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Fotografija na naslovnici: Kmetijstvo ima pomembno vlogo pri varovanju in razvoju kmetijskih zemljišč in je pomemben dejavnik tudi pri razvoju drugih sektorjev (fotografija: Matej Lipar).

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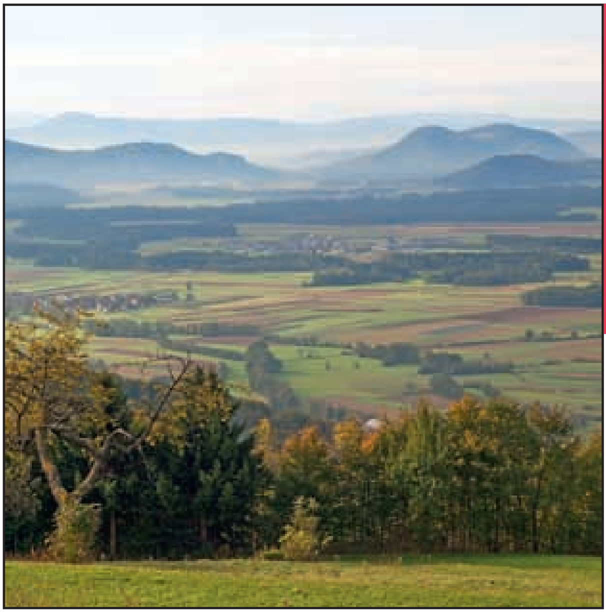
FOREST PATCH CONNECTIVITY: THE CASE OF THE KRANJ-SORA BASIN, SLOVENIA

Maja Polenšek, Janez Pirnat


MAJA POLENŠEK

Western part of the Kranj–Sora Basin viewed from Ambrož pod Krvavcem.

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Forest Patch Connectivity: The Case of the Kranj-Sora Basin, Slovenia

ABSTRACT: This article features a spatial analysis of forest patches, trees, and shrubs outside forests in part of the Kranj-Sora Basin in central Slovenia. Forest patch connectivity is explored using methods derived from graph theory. The graph nodes represent the forest patches and the edges between them represent the shortest connections calculated using a raster layer containing data on the resistance of individual land-use types. The contribution of an individual forest patch to habitat connectivity and availability is calculated using selected indicators. The findings show that the largest forest patches complemented by smaller patches constitute the basic connectivity tool. Thus, habitat size and close-to-nature structure are vital for the conservation of species over short distances. In conclusion, guidelines are presented for managing and mitigating the effects of further clearing the remaining natural vegetation.

KEY WORDS: forestry, geography, forest habitat patches, patch connectivity, graph theory, Kranj-Sora Basin, Slovenia

Povezanost gozdnih zaplat na primeru Kranjsko-Sorškega polja

POVZETEK: V prispevku obravnavamo prostorsko analizo gozdnih zaplat, dreves in grmov zunaj gozda na primeru dela Kranjsko-Sorškega polja v osrednji Sloveniji. S pomočjo metod, ki izhajajo iz teorije grafov, smo preverili povezanost gozdnih zaplat. Vozlišča grafa predstavljajo gozdne zaplate, povezave med njimi pa najkrajše povezave, ki smo jih izračunali na podlagi izdelanega rastrskega sloja, ki vsebuje upore posamezne rabe zemljišč. Prispevek posamezne gozdne zaplate k povezanosti in dostopnosti habitatov smo izračunali s pomočjo izbranih kazalnikov. Ugotovili smo, da so temeljno ogrodje za povezanost največje gozdne zaplate, ki jih dopolnjujejo manjše zaplate. Za ohranjanje vrst sta tako pri kratkih razdaljah najpomembnejši sta velikost in sonaravna zgradba habitata. Na koncu smo podali usmeritve za usmerjanje in blažitev učinkov nadaljnjih krčitev ostankov naravne vegetacije.

KLJUČNE BESEDE: gozdarstvo, geografija, gozdne habitatne zaplate, povezanost zaplat, teorija grafov, Kranjsko-Sorško polje, Slovenija

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1 Introduction

According to traditional landscape-ecology theory, a landscape consists of a matrix as the predominant land-use type, in which other uses are distributed as patches and corridors (Forman 1995). In agricultural landscapes, forest habitat patches are extremely important for ensuring biodiversity. Landscape structure analyses have a significant impact on both the landscape division criteria (Petek 2005) and the understanding of changes occurring within a landscape. Habitat reduction and fragmentation are among the main reasons for biodiversity decline (Collinge 1996; Bailey 2007). Several studies have shown that the entire area of the habitat regardless of its spatial distribution is a dominant factor influencing the survival of a particular species. When the total habitat area within a landscape falls below 50% (Flather and Bevers 2002; Crouzeilles et al. 2014) or, as reported by Andren (1994), below 30%, the distribution of habitat patches becomes equally important as the habitat area. The concept of habitat connectivity makes it possible to understand and measure the interconnected ecological impacts of habitat loss and fragmentation (Laita, Kotiaho and Mönkkönen 2011). The aim of this study is to determine whether the forest habitat patches in the selected study area are functionally connected and to identify the most important connecting forest patches that contribute the most to maintaining forest patch connectivity.

