Intra-network Analysis Based on Comparison Between Graph Theory Approach and Pathwalker

Giovanni Lumia[1], Samuel Cushman[2], Salvatore Praticò[1], and Giuseppe Modica[3](✉)

[1] Dipartimento di Agraria, Università degli studi 'Mediterranea' di Reggio Calabria, Reggio Calabria, Italy
giovanni.lumia@unirc.it

[2] Wildlife Conservation Research Unit, Department of Biology, University of Oxford, The Recanati-Kaplan Centre, Tubney House, Tubney, Oxon OX13 5QL, UK

[3] Dipartimento di Scienze Veterinarie, Università degli studi di Messina, Messina, Italy
giuseppe.modica@unime.it

Abstract. Today there is increasing investigation of how to succeed in land operations without damaging delicate natural ecosystems. Over the past century, the planning of land interventions operated without following a guideline has led to fragmentation of ecosystems and progressive biodiversity loss. Several strategies have emerged in this regard to identify corridors and protected areas on the territory. It is important to compare the very many strategies in the scientific landscape in order to assess the levels of correlation present among them and to understand how to be able to exploit the products of the analyses in our favor in the planning sphere on a territory threatened by pressing anthropization. The present work compared movement simulations produced by Pathwalker software and corridors identified on the territory by Graphab software. In particular, we took advantage of Pathwalker's ability to evaluate movement predictions by taking into account factors such as mortality risk, attraction and energy in the simulation. This work was important because it allowed to classify predictions according to scales of reliability. In particular, we classified the connectivity indices obtained from the elaborations in Graphab according to 4 levels of reliability ranging from a high degree of consistency to a low degree of consistency. Pathwalker simulations were compared to the above indices to assess similarities and differences. This work is important as it allows to give exploit the combination between different connectivity prediction models provide concrete tool to the planner at decision making time.

Keywords: Graph theory · Pathwalker · Comparison · Ecological network

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2023
O. Gervasi et al. (Eds.): ICCSA 2023 Workshops, LNCS 14107, pp. 300–309, 2023.
https://doi.org/10.1007/978-3-031-37114-1_20

1 Introduction

Understanding what techniques and approaches should be followed to protect the environment and habitat loss is one of the hottest topics of scholarly debate in the last century [1–4]. The importance of proper planning of land interventions to avoid fragmentation and loss of biodiversity is now well known. Scientists are questioning what strategies should be followed to give the planner a tool. Numerous approaches based on ecological networks according to single-species or multi-species considerations, graph theory for identifying and weighing network elements, circuit theory, and resistance kernels for simulating animal movements on the land are present in the debate [5–8]. A promising and recent new strategy for simulating movement patterns is Pathwalker [9]; it takes into account in the simulation parameters such as energy, mortality risk, attraction and coefficient that allow the evaluation of an animal's tendency to continue along a direction. Through such additions Pathwalker makes it possible to fill some of the gaps that were often created in more common approaches [10]. In this work we decided to combine graph theory and Pathwalker simulations to evaluate the reliability of the predictions. Initially through graph theory we identified patches, nodes, edges and calculated several connectivity indices commonly used in the literature for evaluating network elements. In a second step we divided according to four levels of consistency values of 3 connectivity indices calculated in Graphab environment. Finally, we divided each connectivity index into 4 consistency levels and used pathwalker motion simulations to evaluate the response of each of the 4 levels.

2 Materials and Methods

2.1 Base Data

The work was carried out on the Reggio Calabria metropolitan area (Fig. 1) over an area covering 47,822.63 ha and including 12 municipalities. The area includes historical buildings [11], cultivated and wooded hilly and mountainous areas and includes beaches and part of the Aspromonte National Park (blue dashed in Fig. 1). The data used in the connectivity simulations come from databases produced in the European context of the Copernicus project (https://land.copernicus.eu/ - last access 30/06/2022). In particular, we have jointly used Corine land Cover data as of 2018 (CLC 2018, which has high level of thematic detail for natural and semi-natural areas) and Urban Atlas as of 2018 (UA 2018, which has high level of thematic and geometric detail for man-made areas). Recent work on the same study area has shown that the combined use of these two data allows for more accurate movement pattern simulations [12].

