Ecography

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Supplementary material

Appendix 1.

Figure A1. Some of the MRC simulated landscape patterns generated for three different percentages of habitat cover (10%, 30% and 50%) and a fixed value of the initial probability (p=0.3). In all the cases the image size is 35×35 pixels.

Figure A2. Distribution of the habitat patches for the Black Woodpecker (*Dryocopus martius*), the Tengmalm's Owl (*Aegolius funereus*) and the Capercaillie (*Tetrao urogallus aquitanicus*) in the analysed landscapes. The study area and spatial extent is the same for the three species.

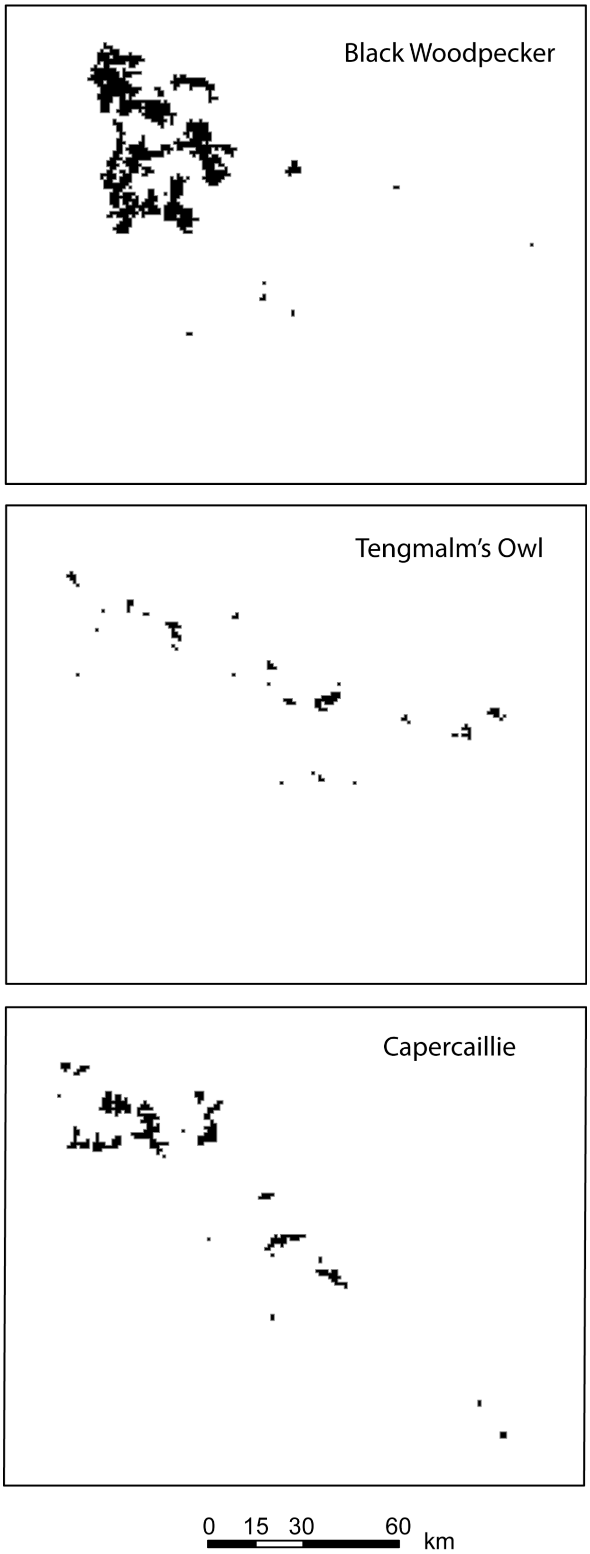

Table A1. Dispersal distances (in pixels) used in the connectivity analysis of the landscape pattern simulations for each amount of habitat cover (from 10% to 50%), corresponding to the results shown in Figure 2. These dispersal distances were calculated as the average of the distances where the contribution of the connector fraction of *IIC* and *PC* was highest in each of the ten landscape simulations generated for a given amount of habitat cover.

	Habitat cover (%)				
Metric	10%	20%	30%	40%	50%
IIC	6.7	4.8	3.2	1.8	1.4
PC	5.2	3.9	2.9	2	1.5

Table A2. Simple spatial metrics summarizing the amount and fragmentation of habitat for each of the three bird species in Catalonia (NE Spain).

	Black Woodpecker	Tengmalm's Owl	Capercaillie
Number of habitat patches	17	28	21
Total habitat area (km^2)	876	112	294
Mean patch size (km^2)	51.5	4.0	14.0
Maximum patch size (km^2)	275	26	64

Table A3. Dispersal distances (in kilometers) at which the connector fraction was highest (for *IIC* and *PC*) in the bird species habitat data.