1.1 Habitat patch connectivity and graph theory

Over the past decade, a number of habitat patch connectivity studies have relied on mathematical graph theory and the network theories derived from it (Bunn et al. 2000; Zetterberg, Mörtberg and Balfors 2010; Saura et al. 2011; Zetterberg 2011; Mazaris et al. 2013). In graph theory, graphs make it possible to combine population processes with spatial patterns and their connectivity at both the level of landscapes and individual patches (Urban and Keitt 2001). A habitat patch connectivity analysis using graph theory methods makes it possible to assess the functional connectivity of individual patches (Laita, Kotiaho and Mönkkönen 2011). In this way one can assess the spatial importance of habitats and their connectivity (Bunn et al. 2000).

1.2 Habitat patch connections

The findings of several studies show that matrix heterogeneity has a strong impact on movement between habitat patches (Ricketts 2001; Russell, Swihart and Feng 2003; Revilla et al. 2004). The matrix is composed of various elements that have different effects on the spatial movement of species. Some land-use types represent barriers that are difficult to cross (e.g., rivers and freeways), whereas others make movement easier, often by providing shelter and food. This determines the resistance – that is, how demanding a specific land-use type is for crossing. Based on this, effective distances are calculated; they represent the shortest functional connections between habitat patches. From the biological perspective, identifying resistance is the most important step in calculating effective distance (Adriaensen et al. 2003).

Methods derived from graph theory were used to calculate the effective distance, whereby the graph nodes were the forest patches and the graph edges with the least resistance for species movement between them were the shortest effective distances (Polenšek 2015).

The predominantly flat northeastern part of the Kranj-Sora Basin was selected as the study area, as shown in Figure 1. This area is strongly affected by intensive farming (Rejec Brancelj 2001) and urbanization. The study area covers 10,423.65 ha, of which the forest covers 3,901.46 ha or 37.4%; in the flat part of the study area forest coverage is even smaller (27.7%). Across the entire study area, the forest is fragmented into 150 patches, ranging in size from 0.25 ha to 718.97 ha (Polenšek 2015).

2 Methods

2.1 Connectivity indicators

Proceeding from graph theory, researchers specializing in landscape ecology and other related disciplines have developed a number of indicators for assessing patch connectivity in landscapes. Bodin and Saura (2010)