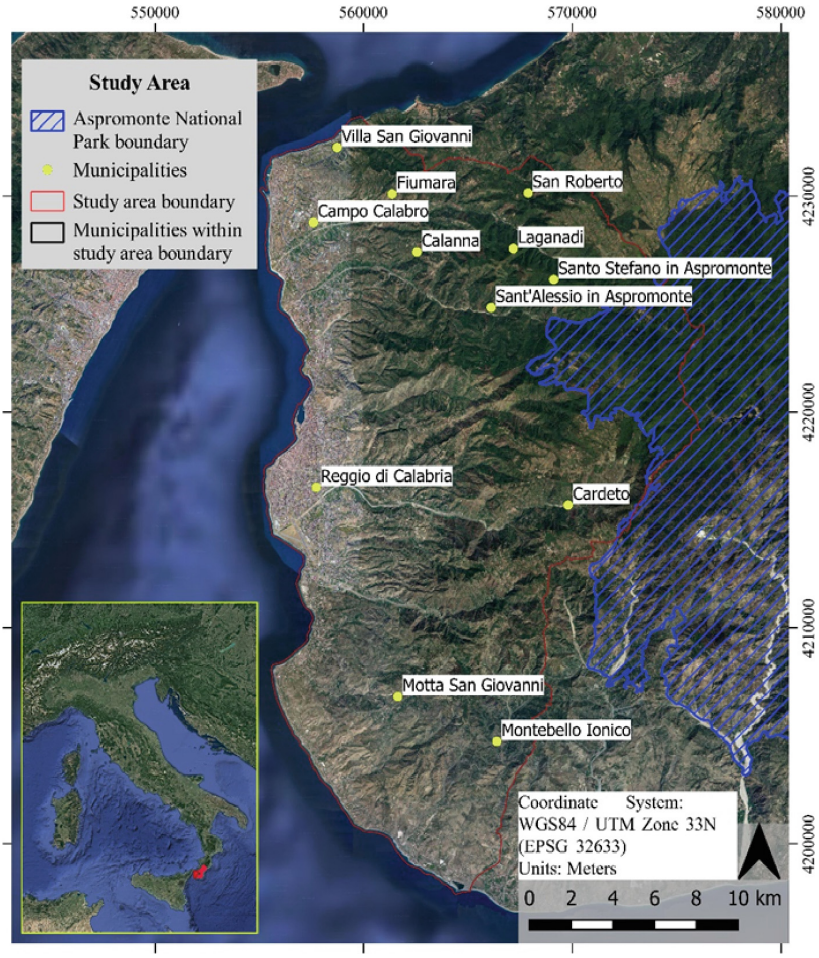


Fig. 1. Geographical location of the study area, in dashed blue the Aspromonte National Park area, in yellow the municipalities within the study area, in red the study area boundary.

The simulations were performed taking into consideration the requirements of 10 selected focal species considering the works in the same area [12–15]. Autoecological information on the species (dispersal distance, home range, habitat suitability) was retrieved from the database on Italic fauna produced by Boitani et al. [16].

2.2 Data Processing

For the first processing done in Graphab, we used the combined map of CLC and UA as the basis on which to perform the simulations. The subsequent considerations that we will list below regarding resistance to movement (understood as the property of the landscape to oppose animal passage with greater or lesser force), home range (understood as the area needed for a species to be able to carry out all primary life functions) and dispersal threshold (understood as the maximum distance an animal can travel to move from one patch to another) were made on the basis of the autecological data collected by Boitani listed in the National Ecological Network (REN) sheets [17].

