Journal of Environmental Management 230 (2019) 413–421

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Navigating protected areas networks for improving diffusion of conservation practices

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ARTICLE INFO

Keywords:
Natura 2000
Conservation prioritization
Co-occurrence network
Network topology
Modularity
Network reduction

ABSTRACT

The Natura 2000 protected area network is the cornerstone of European Union's biodiversity conservation strategy. These protected areas range across multiple biogeographic regions, and they include a diversity of species assemblages along with a diversity of managing organizations, altogether making difficult to pool relevant sites to facilitate the flow of knowledge significant to their management. Here we introduce an approach to navigating protected area networks that has the potential to foster systematic identification of key sites for facilitating the exchange of knowledge and diffusion of information within the network. To demonstrate our approach, we abstractly represented Romanian Natura 2000 network as a co-occurrence network, with individual sites as nodes and shared species as edges, further combining into our analysis network topology, community detection, and network reduction methods. We identified most representative Natura 2000 sites that may increase the transfer of information within the national network of protected areas, detected clusters of sites and key sites for maintaining network cohesiveness, and highlighted the subsample of sites that retain the characteristics of the entire network. Our analysis provides implications for protected area prioritization by proposing a network perspective approach to collaboration rooted in ecological principles.

1. Introduction

Protected areas are established to safeguard biodiversity in the long-term by implementing conservation measures on well-defined territories (Watson et al., 2014). Protected areas are considered as 'networks' when they are under the same jurisdictions and governed by similar principles and regulations (Evans, 2012; Lemos and Agrawal, 2006). The Natura 2000 protected areas network of the European Union (EU) is a cornerstone of the EU's biodiversity conservation strategy. EU Member States are required to designate Special Protection Areas (SPAs, for species covered by Birds Directive) and Sites of Community Importance (SCIs, for habitat and species covered by Habitats Directive) as part of EUs "Natura 2000 network" (Evans, 2012). To fully implement the Birds and Habitats Directives, Member States must take appropriate conservation measures to ensure a Favorable Conservation Status of protected habitats and species at the national and EUs biogeographical region levels (European Commission, 2011). These measures require collaborative approaches to conservation of species and habitats in Natura 2000 sites and sharing of best management and conservation practices (European Commision, 2015).

The high number of Natura 2000 sites (over 27000 in the EU), their distribution across multiple biogeographic regions, and the diversity of their species assemblages, coupled with diverse managing organizations, makes difficult the flow of knowledge and expertise relevant to species and habitat management across Natura 2000 sites (Battisti and Fanelli, 2015; Hoffmann et al., 2018; Rozylowicz et al., 2017).

Research plays a pivotal role in advancing best management practices with the intent of sustaining species and ecosystem services provided by protected areas (Blicharska et al., 2016). Key aspects addressed by Natura 2000 research includes conservation status of species and habitats (Maiorano et al., 2007), spatial connectivity of protected areas (Pereira et al., 2017), identification of the most representative sites for protecting particular taxa (Dimitrakopoulos et al., 2004; Popescu et al., 2013), ecosystem services (Bastian, 2013), governance and societal engagement (Manolache et al., 2018; Nita et al., 2018). Heavily influenced by the multiscale approach of EU biodiversity po-

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https://doi.org/10.1016/j.jenvman.2018.09.088
Received 18 June 2018; Received in revised form 20 September 2018; Accepted 24 September 2018
0301-4797/

licies (Battisti and Fanelli, 2015), existing research on Natura 2000 has been performed from the local (i.e., group of sites within a country's borders) to a continental scale, however, the local approach still dominates (Hoffmann et al., 2018; Nita et al., 2016; Orlikowska et al., 2016; Popescu et al., 2014). Furthermore, studies addressing the potential of collective action and sharing of knowledge among Natura 2000 sites to achieve EU Biodiversity Strategy to 2020 targets are lacking.

To fill this knowledge gap, we employ a well-established analytical tool – network analysis – to identify biological and ecological (i.e., species-based) prospects for cooperation among Natura 2000 sites. Within the framework of network theory, protected areas may be abstractly represented as *nodes* (individual sites), while shared species can be considered *edges* (common species linking two sites). By protecting species occurring in two or more sites (i.e., same resource), the managers of these sites should have motivation for building a collaborative network for conservation management grounded on common species (Bodin, 2017).

The approach has the potential to expand the use of systematic conservation planning, including gap analysis (Margules and Pressey, 2000) by improving the representativeness and effectiveness of protected areas for conserving biodiversity. Furthermore, the adoption of novel approaches to management, the avoidance of ineffective or disruptive practices, the stimulation of co-learning and co-production knowledge, are dependent on information flow within governance networks (Alexander et al., 2016; Alexander and Armitage, 2015; Berardo and Scholz, 2010; Bodin, 2017; Vance-Borland and Holley, 2011).

The goal of this study is to explore the potential of network analysis to facilitate systematic identification of protected areas that are pivotal in fostering the exchange of ecological knowledge and diffusion of information within a network of protected areas. We focused on terrestrial Natura 2000 Sites of Community Importance in Romania (hereafter, Natura 2000 sites), having high ecosystem diversity, and a large number of Natura 2000 sites and protected species (Manolache et al., 2017). These features make the identification of the key sites of interest for various conservation activities a challenge.

In our approach, we combine analysis of network topology, community detection, and network reduction to (1) identify key Natura 2000 sites in terms of their potential to increase the transfer of information within the Romanian network of protected areas, (2) identify groups of closely connected Natura 2000 sites based on species co-occurrence, as well as sites of high conservation value (rich biodiversity and hubs for knowledge transfer), and (3) identify the backbone of Natura 2000 network, a subsample of protected areas which retain characteristics of the entire network but includes sites whose species similarity is larger than random.

