# Resilient ecological networks: a comparative approach

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Resilient ecological networks: a comparative approach / DE MONTIS, Andrea; Ganciu, Amedeo; Cabras, Matteo; Bardi, Antonietta; Peddio, Valentina; Caschili, Simone; Massa, Pierangelo; Cocco, Chiara; Mulas, Maurizio. - In: LAND USE POLICY. - ISSN 0264-8377. - 89:(2019), p. 104207. [10.1016/j.landusepol.2019.104207]

*Published*
DOI:10.1016/j.landusepol.2019.104207

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**Submitted version (Pre-print)**

## Abstract

Resilience is an overarching concept concerning the capacity of complex systems to react to severe crisis by self-organization, innovation and learning and to attain more robust settings than in the original condition. While the theory on resilience has exploded in the last decades, its operationalization is less practiced. A possible way out is the selection of appropriate variables able to measure the behaviour of a system, when it is subject to important stresses. Resilience has been applied to the study of socio-ecological systems, including ecological networks. Ecological networks can reconnect fragmented landscapes through a web of patches intertwined by environmental corridors. In this paper, we aim at assessing the resilience of two ecological networks designed for the towns of Nuoro and Sassari, Italy. The ecological networks are built on the ecological properties of two vegetal target species (i.e. Quercus ilex and Olea europaea) and their seed dispersal through the corresponding frugivorous animal vector species. We have studied the behaviour of the ecological network under different types of attacks to the patches: at random or according to a deterministic choice. Our method allows to compare the dynamic pattern of resilience (i.e. along the process of elimination of patches) and to observe typical behaviour reported in other cases but also interesting peculiarities.

**Keywords**: Ecological networks; resilience; random attack; deterministic attack

## 1. Introduction

Resilience thinking has evolved tremendously in the last decades (Folke, 2016). The concept of resilience, i.e. the ability of complex socio-ecological systems to resist under severe pressures and to eventually attain a new and stronger configuration (Shaw, 2012), is the last in line reference term of sustainability discourse, after concepts such as carrying capacity and ecological footprint. Yet, resilience is a successful issue, as it invokes other contemporary questions related to self-organization, innovation, pro-action, learning, and adaptation. In these senses, resilience prompts us to study the inner reasons of the birth and evolution of complex systems and, ultimately, to understand the identity of socio-ecological systems. So, resilience thinking suggests that policies should be addressed starting from the analysis of the potential of societies interested, which are intrinsically connected to their identity (Folke et al., 2010). The concept of resilience has been first used in domains related to rural landscape analysis and planning and afterwards to addressing policies on urban areas. Typical applications include the study of the behaviour of ecological networks (Ings et al., 2009), which are ensembles of habitat patches (standing for the nodes) intertwined by material or immaterial corridors (constituting the edges). An ecological network is able to reconnect habitats; so, it is very effective in combatting landscape fragmentation. Thus, the identity of an ecological network is very much related to concepts, such as connectivity and effective colonization of the patches (Cumming et al., 2005). While theoretical issues have been quickly constructed and developed on, more operational applications of resilience analysis are still rare. A central question regards the assessment of the inner functions of a complex system and the selection of an adequate set of indicators. Complex networks analysis provides scholars with powerful tools for the investigation of various systems (Albert & Barabási, 2002). The discipline has been successfully adopted for ascertaining the resilience of networked systems in many domains (Gao et al., 2015). The peculiarity of these studies relies in the simulation of the behaviour of a complex network, when it is subject to various forms of disturbance (implying to the removal of nodes or edges).

In this paper, we aim at contributing to the operationalization of resilience thinking by constructing and applying a method for assessing the resilience of two ecological networks designed for the towns of Nuoro and Sassari, Sardinia, Italy. Our investigation starts from, extends and reframes two previous works. The first (De Montis et al., 2019) is a comparative study of those two ENs, which have been modelled as weighted spatial networks. The second one (De Montis et al., 2016) proposed a method for the assessment of the resilience of a smaller pilot EN for Nuoro. We will address our argument in response to the following research questions (RQs). The first one is the following: is it possible to construct a method able to measure the resilience of ecological networks ($RQ_1$)? We will develop on previous research studies and complete the set of indicators adopted for assessing resilience under many perspectives. The second one reads as follows: how can this method be addressed to the comparison of two -or more- ecological networks ($RQ_2$)? We will be framing the method to use simple tools enabling an easy confrontation of the behaviour of ecological networks.

The remainder of this paper develops as follows. In the next section, a state-of-the-art summary is reported on resilience theoretical thinking and practical operationalization through complex networks analysis. In section 3, the methodology is presented with a focus on the reframing of previous studies. In section 4, we present the case study, i.e. two ecological networks for the towns of Nuoro and Sassari. In sections 5 and 6, we, respectively, present and comment the results obtained. Finally, in section 7, we elaborate on concluding remarks and outlook considerations.