For each of the different land use codes, we assigned a value indicating the resistance these environments offer to animal movement in the simulation. Specifically, the land use map was rasterized and resistance values were assigned to each pixel corresponding to the respective land use. The raster was initially at a resolution of 2.5 × 2.5 m later resampled to 10 × 10 m by a bilinear interpolation function, this operation made it possible to lighten processing without losing information about smaller elements in the map (streets and isolated buildings). The assigned values range from 1 (least resistance to movement) to 100 (greatest resistance to movement). The dispersal threshold was set at 2 km, whereas 2 km is a value that allows each of the 10 focal species to move from patch to patch, as seen in previous work on the same area [12]. The minimum home range extension was set at 2 ha following the same assumption made for dispersal threshold. Patches of area inferior to 2 ha were still considered as suitable areas (stepping stones) for animal movement over the territory [18]. Having set all these parameters within the Graphab software we obtained a graphical visualization of the network, composed of nodes, patches, edges, links, and on it we calculated the Integral Index of Connectivity (IIC) [19], Betweenness Centrality index (BC) [8] and Probability of Connectivity (PC) [20] using the Graphab 2.8 software functions.

At this point, starting from the raster data of land use and, using as source points the graph nodes obtained in the previous elaborations in Graphab [21], we formed the basis for launching the following operations in Pathwalker. In particular Pathwalker allows to simulate movements considering three parameters which are energy (mechanism1), risk (mechanism 2) and attraction (mechanism 3) and four different combinations of them (mechanism 4, 5, 6 and 7). For this work we decided to operate with mechanism 7 which is the combination of all three energy, risk and attraction. In addition, we used a parameter to consider in the simulation the tendency of a moving animal to continue on the same path or to change direction. This parameter ranges from 0 (minimum tendency to change direction) to 1 (maximum tendency to change direction); we set it at 0.25. Operations were produced by setting all of these parmeters within the Pathwalker environment and launched through Anaconda's Powershell Prompt.

We then went on to categorize the values of the connectivity indices calculated in Graphab into four levels of consistency for each of IIC, PC and BC. Subsequently, the level of correlation (using Pearson correlation coefficient) with pathwalker simulations was evaluated for each level using RStudio environment.

3 Results

Here we present results regarding network created by graph theory, obtaining predictions of movement patterns by Pathwalker simulations, and comparing the two methods to identify points of affinity or disagreement.

The network obtained by Graphab consists of 328 nodes that resulted in the same number of patches with an average area of 26 ha. The patches cover 8549.91 ha, and the areas most represented by them are the environments classified as forested areas (76% of the total number of patches). Generally, the largest patches are located in areas far from population centers, hilly and mountainous areas, while the smaller patches with greater distance between each other are near population centers and closer to the coast.

Table 1. Overall connectivity indices calculated on the implemented ecological network. See Lumia et al. [12].

Connectivity Indices	Overall
Integral Index of Connectivity (IIC)	0.032
Probability of Connectivity (PC)	0.033
Betweenness Centrality (BC)	0.25

The connectivity indices analyzed tended to have higher values in mountainous and hilly areas than in flat areas and closer to the coast. The values of the connectivity indices IIC, BC and PC (summarized their overall values in Table 1) were divided into 4 levels raging from lower to higher values (Fig. 2, top right, top center and top left) and correlated with the values and of the Pathwalker simulation (Fig. 2 bottom center).

The correlation values (shown in Fig. 3) showed a negative correlation for thresholds 1, 2 and 3 of BC (BC1, BC2 and BC3), thresholds 1, 2 and 3 of PC (PC1, PC2 and PC3) and threshold 1 of IIC (IIC1). In contrast, a positive correlation was found for threshold 4 of BC (BC4), thresholds 4 of PC (PC4) and thresholds 2, 3 and 4 of IIC (IIC2, IIC3 and IIC4).