2. Methods

2.1. Network data

This study focuses on terrestrial Natura 2000 Sites of Community Importance in Romania. From this initial list of 435 Natura 2000 sites and 166 species (EIONET, 2017), we excluded 9 marine sites, 37 terrestrial sites designated only for habitats protection (i.e., no Natura 2000 species protected), and 2 marine species (the common bottlenose dolphin - *Tursiops truncatus,* and the harbour porpoise - *Phoecena phoecena*). The final list of Natura 2000 protected areas analyzed in this study included 389 sites and 164 protected species (Supplementary Table S1, Box 1).

Box 1

Short characterization of the Romanian Natura 2000 area network (Sites of Community Importance) used in this study.

> The analyzed Romanian Natura 2000 network for the protection of species listed by Habitats Directive includes 389 Sites of Community Importance and cover 40275.72 km^2. The size of protected areas varies between 0.03 km^2 and 4536.45 km^2 (average = 103.54, stdev = 307.43). The Natura 2000 network protects 164 species of EU interest, i.e., 46 plants, 54 invertebrates, 26 mammals, 26 fishes, 6 reptiles, and 6 amphibians. The number of species protected within a Natura 2000 site varies between 1 and 64 (median = 6, IQR = 3–12), and as expected, is moderately correlated with the area, the larger sites protecting more species (Kendall tau = 0.49, $p < 0.001$). The top sites in terms of number of protected species (> 40 species) are Iron Gates (Portile de Fier), Domogled Valea Cernei, Calimani Gurghiu, Cheile Nerei Beusnita, Fagaras Mountains and Tur River and by surface (> 1200 km^2) Danube Delta, Fagaras Mountains, Frumoasa, Calimani Gurghiu, Iron Gates.

Based on the map of natural vegetation (Evans, 2012), Romanian Natura 2000 sites are grouped into five biogeographical regions, i.e., Alpine, Continental, Pannonian, Steppic and Black Sea (Iojă et al., 2010). Because we analyzed only the terrestrial sites and species, we considered the neighborhood Steppic and Black Sea regions as one biogeographical region. When a Natura 2000 site overlaps two biogeographical regions, we assigned the respective site to the region with the highest coverage.

We represented Natura 2000 network as a weighted one-mode undirected graph, where two Natura 2000 sites (*nodes* in the network) are considered connected if they share at least one common species (*edges* or *links* in the network) (Wasserman and Faust, 1994). If the two sites are linked by more than a species (i.e., *edge weight* > 1), the similarity of these sites increases which then increases the potential and need for collaboration (Fig. 1).

2.2. Network metrics

The Natura 2000 network-level structure was described employing the following metrics: *network density*, *network transitivity*, *average step length*, and *network diameter*. The centrality of Natura 2000 sites was analyzed using: *degree*, *eigenvector* and *betweennesses* metrics (Bodin and Prell, 2011; Nita et al., 2016; Vance-Borland and Holley, 2011). A detailed description of network terms and metrics is provided in Supplementary Note.

Considering two sites as connected if they share at least a species, network *density* represents the number of connections in the network divided by the total possible connections (Borgatti et al., 2018). Network *transitivity* is a clustering index and represents the ratio between the number of triangles (three connected sites, e.g., sites 1, 2, and 3 directly connected as follow: site 1—site 2, site 2—site 3, and site 3—site 1) and maximum possible triangles in the network. Networks with a transitivity index close to 1 are highly clustered (Wasserman and Faust, 1994). The *average step length* of a network represents the average