## 2. Resilience theory and operationalization: a state-of-the-art summary

Resilience can be defined as the ability of complex systems to resist to very critical disturbances, keep the original characteristics, self-organize and adapt, and eventually evolve by achieving further and stronger conditions (Balsas, 2014; Christopherson et al., 2010; Handmer & Dovers, 1996; Shaw, 2012). The concept was introduced by Holling (1973), who started from the evidence that living systems have multiple basins of attraction and focused on the capacity of ecological ensembles to resist in the face of severe environmental changes by attaining new and unexpected configurations. Along with the integration between ecology and social science, resilience thinking, i.e. the attitude to embed resilience in political discourse, has been referred not only to pure natural but also to broader intertwined socio-ecological systems (SES) (Folke et al., 2010), where the inexplicable traits of society and ecology are key to the description of identity and potential. SES are not just made by the sum of social and ecological characteristics (Cumming, 2011); they "exhibit a range of unique emergent properties and have their own varieties of complex behavior" (Westley et al., 2002). Resilience represents the last key concept after other items that have attracted the interest of scholars interested in sustainability issues: carrying capacity, i.e. the ability of environmental systems to sustain a given charge produced by human settlements and activities (Cohen, 1995), and, as counterpart, ecological footprint, i.e. the Earth space necessary to produce goods and services capable to sustain human ensembles at a certain rate of development (Rees, 1996). But the concept of resilience even in the initial definitions had more to do with proactivity and road mapping paths towards future possibilities to adapt to critical changes by exploiting the best elements even in front of very severe destabilizations.

Thus, resilience thinking has soon become a reference framework for studying complex adaptive systems in inter- and transdisciplinary research (Folke, 2016) encompassing ecology, sociology, psychology, economics, and engineering. The exportability of the approach is one of the main drivers of the success of the concept, which is witnessed in the last two decades by an avalanche of studies. While Folke (2016) reports 250 publications in 2000, the number jumps to nearly 8,000 in February 2019 (Web of Science core collection). Annual citations have transitioned from less than 100 in 1995 (Folke, 2016) to 26,000 circa in 2018. As for the penetration in the grey literature, a recent Google web search with the keys resilience and environment has yielded more than 96 million items. According to Collier et al. (2013), the discourse about resilience attained first rural landscape analysis, planning and management (see also Naveh, 2000 and Palang, Alumae, & Mander, 2000), while only recently and sparsely it is starting to concern urban domains. Collier et al. (2013) affirm that “urban green space policy is increasingly being used as a tool to enhance urban resilience and sustainability”. A paramount example is offered by ecological networks (Ings et al., 2009; Opdam et al., 2006, Janssen et al., 2006) and, in broader terms, green infrastructures (Benedict & Mcmahon, 2002; Meerow & Newell, 2017; Matthews et al, 2015), which act as intertwined systems of habitat patches connected with each other by material and immaterial corridors. These systems are employed to give or restore continuity in fragmented landscapes, where large patches have become smaller and more isolated than in the original condition. In addition, they serve the cause of maintaining system identity through the relations among the nodes, thus, ultimately, contribute to increasing the resilience of the overall ensemble (Cumming et al., 2005).

While research on resilience is mature, its operationalization -i.e. the transition from resilience theory to practice- is much less explored. At the same time, few studies deal with the promising issue of assessing the resilience of SESs. Given the complex nature of SESs, it is very difficult to set up methods and tools able to measure directly the resilience. Those complex systems can be just evaluated indirectly through surrogates, a term adopted instead of the more common “indicators” to stress the choice of indirect measurement (Carpenter et al., 2005). In this respect, the analysis and design of ecological networks can be approached by invoking graph theory and the last advances of complex networks analysis (CNA). CNA provides scientists, planners, and managers with an elegant and powerful set of tools able to disentangle several real-life systems by classifying and characterizing their topological and weighted properties, starting from basic variables (number of nodes and edges), centrality measures, assortativity indexes, etc. (Albert & Barabási, 2002; Dorogovtsev, 2003). The literature on the application of CNA and graph theory to the assessment of ecological networks is very rich (see, inter alia, Fall et al., 2007; Hagen et al., 2012; Urban et al., 2009), while relatively less endowed is the study of the behaviour of ecological networks in the face of critical and adverse situations. In general, the resilience of a network depends on its topological structure and is assessed by monitoring the behaviour of some key variables, when the nodes are subject to random and targeted (centrality based) fatal attacks. Crucitti et al. (2004) have demonstrated that random networks show a similar resilience to both the kinds of attacks, while scale free networks are resilient to random attacks but quite vulnerable to targeted attacks. This confirms (and assesses) an intuition: complex networks need to be developed by protecting their most central nodes. Similarly, Gao et al. (2015) choose "the integral size of the giant component during the whole attacking process" as a measure of resilience. They also stress three methods/policies for increasing the robustness of networks: increase the share of central nodes, design dependency links connecting nodes with similar centrality, and protect the central nodes. In addition, Gutfraind (2012) develops on the need to act on the overall connectivity to "prevent the failure of a single node from causing a far-reaching domino effect". Connectivity is the property that triggers resilient behaviours by "dissipating nascent cascades" Gutfraind (2012). The reaction of complex systems under sever conditions may not evolve in the same pattern. In these cases, it is important to ascertain the thresholds that discriminate different regimes (Carpenter et al., 2005). Similar studies focus on the percolation thresholds, which correspond to the minimal fraction of left nodes or edges that leads to the collapse of the network (Gao et al., 2015; Cohen et al., 2000; Bunde & Havlin, 1996; Gao et al., 2012; Cohen & Havlin, 2010). Other authors focus on planning and management and propose an adaptive management cycle (AMC) for implementing a resilient ecological network (Isaac et al., 2018). They start from spatial network theory and apply it to multispecies ecological networks. The key component of the AMC is the set of indicators, which are referred to the need to achieve Better, Bigger, More, and joined (BBMJ) habitat patches. These indicators will enter a monitoring system able to report on the status of the ecological network, identify plausible conservation actions, and verify their effectiveness. In similar terms, Hernantes et al. (2019) develop on a resilience maturity model (RMM) that addresses the resilience operationalization process for urban communities. The authors indicate a roadmap with the following five maturity stages: starting, moderate, advanced, robust, and vertebrate. The stages indicate the level of effectiveness of a variety of policies, which are classified according to the following four pillars: leadership and governance (L), preparedness (P), infrastructures and resources (I), and cooperation (C) among the stakeholders.