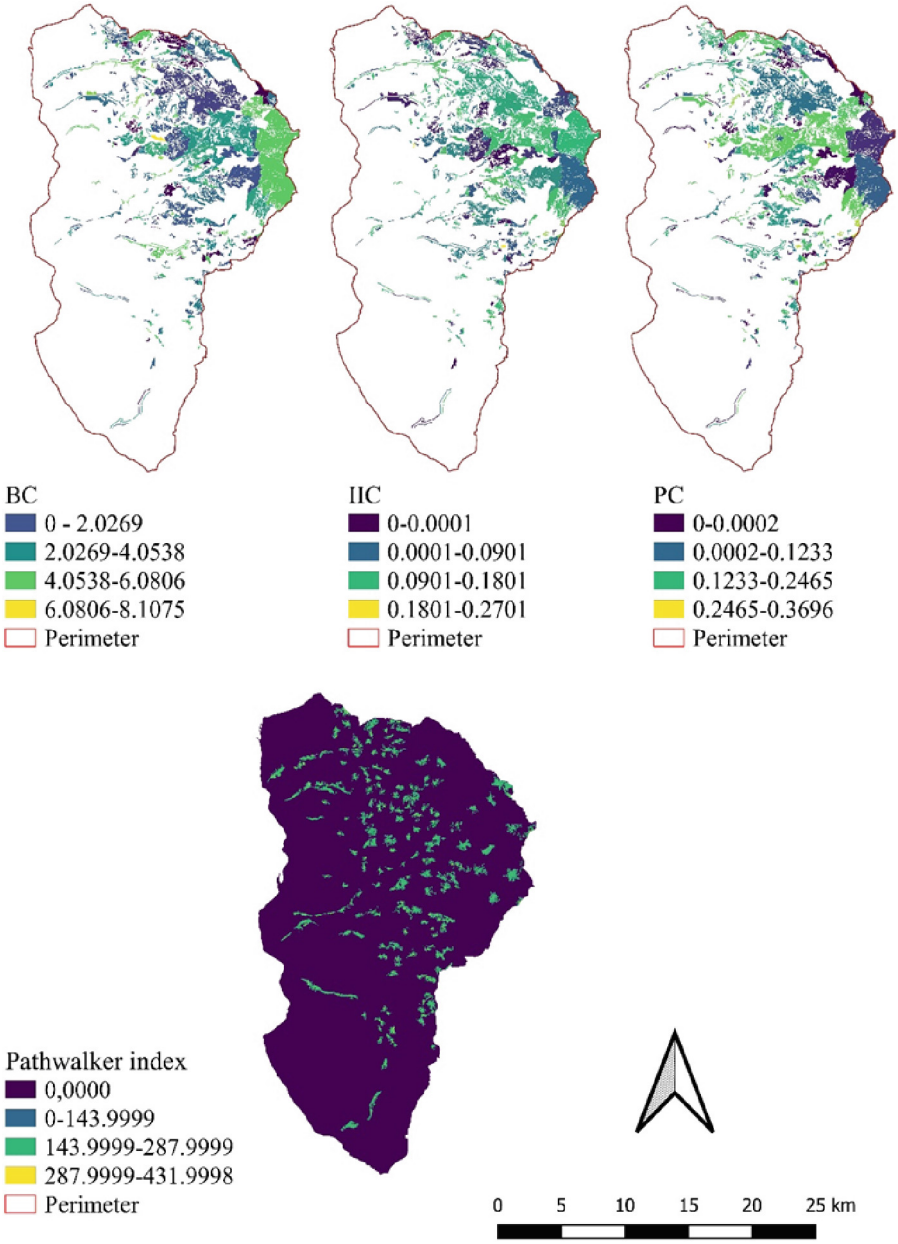


Fig. 2. Pathwalker index (bottom left) and connectivity indices for Betweenness Centrality (top left), Integral Index of Connectivity (top center) and Probability of Connectivity (top right) according to a 4 classes division raging from lower to higher values.