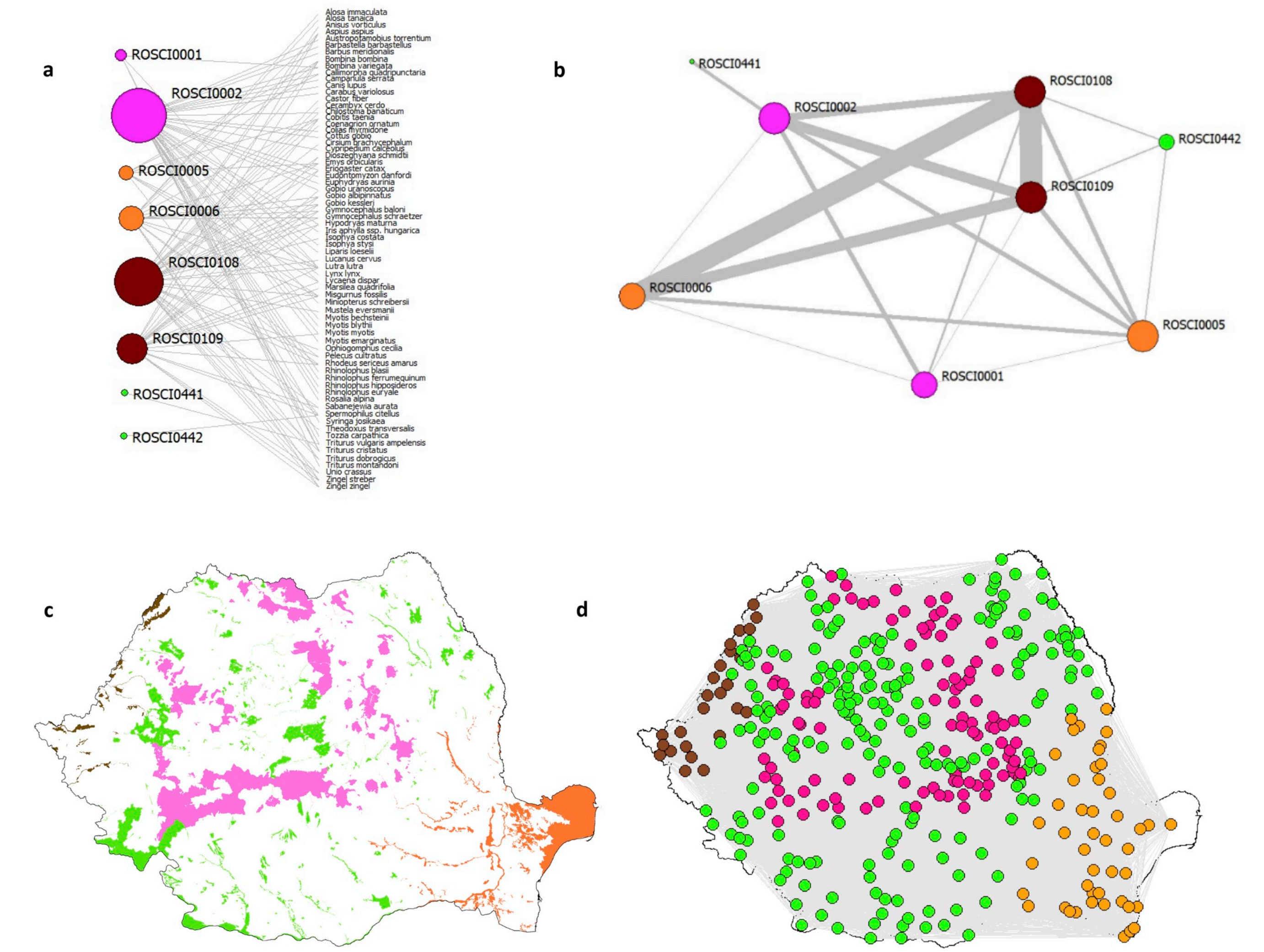

Fig. 1. Network data formation: a) example of a representation of Natura 2000 network as a bipartite network (sites-species network); b) transformation of the bipartite network into an undirected weighted one-mode network (site-site network), where two sites are linked if they share at least a protected species (edge size = number of species in common, node size = node degree); c) true spatial representation of Natura 2000 sites in Romania. Colors denote EU biogeographical regions: Alpine = pink, Continental = green, Steppic and Black Sea = orange, Pannonian = brown; d) network-like spatial visualization of Natura 2000 sites in Romania.

number of Natura 2000 sites that must be navigated to connect any two sites in the network, without considering the physical distance between the sites. The network *diameter* represents the shortest path length between the two most distant indirectly connected sites in the network (Borgatti et al., 2018).

The *degree centrality* of a Natura 2000 site represents the number of connections to other sites in the network with at least one species in common with the focal site. Sites with degree centrality greater than average can be considered as *hotspots* since they include a significant number of species covered by Habitats Directive in Romania. These sites can also be perceived as *hubs* for diffusion of information as they have direct connections (i.e., protecting same species) to a large part of the network (Barabási, 2016; Borgatti et al., 2018). Contrary to degree centrality metric, which highlights the importance of a node at the local level, *eigenvector centrality* informs about the importance of the same node at the network level (Fornito et al., 2016). The eigenvector value of a site is proportional to the sum of the eigenvector centralities of all other sites to which it connects. A Natura 2000 site has high eigenvector centrality if it is connected to other Natura 2000 sites that are themselves well connected (Borgatti et al., 2018). In our context, eigenvector centralities can measure the capacity of a site to disperse information in the network, for example, to share best practices in conservation or, the extent to which a particular Natura 2000 site is located centrally relative to other linked sites (Bodin and Prell, 2011). The *betweenness centrality* provides a different assessment of sites centrality. The metric represents the fraction of short paths between all pairs of Natura 2000 sites in the network, which pass through a given site. Sites with betweenness centrality > 0 connect to other Natura 2000 sites that would be otherwise disconnected or only sparsely connected (Martín González et al., 2010). Natura 2000 sites with high betweenness centrality may act as "bridges" between groups of nodes, keeping groups of sites within the network connected (Fornito et al., 2016). Such Natura 2000 sites control the flow of information and are pivotal in engaging a large part of the network in conservation projects, for example, if one intent to disseminate best practices of management of Natura 2000 to "remote" sites (i.e., Natura 2000 sites with no species in common to the site initiating the best practice).

2.3. Clusters of Natura 2000 sites

We used modularity analysis (Bloomfield et al., 2018; Guimera and Amaral, 2005) to test if the classification of Romania's Natura 2000 network into five EU biogeographical regions is a consequence of dissimilarities of protected species. While we do not expect to match EU