	Black Woodpecker	Tengmalm's Owl	Capercaillie
IIC	1	6	2
PC	2	6	3

Table A4. Mean and standard deviation (SD) of Dif_{ref} values (difference in connectivity loss resulting from the most damaging combined and reference removals) in the ten simulated landscape patterns generated for each percentage of habitat cover. Results are shown separately for each of the three metrics and number of removed patches (*n*). The mean Dif_{ref} values (for 10%, 20%, 30% and 50% of habitat cover) correspond to those shown in Figure 2. Analyses were performed for the distance where the contribution of the connector fraction was highest (see Methods and Table A1 in Supplementary material Appendix 1). The case *n*=1 is not included in this table since in this case all Dif_{ref} values are by definition equal to zero.

	IIC							
	n=2		*n*=3		*n*=4		*n*=5	
Habitat cover (%)	Mean	SD	Mean	SD	Mean	SD	Mean	SD
10 %	14.96	14.99	19.28	18.58	24.36	18.54	42.83	21.36
20 %	8.49	10.54	8.42	13.8	22.1	17.56	32.87	17.8
30 %	9.38	20.25	15.52	22.62	25.62	29.19	16.31	22.21
40 %	9.40	15.23	15.88	20.58	25.48	23.13	34.49	17.93
50 %	10.03	34.35	16.77	26.52	22.46	21.54	40.45	29.63

	PC							
	n=2		*n*=3		*n*=4		*n*=5	
Habitat cover (%)	Mean	SD	Mean	SD	Mean	SD	Mean	SD
10 %	1.66	2.67	8.34	9.75	5.61	9.27	8.37	11.75
20 %	5.25	8.57	3.22	5.97	10.82	13.18	20.81	16.09
30 %	10.79	17.85	6.03	10.32	4.97	10.65	18.61	19.00
40 %	8.68	18.36	1.63	3.83	17.27	15.20	29.00	17.04
50 %	5.12	11.21	14.30	17.10	14.57	16.11	18.13	22.23

	λ_M							
	n=2		*n*=3		*n*=4		*n*=5	
Habitat cover (%)	Mean	SD	Mean	SD	Mean	SD	Mean	SD
10 %	15.02	13.13	38.26	22.32	41.26	30.67	39.45	32.7
20 %	13.81	17.47	25.86	22.7	38.6	25.62	40.87	25.3
30 %	28.95	26.75	50.30	25.41	38.83	31.30	47.30	24.13
40 %	16.05	27.19	16.35	17.67	42.59	16.26	59.68	29.16
50 %	16.62	25.32	29.62	25.53	49.45	32.08	55.19	33.86

Table A5. Percentage of all possible combined removals that were more detrimental for connectivity than the most damaging reference removal (P_{worse}) for the simulated landscape patterns and when the number of removed patches was n=5. The table shows, separately for each of the three considered metrics (*IIC*, *PC* and λ_M), the mean and maximum P_{worse} values for the ten simulated landscape patters generated for each amount of habitat cover (ranging from 10 to 50% of total landscape area). Results for n=5 are shown because it is for this number of removed patches when the largest P_{worse} values were found in the simulated patterns.

	IIC		*PC*		λ_M	
Habitat cover (%)	Mean	Maximum	Mean	Maximum	Mean	Maximum
10 %	0.172	0.772	0.005	0.023	1.264	7.467
20 %	0.042	0.161	0.009	0.059	0.586	3.636
30 %	0.057	0.294	0.007	0.026	0.312	0.999
40 %	0.027	0.119	0.010	0.045	0.320	2.362
50 %	0.057	0.318	0.010	0.072	0.299	1.626

Table A6. Percentage of all possible combined removals that were more detrimental for connectivity than the most damaging reference removal for the three forest bird species habitat distribution data. Results are shown for the three analysed metrics (*IIC*, *PC* and λ_M), for different numbers of removed patches (*n*), and both for the species dispersal distance and for the distance at which the connector fraction of the *IIC* and *PC* metrics was highest in the habitat patterns of each species (the same distance was used for PC and λ_M). Computational limitations did not allow computing all possible patch removal combinations when *n*=5 for the Tengmalm's Owl (the species with the largest number of habitat patches), as indicated by N/A.