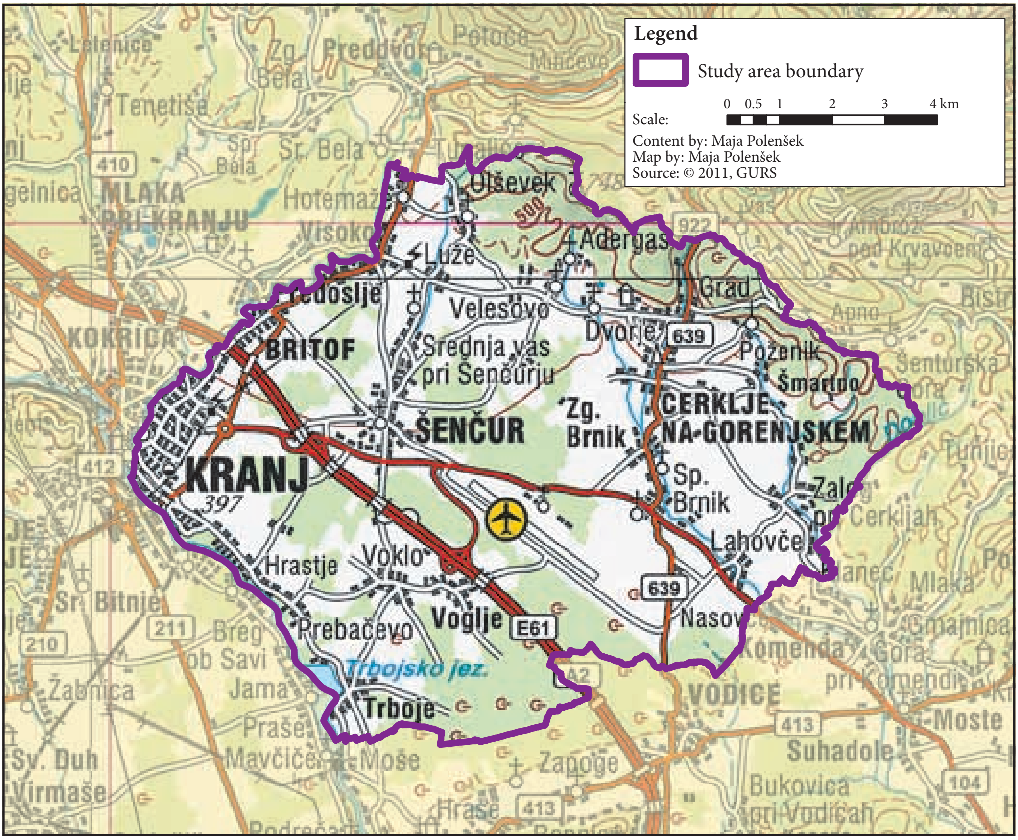

Figure 1: Study area.

suggested the indicators *IIC* and *PC* and their three fractions, and the indicator *BC* to calculate habitat connectivity and availability. These indicators should provide a sufficiently broad picture of habitat connectivity and availability without the unnecessary duplication of indicators.

The Betweenness Centrality (*BC*) indicator is a centrality measure, which means it measures how often a specific node lies on the shortest path between all pairs of nodes. It is expressed with the following equation (Zetterberg 2011):

$$BC_k = \sum_i \sum_j \frac{g_{ij}(k)}{g_{ij}} \tag{1}$$

g_{ij} = the number of the shortest paths between *i* and *j*,
$g_{ij}(k)$ = the number of the shortest paths actually crossing node *k*.

Bodin and Norberg (2007) successfully used this indicator to identify the connecting patches between habitat patches. The Integral Index of Connectivity (*IIC*) is expressed as (Pascual-Hortal and Saura 2006):

$$IIC = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} \frac{a_i a_j}{1 + nl_{ij}}}{A_L^2} \tag{2}$$

where a_i and a_j are the areas of habitat patches *i* and *j*, nl_{ij} is the number of all the links on the shortest path between patches *i* and *j*, and A_L is the total landscape area (the habitat and the matrix).

IIC is based on a binary connectivity model, which means that two patches are either connected or not (e.g., because the distance is too great) with no intermediate modulation of the connection strength (Saura and Pascual-Hortal 2007).

The Probability of Connectivity (*PC*) indicator is a measure that reflects the availability of a given habitat within a landscape. It is defined as the probability that two randomly placed points within the landscape fall into habitat areas that are reachable from one another (interconnected) given a set of *n* habitat patches and the direct connections between them (p_{ij}; Saura and Pascual-Hortal 2007). It is expressed with the following formula:

$$PC = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} a_i a_j p_{ij}^{*}}{A_L^2} = \frac{PCnum}{A_L^2} \tag{3}$$

where a_i and a_j are the areas of habitat patches *i* and *j* (they can also refer to some other patch characteristic such as quality, core area, habitat suitability, etc.), A_L is the total landscape area (the habitat and the matrix), and p_{ij}^{*} is the maximum product probability of all possible paths between patches *i* and *j*.

The significance of an individual habitat patch is computed from the variation in *PC* (dPC_k) or *IIC* ($dIIC_k$) caused by the removal of each individual element from the landscape (Saura and Rubio 2010):

$$dPC_k = 100 \cdot \frac{PC - PC_{remove,k}}{PC} = 100 \cdot \frac{\Delta PC_k}{PC} \tag{4}$$

where dPC_k is the importance of element *k* for maintaining overall habitat availability in the landscape, *PC* is the metric value in the original intact landscape where all elements including *k* are present, and $PC_{remove,k}$ is the metric value after the removal of *k*.

The dPC_k (or $dIIC_k$) values can be composed of three distinct fractions considering the different ways in which a certain landscape element *k* can contribute to habitat availability and connectivity in the landscape (Saura and Rubio 2010):

$$dPC_k = dPCintra_k + dPCflux_k + dPCconnector_k \tag{5}$$

- $dPCintra_k$ is the habitat connectivity or availability within patch *k* that depends on patch characteristics such as habitat area or quality (e.g., the state of its conservation) and is independent of how patch *k* may be connected to other patches;
- $dPCflux_k$ is the area-weighted dispersal flux through the connections of patch *k* to or from all of the other patches in the landscape when *k* is either the starting or ending patch of that connection or flux. It depends on the attribute of patch *k* and its position within the landscape network. It measures how well patch *k* is connected to other patches rather than how important that patch is for maintaining connectivity between the rest of the patches;
- $dPCconnector_k$ is the contribution of patch or link *k* to the connectivity between other patches as a connecting element between them. It depends only on the topological position of a patch or link in the landscape network.