## 3. Methodology

We extend the approach adopted by De Montis et al. (2016), who assessed the resilience of the ecological network (EN) designed for the town of Nuoro, Italy. This EN is built considering the properties of the colonization of two vegetal target species *Olea europaea* and *Quercus ilex* through the dispersal of the seeds realized by the corresponding vector animal species (mostly, birds). The EN is modelled as a weighted network, where the nodes represent the centroids of the habitat patches and the edges the dispersal relation between the patches. The weight is attributed to each edge and measures the sum of seed dispersal probability, which is expressed as:

$$p_{ij} = f(\beta, d_{ij}) \tag{1}$$

where $i$ and $j$ stand for source and destination patches, $d_{ij}$ for the Euclidean distance between the centroid of the patches, and $\beta$ for an impedance coefficient considering the friction to movement due to space and time of propagule dispersal. Dispersal probability can show several regimes obeying, for instance, to exponential or Gaussian distributions (Clark et al, 1999). De Montis et al. (2016) used the concept of dispersal flux from patch $i$ to $j$, according to the following equation:

$$w_{ij} = \frac{ap_i}{ap_{tot}} p'_{ij} \tag{2}$$

where $ap_i$ is the area of source patch $i$ and $ap_{tot}$ is the area of the habitat under examination. $p'_{ij}$ is the probability of seed dispersal from $i$ to $j$, normalized by the sum of $i$'s weights. We adopted a version of equation (2) modified by De Montis et al. (2016), as follows:

$$w_{ij} = \frac{ap_i}{ap_{tot}} (p'_{ij,o} + p'_{ij,q} \cdot 10^{-3}) \tag{3}$$

where $p'_{ij,o}$ is the dispersal probability of Olive and $p'_{ij,q}$ is the dispersal probability of Holm oak. Dispersal capacity of Holm oak was estimated about thousand times weaker than that of Olive (Gómez, 2003; Mulas et al., 2003). According to De Montis et al. (2016) and Gómez (2003), the dispersal probability functions of Olive and Holm oak obey to a log-normal distribution, as follows:

$$p'_{ij,o} = 2.09 + \frac{7489.42}{\sqrt{2 \cdot 3.14} \cdot 0.53 \cdot d_{ij}} e^{\frac{-(\ln \frac{d_{ij}}{247.42})^2}{2 \cdot (0.53)^2}} \tag{4}$$

$$p'_{ij,q} = 2.09 + \frac{748.942}{\sqrt{2\cdot 3.14}\cdot 0.53\cdot d_{ij}} e^{\frac{-(\ln \frac{d_{ij}}{24.742})^2}{2\cdot(0.53)^2}} \tag{5}$$

De Montis et al. (2016) studied the spatial resilience of the EN by evaluating its ability to maintain the original properties (i.e. identity) in critical situations. These are modelled simulating three scenarios, where the patches are deleted because of probabilistic and deterministic fatal attacks. In Table 1, the types of attacks are described.

Please, place Table 1 about here

In the probabilistic approach, nodes are removed randomly to mimic casual errors. In the deterministic approaches, attacks are voluntarily directed to the patches to mimic targeted failures of most critical nodes. Two types of scenarios are considered. In type 1, patches are removed according to the decreasing values of their betweenness centrality (*BC*). *BC* is a very relevant measure of network topologic centrality, as it is a powerful index of global inter-centrality of a node, with respect to the rest of the nodes in the network. According to Freeman (1977), *BC* obeys to the following equation:

$$BC_r = \sum_{i,j\in N} \frac{\rho(i,j,r)}{\rho(i,j)} \tag{6}$$

where $\rho(i,j,r)$ is the number of shortest paths passing through node *r* and $\rho(i,j)$ is the total number of shortest paths in the graph. A shortest path is defined as a path connecting two nodes with the minimum number of edges. Nodes with the highest *BC* act as bridges providing shortcuts for reaching efficiently the other regions of a graph. In type 2, they are deleted, according to the decreasing figures of the probability of planning interference (*PPI*). *PPI* is a measure of the level of patch disturbance produced by land uses established according to the municipal master plan (*MMP*). PPI is calculated, according to the following expression:

$$PPI_i = f(A_i, LI_i, \phi_i) \tag{4}$$

where $A_i$ stands for the surface area of the patch, $LI_i$ for the land index (a combination indication of: i. the maximum volume than can be realized per unit of surface area and ii. the percentage of surface area that can be developed) and $\phi_i$ is a coefficient that accounts for the land use type (residential, industrial, agricultural, etc.) of patch *i*. *PPI* is higher for smaller patches, whose centroid is included in more aggressive (i.e. industrial) land use zones.