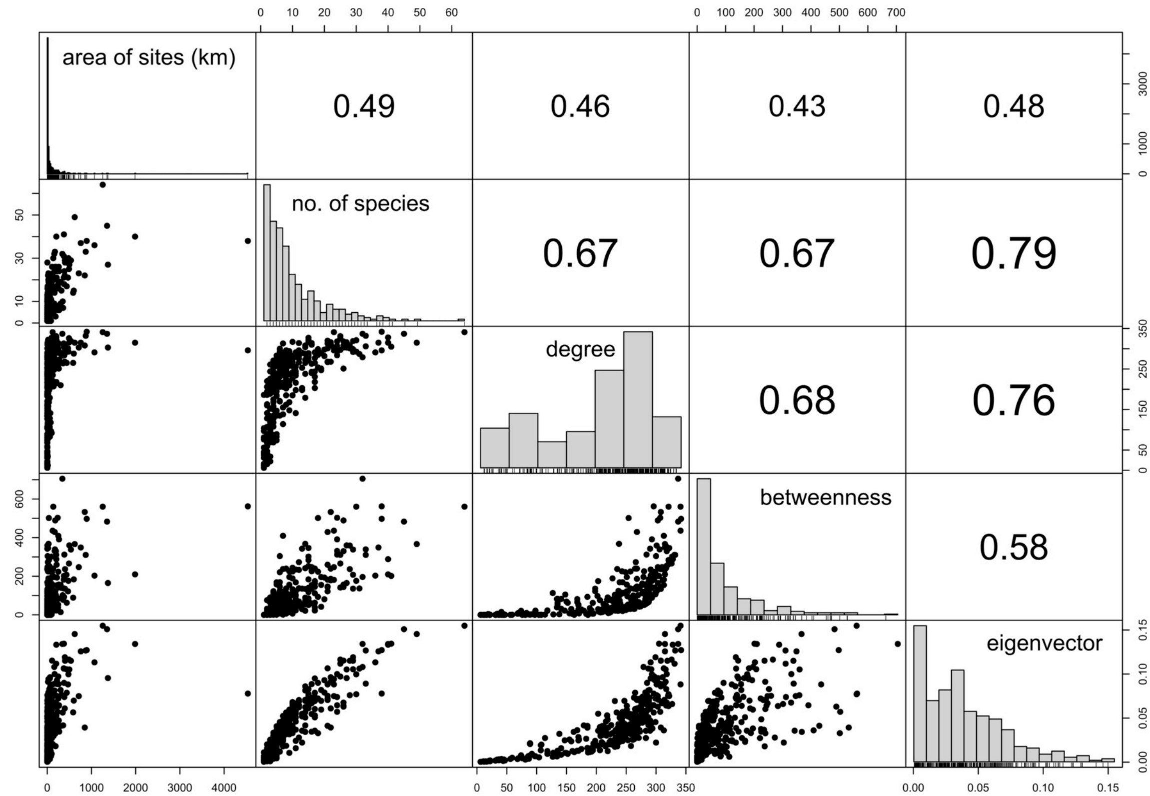

Fig. 2. Correlation charts, Kendall tau correlation coefficients, and histograms of site-level centrality metrics, area of Natura 2000 sites and number of protected species per Natura 2000 site.

biogeographical regions, a modular network endorses patterns of species assemblages throughout Romania's Natura 2000 network, and subsequently a greater diversity when compared to other EU countries which overlap only one or two bioregions. Modularity analysis is based on simulated annealing and identifies *modules*, grouping Natura 2000 sites closely connected to each other than to sites in other modules. We ran the algorithm using edges weighted by number of shared species, iteration factor of 1 and temperature cooling factor of 0.996 (Guimera and Amaral, 2005). The resulted index of modularity (M) measures the extent to which sites have more links within their modules than expected if the linkages are random. Network modularity is statistically significant if the index is higher than that obtained for random networks with the same degree distribution (Guimera et al., 2004).

For each Natura 2000 site, the algorithm provides a standardized within-module degree and a participation coefficient. The standardized within-module degree (z) measures how well-connected a given node is to other nodes in the module. The participation coefficient (P), is close to 1 for nodes with links uniformly distributed among all the identified modules, and 0 if all links are within its' module (Guimera and Amaral, 2005). We used the z and P to classify the Natura 2000 sites into *peripherals* ($z \leq 2.5$ and $P \leq 0.62$, sites sharing few species with sites inside their own module and rarely any to other modules), *connectors* ($z \leq 2.5$ and $P > 0.62$, sites who keep the modules together), *module level hubs* ($z > 2.5$ and $P \leq 0.62$, sites important to the coherence of their own module) and *network level hubs* ($z > 2.5$ and $P > 0.62$, sites important to the coherence of both the network and their own module) (Olesen et al., 2007).

2.4. The backbone of Natura 2000 network

The large number of connections in a network makes it difficult to understand and visualize the actual structure, for example, to identify relevant connections between nodes by plotting the network data (Ahn et al., 2011). Furthermore, networks have a multiscale structure and reducing their size and preserving only the edges with weights above a threshold will destroy the network structure and preserve only the nodes with high degree centrality (Serrano et al., 2009), eliminating sites with low degree centrality but important for information sharing. To filter the network while keeping the multiscale structure, one approach is to retain a node if the probability that an edge's weight is larger than the average value expected in a null model is statistically significant – i.e., disparity filter (Serrano et al., 2009). Following this approach, we filtered the network and kept only those edges which were statistically highly significant ($\alpha = 0.001$), i.e., only the pairs of sites which share more species than expected if the number of shared species is constrained only by sites' degree centrality. We choose 99% statistical significance for demonstration purposes; however, the power can vary according to the objectives of the study and network resilience to fragmentation (Ahn et al., 2011; Serrano et al., 2009). In our case, the backbone of Natura 2000 network will reveal most representative sites for the network (conservation hubs, i.e., sites with high degree centrality and well connected with other sites in the backbone), hidden key sites (sites with very low degree centrality but with statistically significant connections), areas with clusters of Natura 2000 sites in the backbone (e.g., biogeographical regions important for backbone of Natura 2000 network).

Analyses and graphs were produced in R 3.5.0 (R Core Team, 2018) using the *igraph* (Csardi and Nepusz, 2015), *disparityfilter* (Bessi, 2016), *Rnetcarto* (Doulcier, 2015), *PerformanceAnalytics* (Peterson et al., 2015), *ggpubr* (Kassambara, 2017) packages and ArcMap 10.3.1 GIS software (ESRI, Redlands CA).