2.2 Producing a resistance digital data layer

Forest animals that also feed on farmland were used as hypothetical species for determining the relative resistance of individual land-use types. Resistances used by Adriaensen et al. (2003) were used as a basis and adjusted to individual land-use type (Table 1). A smaller number indicates lower resistance for crossing a certain land-use type, and a larger number indicates higher resistance. Forestland has the lowest resistance and represents the graph nodes. The woody growth outside the forest was assigned the same resistance as the forest areas, but it does not form nodes because its area is too small. Regardless of the crop type, farmland was assigned a slightly higher resistance because it mostly does not provide the same shelter as forest areas. Infrastructural areas were divided into highways, state roads, and major municipal roads that differ from one another largely by the volume of traffic and the average vehicle speed. With regard to freeways, passages were also taken into account (primarily underpasses in this case). Freeways, urban land,

and bodies of water, which represent a relative rather than absolute barrier for many animal species, were identified as land types that are the most difficult to cross. In determining the resistance of land-use types that are the most difficult to cross, the findings of Driezen et al. (2007) were taken into account. They show that the distinct difference between the resistances of land-use types that are more difficult to cross and those that are easier to cross is vital in determining resistance.

Table 1: Cell resistance by individual land-use type (Polenšek 2015).

Land-use type	Cell resistance
Forestland (habitat)	1
Trees and shrubs (woody growth)	1
Farmland	5
State roads	20
Municipal roads	10
Urban land	200
Bodies of water	200
Freeways	200
Freeways (municipal road underpass)	50
Freeways (forest road underpass)	30
Freeways (bridge across a river)	20

The land-use vector digital data layer (Grafični podatki RABA … 2012) was converted into a raster data layer with a 1 × 1 m cell size using ArcMap/ArcInfo10.0 in order to correctly capture the line elements and the smallest woody growth (individual trees). The reviewed land-use raster data layer was exported into GEOTIFF format.

2.3 Computing forest patch connectivity

The edge-to-edge inter-patch connections were computed using the *Graphab* 1.1 software package (Foltête, Clauzel and Vuidel 2012), which makes possible calculations across larger areas with a high raster resolution. This software computes the least-cost distances by using Dijkstra's algorithm (Foltête, Clauzel and Vuidel 2012). The movement cost was computed by adding up all of the cell costs within a connection. A connection is measured from the center of the neighboring cell, whereby its cost corresponds to half of the sum of both cells' costs. In the case of a diagonal movement between two cells, the cost sum is multiplied by (Drielsma, Manion and Ferrier 2007).

2.4 Habitat connectivity and availability

The indicators were computed using *Conefor* 2.6 (Saura and Torné 2009) based on the data charts exported from the *Graphab* 1.1 software package (Foltête, Clauzel and Vuidel 2012). Computations were made for inter-patch distances ranging from 100 to 20,000 m at 100 m intervals. For every distance, the relative contribution of the intra, flux, and connector fractions for the *dIIC* and *dPC* indicators was calculated (Saura and Rubio 2010):

$$\theta PCfraction = \frac{\sum_{k=1}^{n} dPCfraction_k}{\sum_{k=1}^{n} dPC_k} \tag{6}$$

Based on an analysis of distances up to 20,000 m across the entire landscape, the distances with the greatest changes in the *dPC* and *dIIC* metric values were identified.

2.5 The most important connecting patches

Baranyi et al. (2011) established that the indicators *BC*, *dIICconnector*, and *dPCconnector* are the most successful among the thirteen indicators most commonly used for identifying the most important connecting patches. They are used to assess not only how well a specific patch is connected with other patches, but also how important it is for maintaining connectivity.

The method of ranking forest patches by priority in terms of their contribution to connectivity was adopted from Lee, Woddy, and Thompsonu (2001), whereby forest patches were ranked by individual indicators (*BC*, *dIICconnector*, and *dPCconnector*). Then their rankings were added up, based on which a new cumulative ranking was defined. For selected movement distances, forest patches were ranked in *IBM SPSS Statistics 21* such that a ranking of 1 was ascribed to the forest patch with the highest score for individual indicator. All of the three indicator rankings by individual forest patch were added up and based on the ranking sums the forest patches were ranked such that the highest ranking was ascribed to the patch with the lowest-ranking sum.