We reframe and expand the method proposed by De Montis et al. (2016) for studying spatial resilience of ENs, along three main issues. The first one regards the transition from the analysis of a single EN to the comparative assessment of the resilience of two -and prospectively many- ENs in the towns of Sassari and Nuoro (see also De Montis et al., 2019). Secondly, we consider a larger EN, since the Nuoro's EN in the beginning showed 236 and now embraces 1,000 patches. The third issue attains the selection of a larger number of variables (surrogates) able to model EN's resilience. Beyond the two variables considered by (De Montis et al., 2016), we have adopted other two variables, according to the AMC framework proposed by Isaac et al. (2018). Thus, we believe that the ideal set of indicators should be able to measure resilience in front of critical situations by monitoring -during patch removal- four properties of the habitat patches, i.e. quality of the colonization (better), extension of the surface area (bigger), minimum number of giant components (less), and maximum connectivity (joined). In Table 2, we report the variables studied in our investigation. Note that in the last column, we substitute "M" ("more") with "L" (the reciprocal "less");

thus, we insert the acronym BBLJ (instead of BBMJ proposed by Isaac et al., 2018), as the identity is maintained, when the corresponding variable is smaller.

Please, place Table 2 about here

The quality indicator *Q* refers to the level of affirmation of the target species in each patch and is calculated attributing -for each target species- a quantitative score (from 0 to 3) to the four stages of the colonization process: absence, renovation, young plants, and affirmation. Better ENs are supposed to be more resilient. The area indicator *A* is obtained summing up the surface area of the patches. Bigger ENs are likely more resilient. The indicator *N* stands for the number of disconnected giant components. Clearly, the smaller this number the more resilient the EN is. The last indicator F(T) consists of the sum of the weights, is calculated according to equation (3), and represents the total residual capacity of seed propagation throughout the EN. The higher F(T), the higher the relational capacity (thus, the resilience) of the EN. As the assessment is conceived in comparative terms, all indicators have been processed in order to normalize the values according to the following well-known min-max transformation:

$$x_n = \frac{x - x_{min}}{x_{max} - x_{min}} \qquad (5).$$

The indicators for both the ecological networks have been calculated by relying upon ad-hoc scripts developed in the Python 3 programming language (version 3.6.6). Python is an object-oriented, high-level and general-purpose programming language that offers both dynamic typing and binding options. Furthermore, it is an interpreted language that supplies, free of charge, countless specific packages for several fields, in order to ease programming development and tasks achievement (Python Software Foundation, 2019). Specifically, the module NetworkX has been used in order to facilitate the calculation of the indicators referred to Nuoro and the Sassari ENs. NetworkX is a Python package that offers several tools for the creation, manipulation, and study of complex networks (Hagberg et al., 2008). This package allows researchers to analyze and build networks, as well as design and implement new network algorithms. For the purpose of the analysis, NetworkX has been used to load the ENs structures in the Python environment and to automatize the probabilistic and deterministic attacks, namely remove node by node from the EN by means of specific rules, to the networks. Specifically, for the probabilistic attack, a Monte Carlo simulation has been implemented and adopted in the script, in order to average the results of 100 random attacks to the ENs. Conversely, the deterministic 1 and 2 approaches have been implemented by removing first the nodes with the highest value of *BC* and *PPI*. Finally, the results have been loaded, managed and normalized by means of Power BI (Microsoft, 2019), a complete business analytics solution to visualize data and share insights, by creating dashboards suitable to compare the different behaviors of the two ENs under the different attacks.

## 4. The case study of two ecological networks in Sardinia (Italy)

We apply our method to the comparative analysis of the resilience of two ENs studied by De Montis et al. (2019). They developed on complex network analyses for assessing centrality measures of two ENs for the Sardinian towns of Nuoro and Sassari, which present different urban and ecological properties. In Figures 1 and 2, we illustrate geographical context and characteristics of the ENs selected.

Please, place Figure 1 about here

Please, place Figure 2 about here

Sardinia is the second largest island of the well-defined geographic area of the Mediterranean basin characterised by a semiarid climate and the presence of the typical ever green maquis with its well-known vegetal and animal species. In this context, Nuoro (37,000 inhabitants) and Sassari (129,000) represent a small and middle size settlement and are located in the central-interior part and in a northern and more coastal zone of the island. Both the centres are provincial chief towns. While Nuoro shows a limited urban expansion and a peri-urban area strongly connected to agro-pastoral activities, Sassari has experienced in the last decades a very relevant expansion of its peripheral residential area that now includes once satellite settlements in contiguity -often-times- with the vast olive crown belting the center (see Figure 1). The ENs have been designed with the aim at reconnecting the external to the interior habitat and increasing (or at least stopping the decrease of) the level of biodiversity through actions typically adopted for defragmentation purposes. The construction of the ENs is based on the activity of two vegetal target species (*Quercus ilex*, *Olea europea*), which are very common in the urban (tree-lined avenues, public and private gardens) of the two towns. The systems include the same number (1,000) of patches (the nodes) -i.e. the habitats that are or can be colonized by the holm oak and olive tree- intertwined by edges representing the existence of seed dispersal between the patches (see Figure 2). Dispersal activity is guaranteed by a reasonable presence of frugivorous animal species (birds) that eat and regurgitate the seeds with a well-known spatial behaviour. The identification of the patches required the use of geographic information in vector and raster format (satellite photographs) and available through institutional web portals (see also De Montis et al., 2019). Information on land use zoning was extracted from the main local planning tools, i.e. the Municipal Master Plan (MMP) of Sassari and Nuoro (Municipality of Nuoro, 2017; Municipality of Sassari, 2015).