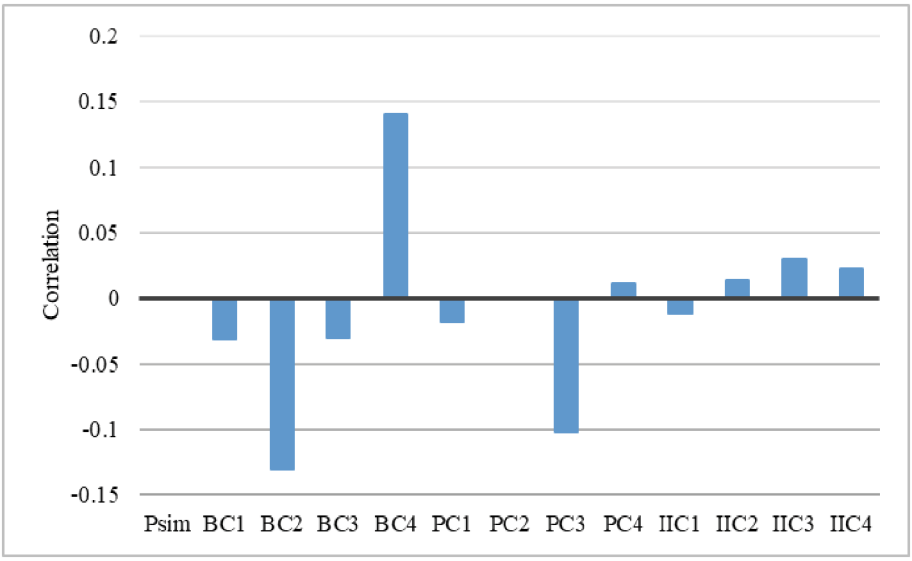


Fig. 3. Correlation values between Pathwalker simulation (Psim) and the 4 thresholds of Betweenness Centrality (BC1, BC2, BC3, BC4), IIC (IIC1, IIC2, IIC3, IIC4) and Probability of Connectivity (PC1, PC2, PC3, PC4).

4 Discussions

A greater number of high area patches in mountainous areas is consistent given the more natural feature of these areas. Indeed, the population centers and areas most occupied by infrastructure and agricultural activities are largely located in the low hill and coastal areas. The trend in the values of the connectivity indices IIC, PC and BC, which were higher near mountainous areas, underscores the greater importance to the network of these areas [12]. Although these results suggest a correct representation of connectivity predictions, correlation analysis with Pathwalker simulations tended to show a negative or slightly positive trend for only a few indices. This was expected. The graphab metrics we used are patch based, and the individual index values refer to the centroids of the patches. In Pathwalker, on the other hand, the movement of the animal is not related to the presence of patches but exploits the mechanism of resistant kernels for simulations. The mechanism of resistant kernels has been shown to be more accurate in predictive terms than the patch-based approach [11–22], this is thus the reason for the general low level of correlation between Graphab and Pathwalker indices. In addition, this phenomenon was expected considering that Graphab does not consider attraction and risk factors. The Pathwalker energy mechanism, understood as the energy budget possessed by an animal that ends its movement when it exhausts it, is the parameter in common with Graphab. The attraction parameter not only evaluates which path is the lowest cost, but also tends to avoid paths where the walker is surrounded by areas of high resistance. The risk parameter, on the other hand, considers the possibility that an animal during a gradually less favorable path will suddenly stop its movement, with a gradually higher probability

as the inhospitality of the area increases. The positively trending correlation values for all category 4 levels of the indices underscores the potential in predictive terms of the joint work of the attraction and risk mechanisms. Returning to the B4, PC4 and IIC4 values, the reason why the correlation levels are higher in these areas seems to be related to the presence of large areas with low levels of resistance that do not have a great effect on the risk and attraction mechanisms. A greater effect on the attraction and risk indices occurs instead where patches become smaller and the distances between them increase. In these areas there emerges an underestimation by the IIC, PC and BC indices against the Pathwalker simulations. We next analyze the effect on the simulation (and on the levels of correlation between Graphab and Pathwalker metrics) of using a parameter that indicates the tendency of a walker to continue along its direction or change path. This parameter is intended to make the animal's movement even more faithful to reality. In fact, in nature, animals exploring the territory may not always choose the path that offers the most resources [23]. For this reason, the effect of taking non-ideal paths in highly fragmented areas is more pronounced. The fact that Pathwalker considers this variable as opposed to Graphab further lowers the correlation levels, especially in the level 1, 2 and 3 areas located in the most fragmented areas.