All data generated or analyzed during this study are included in this published article and its Supplementary Tables S1, S2, and S3.

3. Results

3.1. Natura 2000 network topology

Romania's Natura 2000 network shows a high *density*, with 53% of the maximum possible connections present. However, 40% of 40152 network edges are maintained by one species, and only a small percentage by a larger number of species, for example, only 3.12% by 10 or more species (median = 2, IQR = 1–4). The most similar pair of sites in terms of common protected species contains 33 shared species, followed by three pair of sites with 32 shared species (Cheile Nerei Beusnita—Iron Gates, Domogled Valea Cernei—Calimani Gurghiu, Domogled Valea Cernei—Iron Gates, Domogled Valea Cernei—Cheile Nerei Beusnita; Supplementary Table S2).

Considering the ratio between the number of triangles and the maximum possible closed triangles as a measure of *clustering*, the Romanian Natura 2000 network is highly clustered, with 79% of the maximum possible triplets closed. Furthermore, the network has a low *diameter*, with only 3 sites required for connecting the two most distant connected sites, and the average number of Natura 2000 sites connecting sites not having species in common is 1.47 (*average short path*).

The node level metrics (*degree*, *betweenness*, and *eigenvector centrality*) are correlated and produce reasonably similar ranking (Fig. 2), however, they indicate differing functions of Natura 2000 sites in the network (Valente et al., 2008). Furthermore, as expected, site-level metrics are highly correlated with the number of species but not with the surface of sites.

The *distribution of degree centrality* shows that most Natura 2000 sites share species with a large number of sites in the network, e.g., 65% of sites share species with half of sites in the network (median degree = 237, IQR = 135–279). First three sites in term of degree centrality share species with more than 341 sites (87.66% of the network) and capture almost the entire set of Natura 2000 protected species (Supplementary Table S3). When a focal site protects few species, degree centrality is strongly influenced by the rarity of represented species. For example, the Muntele Mare site (Western Carpathians) protects only one amphibian species, the Yellow-Bellied Toad (*Bombina variegata*), but the site has a high degree centrality (184) because the species is well represented in Romanian Natura 2000. On the contrary, the Rosalia Longicorn (*Rosalia alpina*) is scarcely represented by Romanian Natura 2000 network; as such the Natura 2000 site Cosava Mica (Western Carpathians), which only protects this species, has a low degree centrality (34).

Eigenvector centrality shows that most Natura 2000 sites share species with sites that are themselves well connected (median = 0.033, IQR = 0.012–0.056). This characteristic of Romanian Natura 2000 network facilitates the diffusion of conservation information, as administrators of the sites with high eigenvector can communicate with other administrating sites with a different set of protected species but equally well connected.

The median number of the shortest paths in the network that pass through a node, connecting parts otherwise disconnected (*betweenness centrality*), is also high (49.93, IQR = 124.0–68.10, maximum = 705.17). Sites with very high betweenness can facilitate the diffusion of conservation information through the network, while the sites with betweenness 0 (48 sites in our network) cannot act as a broker of conservation information (Alexander et al., 2016; Bodin and Prell, 2011).

3.2. Modularity of the Natura 2000 network

Romanian Natura 2000 network is modular ($M_{Natura\ 2000} = 0.20 > M_{100\ random\ networks} = 0.13 \pm 0.002$), which denotes that sites can be grouped according to the proportion of their connections within and outside the modules. However, the modularity algorithm identifies three modules, while there are four biogeographical regions (considering Steppic and the Black Sea as a single region). Module 1 includes 163 sites from Alpine and Continental biogeographical regions, while modules 2 and 3 which include 145 and respectively 81 sites are less consistent with biogeographical regions (Fig. 3). Most of the sites in module 3 are *connector sites* because they have many species in common with sites in module 1 or module 2 (Fig. 4). Module 2 includes only three connector sites (Lacul Stiucilor Sic Puini Bontida, Padurea si Lacul Stolnici and Platoul Meledic), while module 1 has no connectors sites. Three sites included in modules 3 and 1 play a critical role in the formation of clusters in the network. Sighisoara Tarnava Mare (module 3) and Calimani Gurghiu (module 1) are *module hubs*, i.e., highly connected sites linked with many sites within their own modules, while Dealurile Clujului de Est, a Natura 2000 site with high degree centrality included in module 3 is a *network hub* (share many species with sites in all three modules). The rest of Natura 2000 sites are *peripheral*, most of their connections being with sites from the same modules (Fig. 4).

3.3. The backbone of Romanian Natura 2000

By retaining only statistically significant edges ($p < 0.001$) the Romanian Natura 2000 network can be reduced from 389 sites and 40152 edges to 140 sites and 323 edges. This reduced network constitutes the backbone of Romanian Natura 2000 network and includes the pair of sites which share more species than expected if the number of shared species is constrained only by sites' degree centrality. The backbone includes sites with high number of protected species (Iron Gates, Domogled Valea Cernei) or degree centrality (e.g., Sighisoara Tarnava Mare) but also sites with only one protected species (e.g., Cosava Mica in Western Carpathians) or very low degree centrality (e.g., Agarbiciu – center of Romania) (Fig. 5). More than 50% from Alpine and Steppic and the Black Sea biogeographic regions are included in the backbone, while most Continental and Pannonian sites are not statistically significant linked with other sites (Table 1).

