis 2008), sustainable urban development (Burinskienė, Rudzkienė 2009) or road safety ranking (Jasiūnienė, Čygas 2013) studies. This study was limited to ecologically compensating infrastructure concept only, and no particular sophisticated ecological data were introduced to the analysis. Since ecological network preserves the whole complexes it is necessary to add more species specific data in order to assess and optimize the whole ecological network as a full-fledged system. It is suggested that criteria importance definition by considering expertise of different researchers should be employed in order to avoid misleading perceptions when prioritizing habitat patches for conservation purposes. Thus, understanding which criteria for which organisms and under what conditions is important, remains a considerable research challenge.

5. Conclusions and proposals

1. Wide ranges of indices can be used to characterize patterns of landscape including ones that quantify landscape connectivity. However, caution must be used when applying landscape connectivity indices, in order to avoid redundancy with other indices that essentially capture similar or even contradictory information, especially when spatial changes occur. Meanwhile, without use of ecological research data during analysis, landscape connectivity indices do not show conservation priorities within given landscapes.

2. There is an increasing interest in prioritization of habitat patches and corridors by their contribution to overall landscape connectivity using different criteria defined by experts. In this context, MC-SDSS techniques using spatial graph-based element properties as a criterion for habitat patch assessment have been shown to be an effective tool in dealing with difficulties that decision makers encounter in handling large pieces of complex information.

3. In order to identify which loss of habitat patch within a component is more important, the link loss (loss of non-cut link – ecological corridor) were simulated and

Fig. 6. Reshuffle of core areas and their impact to overall connectivity of ecological network

habitat patch ranks were recalculated. Calculations showed that loss of non-cutlink affected not only adjacent but also distant habitat patches. The distant habitat patches may become essential, and sometimes the only elements preserving realigned components of an ecological network.

4. Results showed that spatial graph element properties based ranking of habitat patches for conservation purposes show more direct and critical information regarding single habitat patch than connectivity indices alone, especially when changes in a landscape occur. Ranking of all given habitat patches which are evaluated using experts' suggestions allow the employment of more sophisticated ecological data to landscape connectivity analysis in order to manage habitats and to set priorities for all habitat patches within an ecological network.

5. It is suggested that when defining criteria importance by considering the expertise of different researchers, conservation and transport decision makers should be employed in order to avoid misleading perceptions when prioritizing habitat patches for conservation purposes.

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