Forest patches were divided into three groups according to their contribution to connectivity: connecting patches with high impact, connecting patches with low impact, and patches with no impact on connectivity. Based on the indicator-based forest-patch contribution to connectivity within various distances of movement, the first twenty forest patches within the same ranking were ranked under the first group. These patches contribute the most to connectivity according to all three indicators. The second group included forest patches that still have some impact on connectivity in terms of the indicators selected. The last group included those that do not contribute anything to connectivity in terms of any of the three indicators selected.

3 Results

The study area includes 150 forest patches that are connected with 268 functional links. The number of links depends on the longest possible movement distance: the longer the distance, the more links between the forest patches. The threshold where the number of links no longer increased was recorded at a distance of 14,400 m. The distances ranged between 4 and 14,361 m and the median distance was 2,289 m.

3.1 Forest-patch contribution to maintaining habitat connectivity and availability within various movement distances

The changes in *dIIC* and *dPC*, which depend on the longest possible distances, are presented in Figure 2. The *dIIC* scores change incrementally, with the highest score being reached at distances of up to 2,900 and

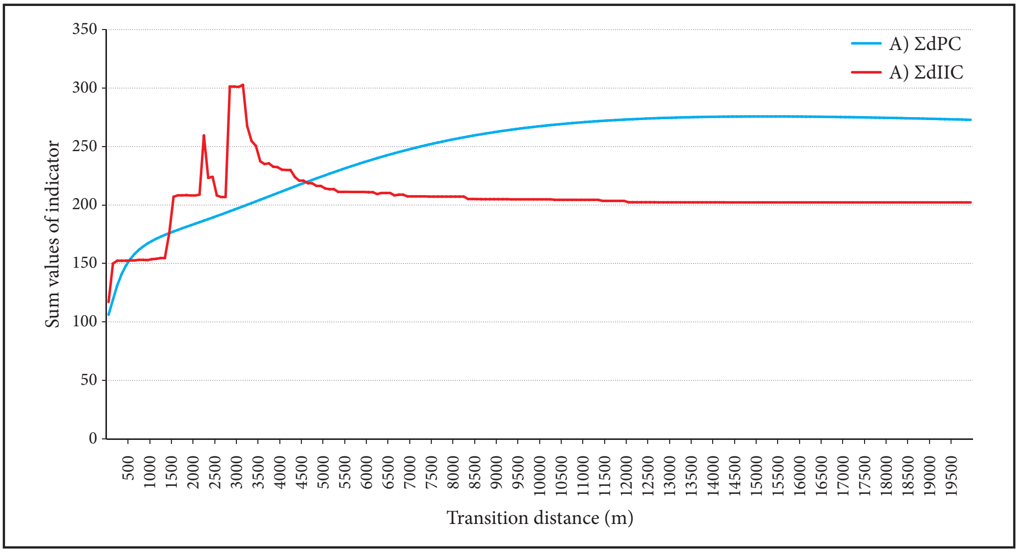

Figure 2: Sums of indicator changes.

3,000 m, and the second-highest scores being reached at distances of up to 200, 1,500, and 2,300 m. The *dPC* scores do not show such distinct variations as *dIIC*. The highest score is achieved at a distance of up to 15,500 m. Slightly greater changes in the *dPC* indicator are evident within distances of up to 700 or 800 m and 7,300 m. Within these distances, the importance for connectivity is the greatest, and the role of patches in maintaining the connectivity of the overall forest-patch network decreases with the increase in distance.

Individual relative fraction contributions for *dIIC* are presented in Figure 3. Within movement distances of up to 100 m, the majority of forest patches are not connected with one another, which is reflected in both the large number of graph components and the high contribution of the *dIICintra* fraction. The contribution of *dIICintra* already decreases significantly within distances of up to 200 m, whereas the contribution of *dIICflux* increases. Within distances of up to 1,500 m, the contribution of *dIICconnector* increases. A major increase in *dIICconnector* then occurs within distances of up to 2,300 m. The *dIICconnector* fraction contributes the most within distances between 2,900 and 3,200 m. Within distances up to 5,100 m, the fraction ratio slowly stabilizes at two-thirds of *dIICflux* and one-fifth of *dIICconnector*, and the remainder pertains to *dIICintra*.

The contributions of the *dPC* fraction are presented in Figure 4. Similarly, the *dPCintra* fraction predominates within short movement distances, whereas *dPCflux* predominates within distances of up to 500 m. Within distances of up to 8,200 m, the ratios slowly stabilize, with one-third pertaining to *dPCconnector*, 9% to *dPCintra*, and the rest to *dPCflux*.