## 5. Results

In this section, we assess the resilience of the ENs of Nuoro and Sassari by presenting the results of the application of the BBLJ framework illustrated in Table 2. We do so with the help of three dashboards showing the decay trend of the four variables chosen during the node removal, according to the probabilistic (Figure 3), deterministic 1 (Figure 4), and deterministic 2 (Figure 5) approaches.

please, place Figure 3 about here

As for the probabilistic approach illustrated in Figure 3, both the ENs display a very good resilience. *Q* decays with a very similar linear trend for both the ENs. Likewise, A decreases roughly linearly in the two cases with alternate slight prevalence of Sassari's value with respect to Nuoro's. As for the N, the ENs remain organized in one giant component even when more than 90% of the patches is deleted. Nuoro's EN breaks in two sub-networks slightly earlier than Sassari's. The residual dispersal capacity decreases gradually and according to an exponential trend and approaches zero, when roughly the 80% of the patches is removed. *F*(*T*) is always larger for Nuoro's EN: a clear sign of a higher resilience of this EN with respect to the other.

please, place Figure 4 about here

A very different picture emerges, when we monitor the behaviour of the ENs under attacks obeying to the deterministic 1 approach with the preferential removal of the highest *BC* patches (Figure 4). *Q* decays sharply along a downward sloping line, whose steepness is sensibly higher than the corresponding line plotted in Figure 2-A. *Q* halves (in this sense, ENs' resilience halves), when only 20% of the nodes is removed. It approaches zero, just after 40% of the patches removed. *A* presents a stepwise decreasing trend (more evident for Nuoro's EN) showing severe reductions clearly visible since the removal of even very limited share of total number of patches. Overall, Sassari's EN remains more extended than the other EN. As for the *N* indicator, both the ENs start the subdivision into many networks, when roughly 30% of the patches is terminated. Sassari's EN breaks slightly earlier that Nuoro's EN. The residual dispersal capacity decreases at relevant and stepwise paces and tends to zero after 35% of the patches is deleted. In this respect, Nuoro's EN almost always shows a higher resilience than Sassari's EN.

please, place Figure 5 about here

As for the deterministic 2 approach targeting the attacks first to the removal of the patches with the highest values of *PPI*, Figure 5 demonstrates that both the ENs react exceptionally well. *Q* decays with slower pace even with respect to the corresponding trend reported for the probabilistic approach in Figure 2-A. It halves, when approximately 70% of the patches are removed. Sassari's EN is always more resilient than Nuoro's. With reference to indicator *A*, the very long plateau of the curves signifies that the ENs' total residual surface area remains unaltered until roughly 60% of the patches are removed. For the larger (i.e. more resilient, in this respect) EN of Nuoro, this condition holds even when 80% of the patches are deleted. Almost until the total deletion of the patches, the ENs maintain a structure consisting in a unique connected component (Figure 5-C). The ENs are more resilient in this case than under the probabilistic approach to the removal of patches (Figure 3-C). For both the ENs, total residual dispersal capacity decreases according to a linear regime; thus, the decay is slower than the corresponding trend obtained in the case of probabilistic approach to the removal of patches. Also, in this case, Nuoro's EN maintains a higher total residual dispersal capacity (i.e., is more resilient) that Sassari's EN.

## 6. Discussion

The application of the BBLJ indicator-based assessment to the comparative evaluation of spatial EN resilience yields a picture, where some major results emerge. The first regards the confirmation of the evidence found by De Montis et al. (2016) for a smaller (i.e. with a much smaller number of patches) pilot EN in Nuoro. Both the ENs are more resilient in the face of a random removal of the patches (in the probabilistic approach) than against the deterministic 1 approach, where the attacks are targeted first to the highest *BC* patches. Comparing this result to what Crucitti et al. (2004) have found, we could infer that both the ENs belongs to the class of scale-free (or, at least, broad law) networks, which are proved to react with a much lower resilience. In addition, we can advance that this higher resilience to random removal of patches is an invariant (not dependent on the size, i.e. number of patches) property (at least of) of the Nuoro's EN. This also prompts a corollary observation, which agrees to the following intuitive concept: irrespectively of the size, the best way to increase the resilience of an EN is taking care of foremostly the high *BC* patches, which act as global hubs providing useful nodes for shortcuts (easy ways to the dispersal of seeds). The second issue attains the evidence that often-times Nuoro's EN is more resilient than Sassari's EN. This is due to several intertwined situations attaining probably the pattern of extension and quality of the patches, due to more favourable conditions of colonization and development of the vegetal species in Nuoro than in Sassari. A third important result regards the very good reaction of the ENs to the deterministic 2 approach ruling the attack of the patches, which are removed first when the *PPI* is higher. This clearly means that spatial planners of the towns of Nuoro and Sassari have protected the landscape -even unconsciously- so that the designed ENs are more resilient than in the case of probabilistic approach to the removal of patches, according to a random distribution (mimicking the absence of planning). One more issue emerges, when we compare these results to the Nuoro EN's reaction to deterministic 2 approach removal of patches described by De Montis et al. (2016). The roughly five-times larger EN here designed for Nuoro displays a much greater resilience with respect to the smaller pilot EN. This suggests that the interplay between land use pattern agreed in the MMP of Nuoro and spatial distribution of the patches favours the development of a larger EN. With a different outcome with respect to the reaction to deterministic 1 approach to the removal of patches, in this case resilience is proportional to the size (i.e. the number of patches). There are reasons to believe that this very good performance obtained without an EN protection-oriented design of the MMP could increase, if the design of that planning tool is explicitly directed to the development of an EN.