4. Discussion

The continental approach to conservation in EU currently lacks efficient instruments for coordinating conservation initiatives at national and supranational levels (Battisti and Fanelli, 2015; Hochkirch et al., 2013; Hoffmann et al., 2018). Our network-based analysis using Romanian Natura 2000 sites and species at the national level provides a tool for developing biologically and ecologically-sound collaboration networks by highlighting those Natura 2000 sites which are best positioned for an efficient knowledge transfer and diffusion of information within the network (Prell et al., 2009). By engaging with sites that are key components for information sharing, managers and conservation practitioners have the opportunity to adopt innovative conservation practices, thus motivating collective learning and knowledge co-production, as well as the avoidance of ineffective or disruptive conservation practices (Alexander et al., 2016; Bodin, 2017).

The Romanian Natura 2000 network is very dense, compact, and highly clustered. Considering the shared species as connectors, the network-level metrics suggest a high potential for information sharing at network and local levels (Alexander et al., 2016; Borgatti et al., 2018). These metrics are also useful to characterize the network from an ecological perspective. High network density suggests a cohesive and resilient network, similar to a pollination network with high connectance (Cumming et al., 2010). Because over 40% of the connections within Natura 2000 sites in our study are maintained by only one species and the median number of protected species in a Natura 2000 site is higher (6 species, see Box 1), a large part of cohesivity is due to associations between ecologically dissimilar sites (Bloomfield et al., 2018).

The position of a Natura 2000 site in the national network was analyzed by considering the degree, eigenvector, and betweennesses

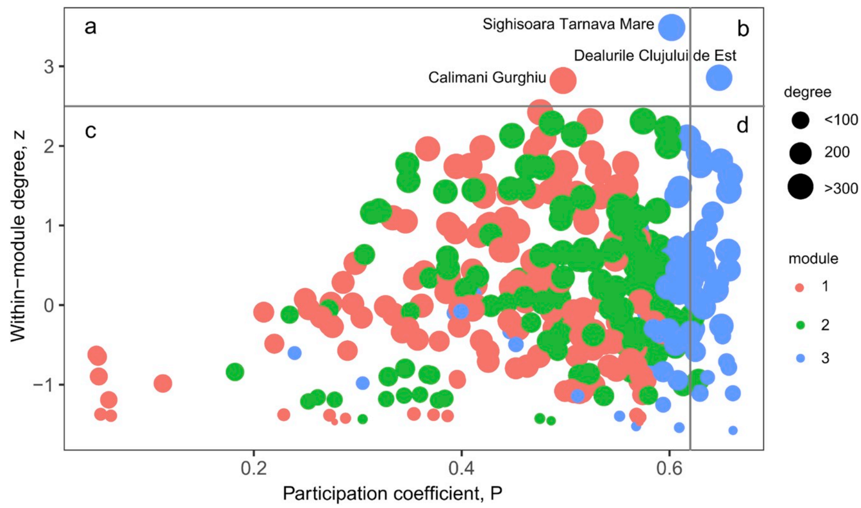

Fig. 3. Distribution of Natura 2000 sites according to their role in the modular network: a) module hubs; b) network hub; c) peripheral sites; d) connector sites.

centralities. As in other co-occurrence networks, these metrics are correlated to species richness (Bloomfield et al., 2018; Cumming et al., 2010; Hoffmann et al., 2018) (see Fig. 2), thus, providing insight on the roles and positions of Natura 2000 administrators in an information sharing network (Alexander and Armitage, 2015) while taking into account sites species diversity.

The degree centrality is one of the most used node-level metric to assess opportunities for collaboration and information sharing of a focal node (Alexander et al., 2016; Borgatti et al., 2018). The distribution of degree centrality in Romanian Natura 2000 network did not follow a power-law distribution (see Fig. 2), which would be indicative of a small set of well-connected sites (degree centrality above average) as hubs for information sharing (Barabási, 2016). In our study, most sites share species with a large part of the network, suggesting that many of high degree sites may act as knowledge dispersers, and the information is highly probable reaching a substantial part of the network if the communication activities are well planned (Mbaru and Barnes, 2017; Nita et al., 2018). However, top sites, such Sighisoara Tarnava Mare, Padurea Barnova Repedea, and Iron Gates which share species with > 87% of the Romanian Natura 2000 network, may be considered as key hubs for the dissemination of information due to their sizeable number of potential connections. Because the sites degrees depend on the number of occurrences of a species across the network (Borgatti et al., 2018; Fornito et al., 2016), a relatively high degree centrality