3.2 The most important connecting patches within the movement distances selected

Based on the changes in *dIIC* and *dPC* scores within various distances, the distances where both indicators feature the greatest changes in habitat connectivity and availability were selected. Thus, five distances were selected: 800, 1,500, 3,000, 7,100, and 15,500 m. In Figure 5, forest patches are ranked into three groups by their importance for maintaining connectivity between other forest patches within all five distances.

The area of the twenty most important connecting patches increases with the greatest possible distance, so that they cover 44% of the forest in the study area within distances of up to 800 m, and 86% within distances of up to 15,500 m (Table 2). Forty-one most important connecting patches were identified within all of the distances examined in greater detail. Eight forest patches are important within all distances and eighteen patches only occur within one distance. The areas of important connecting patches range from 0.62 to 718.98 ha, with larger patches predominating.

In addition to the twenty most important forest patches identified, other forest patches also contribute to maintaining connectivity to some degree. With the increase in distance, their number increases from 42 to 70% of all forest patches and, vice versa, their total area decreases from 51 to 13% of the total forest area. A part of the forest patches does not have any impact on connectivity. Just under half (45%) of such patches are within short distances, but they cover only 5% of the total forest area. Their number decreases significantly with distance: to at least as little as one-sixth of all forest patches or 1% of the forest area.

4 Discussion

The Integral Index of Connectivity (*dIIC*) most clearly shows the critical distances because it uses a binary connections model, in which the connection either exists or does not. However, this index divides the landscape

Table 2: Forest patches ranked by importance as connecting patches within various distances ($n = 150$).

	Forest patches					
	Most important connecting patches		Less important connecting patches		Without impact on connectivity	
Distance (m)	*n*	ha	*n*	ha	*n*	ha
800	20	1,728.27	63	1,991.61	67	181.58
1,500	20	1,838.22	71	1,910.21	59	153.03
3,000	20	2,777.40	95	1,067.75	35	56.31
7,100	20	3,371.04	103	482.36	27	48.06
15,500	20	3,355.27	105	499.28	25	46.92

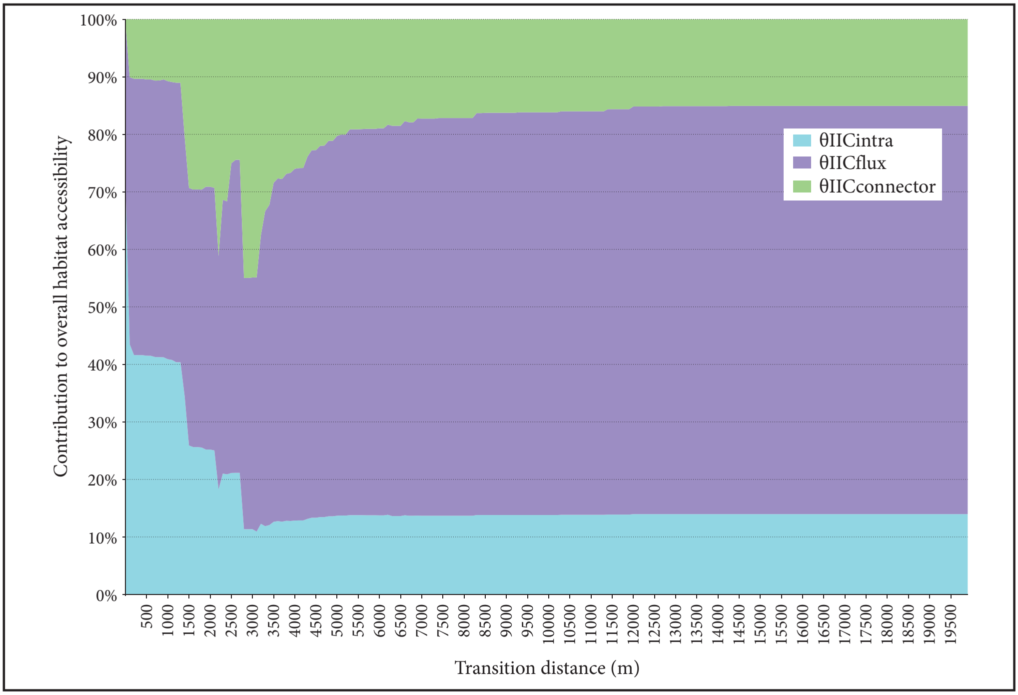

Figure 3: Relative contribution of an individual dIICk fraction.