## 7. Conclusions

In this paper, we have presented an operationalization of the assessment of the resilience of ENs. In our exercise, we have demonstrated that understanding resilience is the first step toward an efficient management and planning of actions directed to strengthen the same ENs. With respect to the research questions indicated in the Introduction, we elaborate on some concluding remarks. As for $RQ_1$ (is it possible to construct a method able to measure the resilience of ecological networks?), we have developed on the framework proposed by Isaac et al. (2018), who stress that ideal EN resilience assessment frameworks rely on a set of indicators that, even as surrogate (i.e. indirect) measures, are able to scope resilience under different perspectives. According to this suggestion, we have reframed an approach to resilience assessment proposed by De Montis et al. (2016) by monitoring the decay of four main characteristics of an EN when subject to critical disturbances simulated by probabilistic and deterministic removal of the patches. Doing so, we obtained a more complete picture of the resilience trajectory, as four different phenomena are illustrated. With respect to $RQ_2$ (how can this method be addressed to the comparison of two -or more- ecological networks?), we have sought the tools and algorithms to an easy management of the reading and interpretation of the results. In this sense, indicator values have been normalized properly and plotted in unique dashboards corresponding to each patch removal pattern. These modifications allow an easy grasping of the main phenomena characterizing the reaction of the two ENs, in front of the different types of attacks. A complex picture emerges, as for some indicators Nuoro’s EN is more resilient and for others not. This suggests that resilience assessment implies not trivial and composed judgement and should not be tackled in binary terms.

While the results commented are relevant, this work opens the way to other important issues. The first regards the need to test the validity of the policy outcomes in a real-world experiment. One of the main actions to be recommended after the spatial resilience analysis is the protection first of the high *BC* patches of the ENs. In fact, a series of targeted attacks to the most global-central patches leads to the dissection of the ENs in a relatively short round. Monitoring protection actions on selected patches would require resources and time enough to apply those actions and follow up the performance of the ENs (i.e. quality of colonization by the target species). In addition, proper testing should be developed to ascertain the level of fitness of the modelled outcomes and the effective functional properties of the ENs. The excellent resilience of both the ENs in front of the deterministic 2 approach recalls the need to monitor the ENs' evolution under the land use regime indicated by the MMPs. In this way, we could verify whether the modelled resilience performance promised are effectively maintained in the medium and long run. The second attains a finer study of the decay of the variables describing ENs' resilience. In our investigation, we just assess a general downward sloping trend of the four variables, which sometimes present a smooth decrease and other times mark more evident and stepwise diminutions. The decrease of resilience may lead to configurations, where the system -even weaker than before- is still able to recover and eventually attain newer and stronger settings. But it may also evolve into more severe situations, where too low values of resilience measures are a sign of the attainment of too depleted characteristics. In these conditions, the ENs may not be able to recover unless very radical, extensive and expensive actions are immediately applied. The existence of one or more thresholds could explain different patterns of ENs' reactions (i.e. resilience paths). We will be focusing on these issues in future studies.

**Acknowledgement**. This work is connected to the research project "Ecological networks and landscape planning: case studies in Sardinia" approved after peer review evaluation by the University of Sassari and funded by Fondazione di Sardegna.

## References

1. Albert, R., & Barabási, A.L. (2002). Statistical mechanics of complex networks. Review of Modern Physics, 74(1), 47–97. https://doi.org/10.1103/RevModPhys.74.47.
2. Balsas, C.J.L. (2014). Downtown resilience: A review of recent (re)developments in Tempe, Arizona. Cities, 36, 158-169. http://doi.org/10.1016/j.cities.2012.10.002
3. Benedict, M.A. & Mcmahon, E.T. (2002). Green Infrastructure: Smart Conservation for the 21st Century. Washington: Sprawl Watch Clearinghouse. http://www.sprawlwatch.org/greeninfrastructure.pdf
4. Bunde, A., Havlin, S. (1996). Fractals and Disordered Systems. New York (NY): Springer.
5. Carpenter, S.R., Westley, F. & Turner, M.G. (2005). Surrogates for resilience of social-ecological systems. Ecosystems, 8(8), 941-944. http://doi.org/10.1007/s10021-005-0170-y
6. Clark, J.S., Silman, M., Kern, R., Macklin, E., HilleRisLambers, J., 1999. Seed dispersal near and far: patterns across temperate and tropical forests. Ecology, 80(5), 1475-1494. https://doi.org/10.1890/0012-9658(1999)080[1475:SDNAFP]2.0.CO;2
7. Christopherson, S., Michie, J., and Tyler, P. (2010). Regional resilience. Theoretical and empirical perspectives. Cambridge Journal of Regions, Economy and Society, 3(1), 3–10. http://doi.org/10.1093/cjres/rsq004
8. Cohen, J.E. (1995). Population growth and earth’s human carrying capacity. Science, 269(5222), 341-346. http://doi.org/10.1126/science.7618100
9. Cohen, R., Erez, K., Ben-Avraham, D., & Havlin, S. (2000). Resilience of the Internet to random breakdowns. Physical Review Letters, 85, 4626-4628. http://doi.org/10.1103/PhysRevLett.85.4626
10. Cohen, R. & Havlin, S. (2010). Complex Networks: Structure, Robustness and Function. Cambridge, UK: Cambridge University Press.
11. Collier, M. J., Nedović-Budić, Z., Aerts, J., Connop, S., Foley, D., Foley, K., … Verburg, P. (2013). Transitioning to resilience and sustainability in urban communities. Cities, 32, S21–S28. http://doi.org/10.1016/j.cities.2013.03.010
12. Crucitti, P., Latora, V., Marchiori, M., & Rapisarda, A. (2004). Error and attack tolerance of complex networks. Physica A: Statistical Mechanics and its Applications, 340(1-3), 388-394. http://doi.org/10.1016/j.physa.2004.04.031
13. Cumming, G.S., Barnes, G., Perz, S., Schmink, M., Sieving, K. E., Southworth, J., … Van Holt, T. (2005). An exploratory framework for the empirical measurement of resilience. Ecosystems, 8, 975–987. http://doi.org/10.1007/s10021-005-0129-z
14. De Montis, A., Caschili, S., Mulas, M., Modica, G., Ganciu, A., Bardi, A., … Fichera, C. R. (2016). Urban-rural ecological networks for landscape planning. Land Use Policy, 50, 312–327. http://10.1016/j.landusepol.2015.10.004
15. De Montis, A., Ganciu, A., Cabras, M., Bardi, M., Mulas, M. (2019). Comparative Ecological Network Analysis: An Application to Italy. Land Use Policy, 81, 714-724. http://doi: 10.1016/j.landusepol.2018.11.043