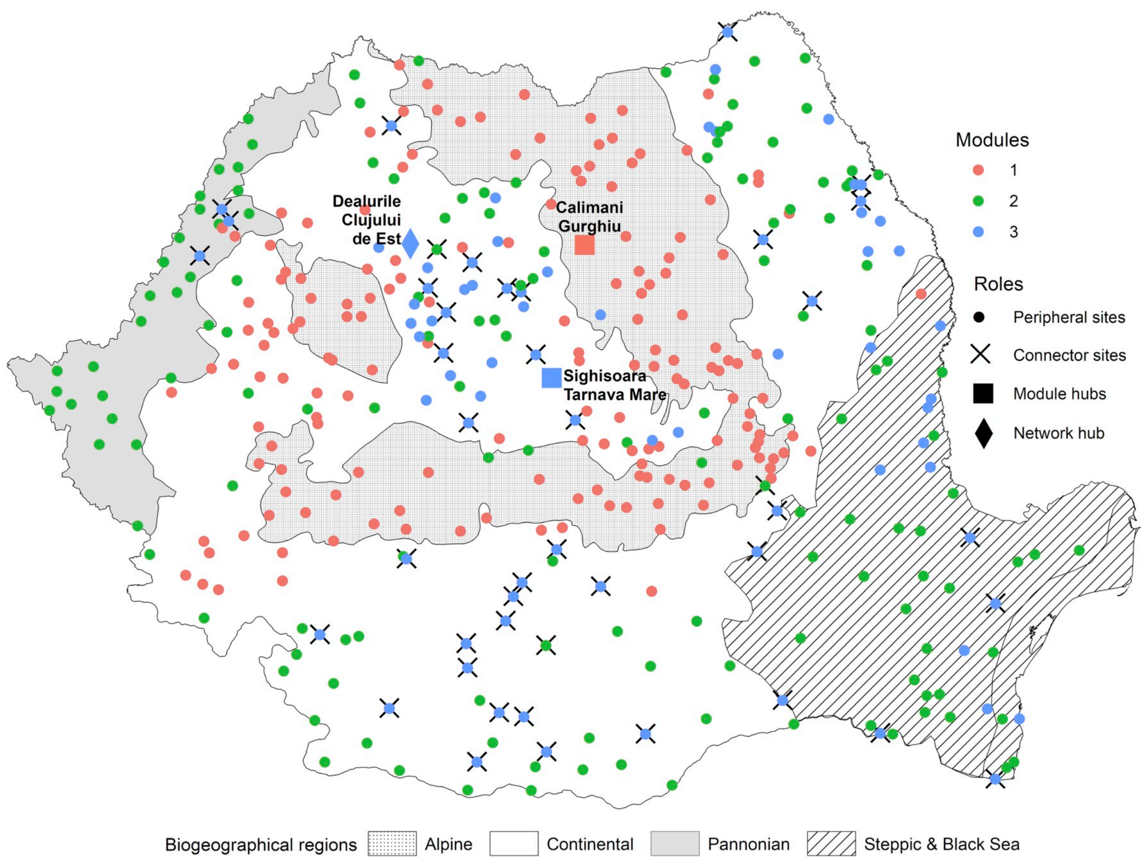

Fig. 4. Spatial representation of Romanian Natura 2000 sites according to their roles in the network (symbols) and membership to identified modules (colors).

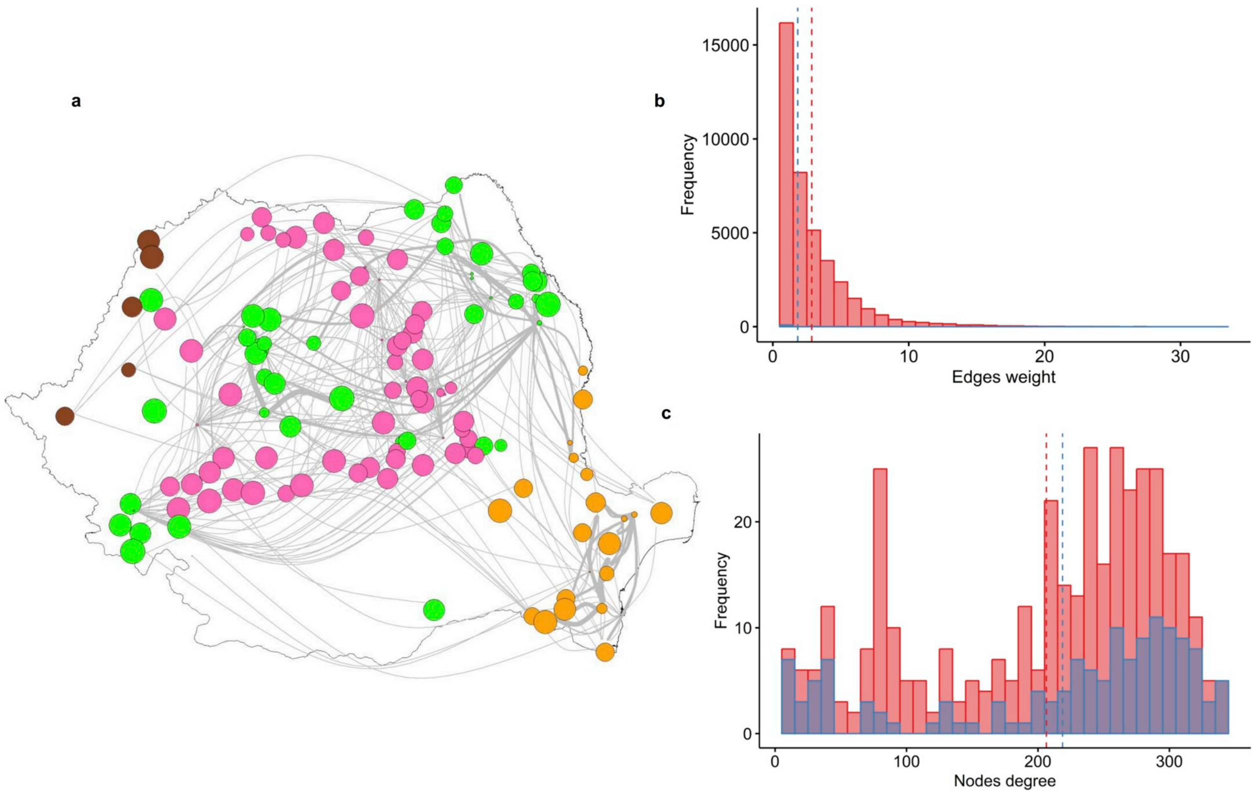

Fig. 5. Backbone of Romania Natura 2000 network. a) Natura sites and edges retained in the backbone network (nodes size = degree, edges weight = number of species in common, colors = biogeographical regions: Alpine = pink, Continental = green, Steppic and Black Sea = orange, Pannonian = brown). b) Edges weights distribution in the initial (red) and backbone network (blue). c) Nodes degree distribution in the initial (red) and backbone network (blue). Dotted lines in b) and c) indicate the average edges weight and nodes degree in the initial and backbone networks. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Reduction of Romanian Natura 2000 network by biogeographic regions using the disparity filter (α = 0.001).