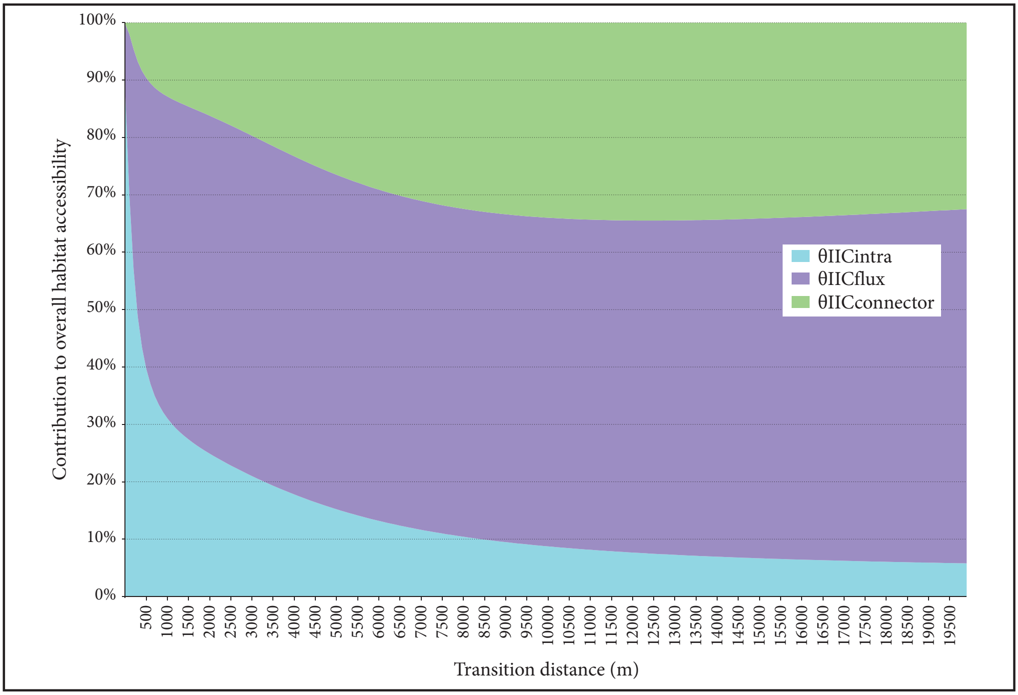

Figure 4: Relative contribution of an individual dPCk fraction.