16. Dorogovtsev, S.N., Goltsev, A.V., Mendes, J.F.F., & Samukhin, A.N. (2003). Spectra of complex networks. Physical Review E, 68, 046109 (1-10). https://doi.org/10.1103/PhysRevE.68.046109.
17. Fall, A., Fortin, M.J., Manseau, M., & O’Brien, D. (2007). Spatial graphs: principles and applications for habitat connectivity. Ecosystems, 10, 448–461. https://doi.org/10.1007/s10021-007-9038-7.
18. Folke, C., Carpenter, S.R., Walker, B., Scheffer, M., Chapin, T., & Rockström, J. (2010). Resilience thinking: Integrating resilience, adaptability and transformability. Ecology and Society, 15(4), 20. http://doi.org/10.5751/ES-03610-150420
19. Folke, C. (2016). Resilience (Republished). Ecology and Society, 21(4), 44. http://doi.org/10.5751/ES-09088-210444
20. Freeman, L.C., 1977. A set of measures of centrality based on betweenness. Sociometry, 40, 35-41. http://doi.org/10.2307/3033543
21. Gao, J., Buldyrev, S.V., Stanley, H.E., & Havlin, S. (2012). Networks formed from interdependent networks. Nature Physics, 8, 40-48. http://doi.org/10.1038/nphys2180
22. Gao, J., Liu, X., Li, D., & Havlin, S. (2015). Recent progress on the resilience of complex networks. Energies, 8(10), 12187-12210. http://doi.org/10.3390/en81012187
23. Gómez, J.M., 2003. Spatial patterns in long-distance dispersal of Quercus ilex acorns by jays in a heterogeneous landscape. Ecography, 26, 573-584. https://doi.org/10.1034/j.1600-0587.2003.03586.x
24. Gutfraind A. (2012). Optimizing Network Topology for Cascade Resilience. In: Thai M., Pardalos P. (eds) Handbook of Optimization in Complex Networks. New York, NY: Springer, 37-59. http://doi.org/10.1007/978-1-4614-0857-4_2
25. Hagberg, A.A., Schult, D.A. & Swart P.J. (2008). Exploring network structure, dynamics, and function using NetworkX. In Varoquaux G., T. Vaught & J. Millman (Eds) Proceedings of the 7th Annual Python in Science Conference (SciPy2008), Pasadena, California, USA, 19-24 August 2008, pp. 11–15. http://conference.scipy.org/proceedings/scipy2008/ [accessed 1 April 2019]
26. Hagen, M., Kissling, W.D., Rasmussen, C., De Aguiar, M.A.M., Brown, L.E., Carstensen, D.W., Alves-Dos-Santos, I., Dupont, Y.L., Edwards, F.K., Genini, J., Guimarães, P.R., Jenkins, G.B., Jordano, P., Kaiser-Bunbury, C.N., Ledger, M.E., Maia, K.P., Darcie Marquitti, F.M., Mclaughlin, Ó., Morellato, L.P.C., O’Gorman, E.J., Trøjelsgaard, K., Tylianakis, J.M., Morais Vidal, M., Woodward, G., & Olesen, J.M. (2012). Biodiversity, species interactions and ecological networks in a fragmented world. Advances in Ecological Research, 46, 89–210. https://doi.org/10.1016/B978-0-12-396992-7.00002-2.
27. Handmer, J. & Dovers, S. (1996). A typology of resilience. Rethinking institutions for sustainable development. Industrial and Environmental Crisis Quarterly, 9(4), 482–511. http://doi.org/10.1177/108602669600900403
28. Hernantes, J., Maraña, P., Gimenez, R., Sarriegi, J. M., & Labaka, L. (2019). Towards resilient cities: A maturity model for operationalizing resilience. Cities, 84, 96-103. http://doi.org/10.1016/j.cities.2018.07.010