Biogeographic region	Number of sites retained in the backbone	% from initial network
Alpine	60	56%
Continental	52	24%
Pannonian	5	20%
Steppic and Black Sea	23	50%

may be expected due to the presence of a species well-represented in Natura 2000 network. Thus, when the number of protected species in a Natura 2000 site is low, the importance for collaboration and information sharing must also consider the species richness.

Unlike in other networks, such as pollination and food webs networks (Cumming et al., 2010; Martín González et al., 2010), distribution of eigenvector centrality shows a large group of Natura 2000 sites with high eigenvector scores. This suggests that there are alternatives to efficient knowledge sharing beyond the handful of top-tier sites (Fornito et al., 2016), allowing for other well-positioned sites to efficiently distribute information within the network. Selection of influential alternative dispersers may be made by comparing rankings based on eigenvector centrality with the one produced by betweennesses centrality, as the nodes with high values of these centrality metrics are well positioned to facilitate and control the diffusion of information at network level (Alexander et al., 2016; Motta et al., 2017; Nita et al., 2016).

Despite high network-level connectivity, low network diameter, and the large number of Natura 2000 sites with above-average degree centrality, the Romanian Natura 2000 network is modular, and sites may be grouped by their linkage affinity in three modules. The modules are identified by their statistically significant strength of the links between sites (Guimera and Amaral, 2005; Guimera et al., 2004; Olesen et al., 2007), measured as the number of shared species (edge weight). As expected, the identified modules are not consistent with the number of EU biogeographical regions overlapping Romania, which were delineated based on habitats (Evans, 2012). In our species-based modularity analysis, most Natura 2000 sites from Alpine and Continental biogeographical regions are grouped in a single module (i.e., species-based bioregion), while the sites from Steppic, Black Sea, and Pannonian biogeographical regions are arbitrarily dispersed across modules. In modular networks, the information exchange is easier between the sites that are part of the same module, and in order to reach sites from other modules, they must pass through one or more sites with among-module connectivity role (connector sites, module hubs, network hubs) (Olesen et al., 2007). Thus, when the entire Natura 2000 network is targeted, giving priority to sites with key functional role could be more biologically meaningful than ranking the sites based on non-weighted centrality metrics (degree, betweennesses, eigenvector). In our network, there are many connector sites in module 3 (40 out of 81 sites) but module 2 only includes three such sites. If these sites do not engage in knowledge sharing, the network becomes fragmented (Fornito et al., 2016), and the information sharing among modules becomes challenging. By taking these strengths and weaknesses into account in future management strategies, Natura 2000 managers may create more stable knowledge-sharing structures in networks (Chen et al., 2018). Furthermore, modularity analysis identifies four sites of high interest for conservation. These Natura 2000 sites are vital for information sharing at module-level (Sighisoara Tarnava Mare for module 3 and Calimani Gurghiu for module 1, module hubs) and both module and network-level (Dealurile Clujului de Est – network hub). Because of its share of many links with sites in all three modules, Dealurile Clujului de Est emerges as pivotal Natura 2000 site is Romania, with every species protected there being critical for maintaining the coherence of Romanian Natura 2000 network.

Filtering networks to identify what Natura 2000 sites and links are important to transferring information represents another approach to understanding network structures (Serrano et al., 2009). Extraction of a dominant set of connections for each Natura 2000 site was based on the strength of connections between sites (Ahn et al., 2011), measured as shared species. By retaining pairs of Natura 2000 sites with dominant connections (Serrano et al., 2009), the network was greatly reduced: the number of sites was reduced by 64%, and the number of connections by 99.2%. As such, the backbone network retained sites and connections important for knowledge-sharing, which otherwise would have been hidden and hard to identify with other network analysis tools. Alpine and Steppic and the Black Sea biogeographic regions retained more than 50% of Natura 2000 sites, which highlights the importance of these areas for conservation. As a result, the backbone of Romanian Natura 2000 network is a map of the significant sites and connections, as in other conservation planning approaches (Kukkala and Moilanen, 2013; Margules and Pressey, 2000).

5. Conclusions

Our network approach provides a tool for building collaborative partnerships for managing Natura 2000 sites at the national level. Effective collaboration between site managers relies on improved communication, and protecting the same species might be a good opportunity to share conservation strategies and cooperation. Additionally, our analysis highlights implications for protected area prioritization by taking a network assessment approach to collaboration, while being rooted in ecological principles. The network theory approach could be also used in addressing management and representation gaps in the protected areas (Hoffmann et al., 2018) by highlighting isolated Natura 2000 sites from a knowledge transfer perspective. The establishment of Natura 2000 network along with the advances in designating the sites, was the initial step in ensuring the protection of habitats and species for long-term (Evans, 2012). Strengthening the implementation of conservation policies and adopting best management strategies should provide new knowledge transfer opportunities to support effective Natura 2000 network management (Hochkirch et al., 2013; Pellegrino et al., 2017).

Acknowledgments

This work was supported by a grant of the Romanian National Authority for Scientific Research (https://uefiscdi.ro/), PN-III-P4-ID-PCE-2016-0483. LR and AN contributed equally to this paper. Editing and proofreading by Edward F. Rozylowicz streamlined the flow and message of this manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2018.09.088.

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