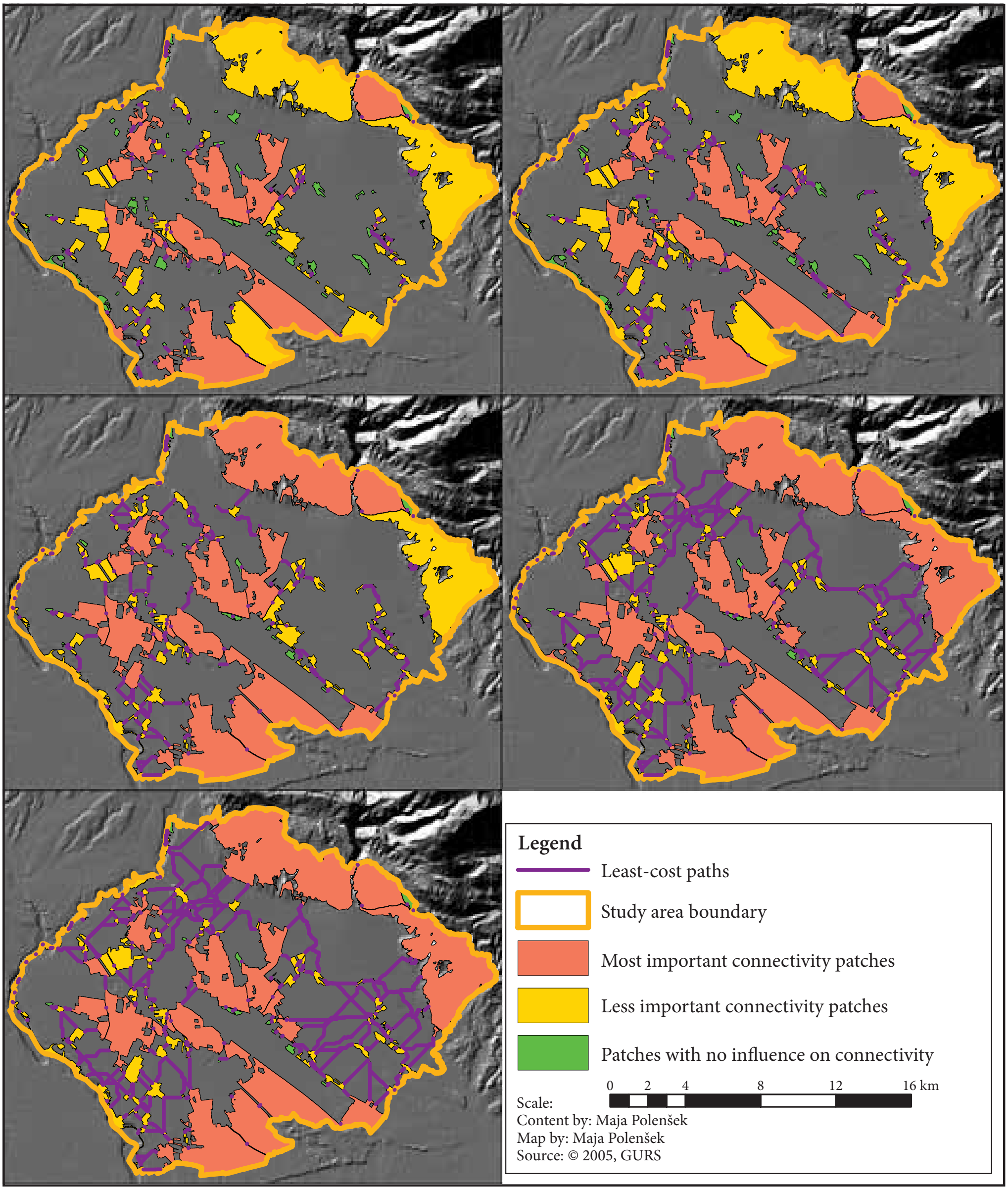

Figure 5: Forest patches by importance.

network into two unconnected parts (Bodin and Saura 2010). With the Probability of Connectivity (*PC*) indicator, the critical distances are much less clear because it uses a probability model, in which the loss of a connecting patch only reduces the amount of flux. Unlike *dIIC*, thanks to the probability model *dPC* also detects changes in landscape network connectivity within longer distances.

Within short distances, the share of connected patches is small, resulting in a higher share of completely isolated patches. The land-use types that are more difficult to cross have a greater impact on movement than those easier to cross. In the case at hand, the negative impact of roads and settlements within short distances is greater than the positive impact of woody growth. The spatial distribution of patches does not play a significant role. The importance of habitat patch connectivity increases rapidly with the increase in the longest possible distance. Within medium distances, the connecting patches are the most important, enabling the connectivity of more remote patches. Contrary to short distances, the areas within the matrix that are easier to cross (in this case, woody growth) have a greater impact. Within longer distances, forest patches again lose importance as connecting patches because of the increased number of direct connections. Remote patches also become interconnected and depend less on the connecting patches. The selection of the most important connecting patches that contribute the most to maintaining habitat connectivity and availability compared to other forest patches showed that large forest patches in particular are the most important because the movement distances increase significantly with their loss. At the same time, they are complemented by smaller forest patches, whose distribution contributes to better connectivity of remote forest patches. A comparison of selected movement distances showed that within all of the distances examined the most important connecting patches do not change significantly.

In Europe, a new 2014–2020 agricultural policy is under preparation, which also includes a green component, for which a third of subsidy funds will be earmarked (Overview of CAP … 2013). This green component will also include areas with ecological significance. Based on the study presented here, as well as other studies, it is recommended that these areas also include habitat-significant forest patches, especially those whose area, close-to-nature structure, and spatial distribution are vital to maintaining spatial connectivity. This especially applies to intensively cultivated landscapes with a small share of natural vegetation, which should include a wide range of forest patches and woody growth typical of individual landscapes.

5 Conclusion

Based on the findings presented here, the main guidelines for maintaining forest-patch connectivity in future clearing of forests in agricultural landscapes can be summed up as follows:

- Individual forest-patch characteristics such as habitat size and close-to-nature structure are the most important for species conservation over short distances;
- Priority should be given to conserving the largest forest patches, especially those with a higher share of core area;
- Priority should be given to conserving all of the most important connecting patches, especially those with the most natural structure;
- When clearing part of a patch, this should be done in a way that divides its shape and affects its core environment as little as possible;
- Forest patches that make it possible to conserve the most vital functions should be maintained;
- Another goal is to conserve larger forest patches, even though their current structure has been severely altered. It is much easier to manage the development of existing forest areas than to plan new ones on predominantly intensively farmed land.

All of these guidelines also have solid support in established literature on landscape ecology (Forman 1995) because the pattern of large natural vegetation patches with corresponding connections is considered the most suitable support for biodiversity conservation in agricultural landscapes.

6 References

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