	Results for the species dispersal distance											
	Black Woodpecker				Tengmalm's Owl				Capercaillie			
	n=2	*n*=3	*n*=4	*n*=5	*n*=2	*n*=3	*n*=4	*n*=5	*n*=2	*n*=3	*n*=4	*n*=5
IIC	0	0	0	0	0	0	0	N/A	0	0.013	0	0.001
PC	0	0	0	0	0	0	0.001	N/A	0	0.013	0	0.001
λ_M	0	0	0	0	0	0.010	0.013	N/A	0.238	0.063	0.102	0.050

	Results for the dispersal distance at which the contribution of the connector fraction is highest											
	Black Woodpecker				Tengmalm's Owl				Capercaillie			
	n=2	*n*=3	*n*=4	*n*=5	*n*=2	*n*=3	*n*=4	*n*=5	*n*=2	*n*=3	*n*=4	*n*=5
IIC	0	0	0	0.001	0	0.010	0.013	N/A	0	0	0	0.001
PC	0	0	0	0	0	0.025	0.011	N/A	0	0.013	0	0.001
λ_M	0	0	0.001	0	1.323	2.590	3.567	N/A	0.476	0.376	0.493	0.167

Appendix 2

This appendix describes (i) why and how the generalized network centrality metrics were included in the patch removal experiments, in order to evaluate if the incorporation of these metrics allowed obtaining a more robust set of priorities that would better represent the contribution of the patch when further habitat losses may accumulate in the landscape and (ii) the results obtained in this respect.

i. Motivation and methods

Bodin and Saura (2010) related the *dIIC* and *dPC* values to the Betweenness Centrality metric (*BC*) (Freeman 1977), which captures how much a patch sits in between the shortest or more favourable movement routes between other patches. Furthermore, *BC* was generalized to better account for the ecological impacts of varying habitat patch area (or quality) and decreased dispersal probabilities over longer distances, and to match with the analytical framework of the *IIC* and *PC* metrics (Bodin and Saura 2010). The resultant generalized centrality metrics (BC^{IIC}, BC^{PC}) were integrated in a common modelling framework for assessing patch importance, allowing to link patch removal experiments with network analysis in the intact landscape. Bodin and Saura (2010) showed that the centrality metrics were able to capture some aspects related to the network vulnerability and reorganization after disruptions, which could be of interest to assess how much the loss of a given habitat patch affects the vulnerability of the network to further patch removals. For this reason, we here examined if the BC^{IIC} and BC^{PC} metrics , which provide patch-level values without need for removal experiments, could be used as a practical and additional criteria for patch prioritization that, combined with the individual patch removals, may reduce the potential differences between the combined and reference removals. Such analysis was only tackled for the *dIIC* and *dPC* metrics because these metrics are those that have been integrated in a single analytical framework and units of measurement with the network centrality metrics (Bodin and Saura 2010), which is not the case for λ_M.

For this purpose, we normalized (μ = 0 and σ = 1) the values of the *dIIC*, *dPC*, BC^{IIC} and BC^{PC} metrics, resulting in $dIIC_{norm}$, dPC_{norm}, BC^{IIC}_{norm} and BC^{PC}_{norm} normalized values. We generated new patch importance values (*X*) that accounted both for $dIIC_{norm}$ or dPC_{norm} and for BC^{IIC}_{norm} and BC^{PC}_{norm} respectively, with a given relative weight *y* for the latter (ranging from 0 to 1):

$$X = dIIC_{norm} * (1 - y) + BC^{IIC}_{norm} * y$$

$$X = dPC_{norm} * (1 - y) + BC^{PC}_{norm} * y \qquad \text{(Eq. 1)}$$

The composite metric *X* was used to rank the patches by their importance for connectivity and therefore to obtain the new least damaging and most damaging reference removals (similarly to what described in the previous section for *dIIC*, *dPC*, and $d\lambda_M$) but now accounting for patch centrality considerations. We calculated *X* and the reference removals in all the landscape pattern simulations for *n*=5 (because we expected larger differences between the combined and reference removals for larger *n*) and for 11 values of *y* uniformly distributed in the range from 0 to 1.

ii. Results

Incorporating the generalized network centrality metrics in the prioritization of individual habitat patches did not significantly increase the similarities between the most damaging reference and combined removals compared to what given by *IIC* or *PC* alone. The increases in similarities by incorporating the centrality metrics in the reference removal were anecdotal; they never decreased the Dif_{ref} values by more than 5-10% (e.g., Dif_{ref} from 20% to 19% or 18%), and that only occurred when a moderate weight was given to the centrality metrics in the prioritization procedure (low values of *y*). These results were obtained independently of the habitat amount in the landscape simulations and of the type of metric considered (either binary or probabilistic).

References not cited in the main text

Freeman, L. C. 1977. Set of measures of centrality based on betweenness. – Sociometry 40: 35–41.

Appendix 3.