5 Conclusions

In this work, we compared connectivity metrics and motion simulations to identify network weaknesses and, what factors under certain conditions affect the predictions. Specifically, the values of the IIC, BC and PC metrics were divided into 4 levels of consistency, and for each level, the level of correlation with Pathwalker simulations over the same area was analyzed. It was found that Pathwalker's ability to consider factors such as energy, attraction and mortality risk allows it to provide a higher level of detail in predictive terms. Especially the where the natural areas are found to be more fragmented, considering more behavioral factors allows for a more realistic representation of the animal's movements, which is consistent with what is in the literature [10]. The land use resolution used is undoubtedly a limitation that can be overcome in future elaborations. In particular, for the same study area, a habitat map could be used instead of a simple land use map (the implementation of which was planned under the Natura 2000 context: https://www.isprambiente.gov.it/it/servizi/sistema-carta-della-natura - last access 17/05/2023). The use of other statistical analyses could also be considered in the future to highlight other network characteristics [24]. This work has given rise to new insights into the issues of connectivity prediction. We have shown how the reliability of predictions can vary within the same network in dependence on structural factors (of the network), behavioral factors (of the animal species) and the method used (graph theory and Pathwalker).

References

1. Guo, Y., Liu, Y.: Connecting regional landscapes by ecological networks in the Greater Pearl River Delta. Landsc. Ecol. Eng. **13**, 265–278 (2017). https://doi.org/10.1007/S11355-016-0318-2/FIGURES/8