This appendix describes and discusses the reasons why the reported differences between the most damaging combined and reference removals were:

(i) smaller for the habitat availability (reachability) metric based on a probabilistic connection model (PC) than for the equivalent metric based on a binary connection model (IIC),

(ii) smaller for the habitat availability (reachability) metrics than for the metapopulation capacity,

(iii) smaller when the connectivity analysis was performed for larger dispersal distances (more mobile species).

i. IIC vs. PC: binary vs. probabilistic network models

IIC and *PC* share the same conceptual and analytical background (connectivity measured as the amount of reachable habitat in the landscape) but differ in the network model they use for assessing connectivity (i.e. binary/unweighted links for *IIC*, and probabilistic/weighted links for *PC*). Therefore is in this latter aspect where we should find the explanation for the different results here obtained for *IIC* and *PC*. Previous studies have reported the differences in the patch prioritizations provided by each of these metrics and, more importantly, the higher importance that *IIC* assigns to stepping stones or connecting elements compared to *PC* (Bodin and Saura 2010, Baranyi et al. 2011, Rubio and Saura 2012). Since a binary network may more sharply depend on the presence of a particular habitat patch than a probabilistic network, the impact of losing an individual connecting element is generally higher for *IIC* than for *PC*, which also translates into a higher difference between the most damaging reference and combined removals here found for *IIC* in most of the cases (Fig. 2).

ii. Metapopulation Capacity: the metrics that do not account for connectivity within patches are more sensitive to the way patch removals are assessed

The Metapopulation Capacity (λ_M) is basically computed from a matrix of probabilities and information on habitat patch areas, which is the same type of input as for the *PC* probabilistic metric. However, the differences between the reference and combined removals were much higher for λ_M than for *PC*. λ_M was the metric that provided the least reliable results when trying to identify, through single patch removals from the initial landscape, the set of patches that actually turned out to be (when all possible combinations were tested) the most damaging as measured by λ_M itself (Table 1, Figs. 2 and 3). In addition, for λ_M we found that in some cases up to almost 8% of all the possible combined removals actually had more detrimental effects than the reference removal identified for this metric, while the same figure was always below 0.8% and 0.08% for *IIC* and *PC* respectively. To explain the reason for such results, we have to recall the conceptual and analytical differences between λ_M and the habitat availability (reachability) metric *PC* (or *IIC*). *PC* quantifies both connectivity within and among habitat patches when setting conservation priorities, while λ_M assigns no value to an isolated patch even if it is large and contains a large amount of habitat resources (Saura and Rubio 2010). The amount of connected habitat within patches (intrapatch connectivity) is independent of the spatial relationships or interactions with other habitat patches in the landscape and, therefore, it is not affected at all by whether other patches have been previously removed from the landscape or not. Accounting for the connectivity within habitat patches increases stability in this type of prioritizations of habitat patches for connectivity conservation. For this reason, those metrics that, like *PC*, jointly consider intrapatch and interpatch connectivity, will produce comparatively more similar reference and combined removal sequences than those only accounting for interpatch connectivity (such as λ_M).

iii. Conservation priorities are easier to set for species with large dispersal abilities

When species have poor movement abilities, the amount of habitat resources they can use is largely determined by the habitat area and quality within the patches where they dwell (intrapatch connectivity), given their little chances of reaching other resources in distant habitat patches (Saura and Rubio 2010). For this reason, and considering the stability to conservation priorities given by the within-patch component of connectivity as described above, we found for the habitat reachability metrics *IIC* and *PC* a higher similarity between the reference and combined removals for very short dispersal distances, while quite the opposite occurred for λ_M. The importance of a patch in terms of the expected amount of dispersal flux it can receive (the aspect basically considered by λ_M) is, for short dispersal distances, largely dependent on whether immediately neighbouring habitat patches exist or not, and therefore, dependent as well on whether these patches have been previously removed or not from the landscape. Hence, if habitat losses affect any of those typically very few nearby habitat patches, the assessed importance of the remnant focal patch can decrease sharply, which is reflected in the large differences between the most damaging reference and combined removals for λ_M particularly for short dispersal distances (Fig. 3).

On the contrary, when the dispersal abilities are very large, any patch is strongly connected to all other patches in the landscape. The ability of such a mobile species to successfully reach other habitat patches does not depend on the existence of other intermediate stepping stone patches. Therefore, such ability is largely maintained independently of whether some other patches have been previously removed from the network or not (i.e. there would be a lower sensitivity to the changes and habitat losses in the surrounding areas). For this reason, we found that the differences between the reference and combined removals tended to vanish for large dispersal distances for all metrics (Fig. 3). For species with large dispersal abilities, the conservation priorities can be set with much more confidence, i.e. with much less concern on the particular way (spatial arrangement) in which the habitat losses in the rest of the landscape may happen in the future.

References not cited in the main text

Baranyi, G. et al. 2011. Contribution of habitat patches to network connectivity: redundancy and uniqueness of topological indices. – Ecol. Indic. 11: 1301–1310.

Rubio, L. and Saura, S. 2012. Assessing the importance of individuals habitat patches as irreplaceable connecting elements: an analysis of simulated and real landscape data. – Ecol. Complex. 11: 28–37.