2. Tarabon, S., Godet, C., Coskun, T., Clauzel, C.: Coupling spatial modeling with expert opinion approaches to restore multispecies connectivity of major transportation infrastructure. Landsc. Urban Plan. **221**, 104371 (2022). https://doi.org/10.1016/j.landurbplan.2022.104371
3. Casas, E., et al.: Macroalgae niche modelling: a two-step approach using remote sensing and in situ observations of a native and an invasive Asparagopsis. Biol. Invasions **23**(10), 3215–3230 (2021). https://doi.org/10.1007/s10530-021-02554-z
4. Spatari, G., Lorè, I., Viglianisi, A., Calabrò, F.: Economic feasibility of an integrated program for the enhancement of the Byzantine heritage in the Aspromonte National Park. The Case of Staiti, pp. 313–23 (2022). https://doi.org/10.1007/978-3-031-06825-6_30
5. Kaszta, Ż, Cushman, S.A., Sillero-Zubiri, C., Wolff, E., Marino, J.: Where buffalo and cattle meet: modelling interspecific contact risk using cumulative resistant kernels. Ecography **41**, 1616–1626 (2018). https://doi.org/10.1111/ecog.03039
6. Wang, G., Cushman, S.A., Wan, H.Y., Liu, M., Jombach, S.: Comparison of least-cost path and UNICOR cumulative resistant kernel analyses in mapping ecological connectivity networks in Luohe Region, China. J. Digit. Landsc. Archit., 176–90 (2022). https://doi.org/10.14627/537724018
7. An, Y., Liu, S., Sun, Y., Shi, F., Beazley, R.: Construction and optimization of an ecological network based on morphological spatial pattern analysis and circuit theory. Landsc. Ecol. **36**, 2059–2076 (2021). https://doi.org/10.1007/S10980-020-01027-3/FIGURES/8
8. Foltête, J.-C., Clauzel, C., Vuidel, G., Tournant, P.: Integrating graph-based connectivity metrics into species distribution models. Landsc. Ecol. **27**, 557–69 (2012)
9. Unnithan Kumar, S., Kaszta, Ż., Cushman, S.: Pathwalker: user guide. n.d
10. Unnithan Kumar, S., Cushman, S.A.: Connectivity modelling in conservation science: a comparative evaluation. Sci. Rep. **12**, 16680 (2022). https://doi.org/10.1038/s41598-022-20370-w
11. Calabrò, F., Iannone, L., Pellicanò, R.: The historical and environmental heritage for the attractiveness of cities. the case of the Umbertine forts of Pentimele in Reggio Calabria, Italy. In: Bevilacqua, C., Calabrò, F., Della Spina, L. (eds.) NMP 2020. SIST, vol. 178, pp. 1990–2004. Springer, Cham (2021). https://doi.org/10.1007/978-3-030-48279-4_188
12. Lumia, G., Praticò, S., Di Fazio, S., Cushman, S., Modica, G.: Combined use of urban Atlas and Corine land cover datasets for the implementation of an ecological network using graph theory within a multi-species approach. Ecol. Indic. **148**, 110150 (2023). https://doi.org/10.1016/j.ecolind.2023.110150
13. Modica, G., Praticò, S., Laudari, L., Ledda, A., Di Fazio, S., De Montis, A.: Implementation of multispecies ecological networks at the regional scale: analysis and multi-temporal assessment. J. Environ. Manag. **289** (2021). https://doi.org/10.1016/j.jenvman.2021.112494
14. Lumia, G., Modica, G., Praticò, S., Cusman, S.: Comparison of patch-based and synoptic connectivity algorithms with graph theory metrics (2023). Under review
15. Lumia, G., Modica, G., Unnithan-Kumar, S., Cushman, S.: Using simulation modeling to demonstrate the performance of graph theory metrics and connectivity algorithms (2023). Under review
16. Boitani, L., Falcucci, A., Maiorano, L., Montemaggiori, A.: Italian ecological network: the role of protected areas in the conservation of vertebrates (2003)
17. Boitani, L., Corsi, F., Falcucci, A., Marzetti, I., Masi, M., Montemaggiori, A., et al.: Rete Ecologica Nazionale. Un approccio alla conservazione dei vertebrati Italiani (2002)
18. Saura, S., Bodin, Ö., Fortin, M.-J.: EDITOR'S CHOICE: stepping stones are crucial for species' long-distance dispersal and range expansion through habitat networks. J. Appl. Ecol. **51**, 171–182 (2014). https://doi.org/10.1111/1365-2664.12179
19. Pascual-Hortal, L., Saura, S.: Comparison and development of new graph-based landscape connectivity indices: towards the priorization of habitat patches and corridors for conservation. Landsc. Ecol. **21**, 959–967 (2006). https://doi.org/10.1007/s10980-006-0013-z

20. Saura, S., Pascual-Hortal, L.: A new habitat availability index to integrate connectivity in landscape conservation planning: comparison with existing indices and application to a case study. Landsc. Urban Plan. **83**, 91–103 (2007). https://doi.org/10.1016/j.landurbplan.2007.03.005
21. Foltête, J.-C., Vuidel, G., Savary, P., Clauzel, C., Sahraoui, Y., Girardet, X., et al.: Graphab: an application for modeling and managing ecological habitat networks. Softw. Impacts **8**, 100065 (2021). https://doi.org/10.1016/j.simpa.2021.100065
22. Cushman, S., Lewis, J., Landguth, E.: Why did the bear cross the road? Comparing the performance of multiple resistance surfaces and connectivity modeling methods. Diversity **6**(4), 844–854 (2014). https://doi.org/10.3390/d6040844
23. McGarigal, K., Stafford, S., Cushman, S.: Multivariate Statistics for Wildlife and Ecology Research. Springer, New York (2000). https://doi.org/10.1007/978-1-4612-1288-1
24. Vizzari, M., Sigura, M.: Urban-rural gradient detection using multivariate spatial analysis and landscape metrics. J. Agric. Eng. **44**, 453–459, Article no. e91 (2013). https://doi.org/10.4081/jae.2013.(s1):e91