29. Holling, C.S. (1973). Resilience and Stability of Ecological Systems. Annual Review of Ecology and Systematics, 4, 1–23. http://doi.org/10.1146/annurev.es.04.110173.000245
30. Ings, T.C., Montoya, J.M., Bascompte, J., Blüthgen, N., Brown, L., Dormann, C. F., … Woodward, G. (2009). Ecological networks-beyond food webs. The Journal of Animal Ecology, 78(1), 253–69. http://doi.org/10.1111/j.1365-2656.2008.01460.x
31. Isaac, N.J.B., Brotherton, P.N.M., Bullock, J.M., Gregory, R.D., Boehning-Gaese, K., Connor, B., … Mace, G.M. (2018). Defining and delivering resilient ecological networks: Nature conservation in England. Journal of Applied Ecology, 55(6), 2537-2543. http://doi.org/10.1111/1365-2664.13196
32. Janssen, M.A., Bodin, Ö., Anderies, J.M., Elmqvist, T., Ernstson, H., McAllister, R. R. J., … Ryan, P. (2006). Toward a network perspective of the study of resilience in social-ecological systems. Ecology and Society, 11(1). http://www.ecologyandsociety.org/vol11/iss1/art15/
33. Matthews, T., Lo, A.Y., & Byrne, J.A. (2015). Reconceptualizing green infrastructure for climate change adaptation: Barriers to adoption and drivers for uptake by spatial planners. Landscape and Urban Planning, 138, 155-163. http://doi.org/10.1016/j.landurbplan.2015.02.010
34. Meerow, S., & Newell, J.P. (2017). Spatial planning for multifunctional green infrastructure: Growing resilience in Detroit. Landscape and Urban Planning, 159, 62-75. http://doi.org/10.1016/j.landurbplan.2016.10.005
35. Microsoft (2019). Power BI. https://powerbi.microsoft.com/en-us/what-is-power-bi/ [accessed 1 April 2019]
36. Mulas, M., Perinu, B., Ruiu, E.P., 2003. Ecologia delle forme selvatiche di Olea europaea L. in una formazione a macchia mediterranea, [Wild Olea europaea L. ecology in a maquis plant cover] Atti del III Congresso Nazionale SISEF "Alberi e Foreste per il Nuovo Millennio", Viterbo, 15-18 ottobre 2001, pp. 159-165.
37. Municipality of Nuoro (2015). Piano Urbanistico Comunale [Municipal Master Plan]. *Official bulletin of the Autonomous Region of Sardinia (BURAS),11*, March 12, 2015.
38. Municipality of Sassari (2014). Piano Urbanistico Comunale [Municipal Master Plan]. *Official bulletin of the Autonomous Region of Sardinia (BURAS),58*, December 11, 2014.
39. Naveh, Z. (2000). What is holistic landscape ecology? A conceptual introduction. Landscape and Urban Planning, 50, 7–26. http://doi.org/10.1016/S0169-2046(00)00077-3
40. Opdam, P., Steingröver, E., & Rooij, S. Van. (2006). Ecological networks: A spatial concept for multi-actor planning of sustainable landscapes. Landscape and Urban Planning, 75(3–4), 322-332. http://doi.org/10.1016/j.landurbplan.2005.02.015
41. Palang, H., Alumae, H., & Mander, U. (2000). Holistic aspects in landscape development: A scenario approach. Landscape and Urban Planning, 50(1–3), 85–94. http://doi.org/10.1016/S0169-2046(00)00081-5
42. Python Software Foundation (2019). Python Language Reference, version 3.6. http://www.python.org [accessed 1 April 2019]
43. Rees, W.E. (1996). Revisiting carrying capacity: Area-based indicators of sustainability. Population and Environment, 17(3), 195-215. http://doi.org/10.1007/BF02208489

44. Shaw, K. (2012). The rise of the resilient local authority? Local government studies, 38(3), 281–300. http://doi.org/10.1080/03003930.2011.642869
45. Urban, D.L., Minor, E.S., Treml, E.A., & Schick, R.S., 2009. Graph models of habitat mosaics. Ecology Letters, 12, 260–273. https://doi.org/10.1111/j.1461-0248.2008.01271.x.
46. Westley, F., Carpenter, S.R., Brock, W.A., Holling, C.S., & Gunderson, L.H. (2002). Why systems of people and nature are not just social and ecological systems. In L.H. Gunderson and C. Holling (Eds), Panarchy: Understanding Transformations in Human and Natural Systems. Washington: Island Press, 103–119. http://doi.org/10.1098/rspb.1991.0121

List of Tables' captions

Table 1

| **Type of attack** | **Description** |
|---|---|
| Probabilistic | Patch are deleted randomly |
| Deterministic 1 | Patch are terminated, according to inverted order of BC |
| Deterministic 2 | Patch are terminated, according to inverted order of PPI |

Table 2

| **Variables** | **Code** | **Description** | **BBLJ indicator type** |
|---|---|---|---|
| Quality | Q | Sum of the patch degree of vegetal development of the target species | Better |
| Area | A | Sum of the extension of the patch surface area | Bigger |
| Components | N | Number of disconnected network giant components | Less |
| Dispersal | F(T) | Sum of the weights (probability of seed dispersal among the patches) | Joined |

List of Figures' captions

Figure 1 Regional and municipal context of the areas selected for building the ecological networks of Nuoro (left) and Sassari (right).

Figure 2 Weighted network representation of the ecological networks of Nuoro (left) and Sassari (right).

Figure 3 Comparative spatial resilience analysis of the ecological networks of Nuoro and Sassari under probabilistic attack. In the dashboard, BBLJ indicators are plotted by number of removed nodes. Diagrams are set clockwise starting from top left: Q, A, N, and F(T). All indicators but N are normalized. Curves for Nuoro's EN are marked in green, for Sassari's EN in black.

Figure 4 Comparative spatial resilience analysis of the ecological networks of Nuoro and Sassari under (deterministic 1) BC attack. In the dashboard, BBLJ indicators are plotted by number of removed nodes. Diagrams are set clockwise starting from top left: Q, A, N, and F(T). All indicators but N are normalized. Curves for Nuoro's EN are marked in green, for Sassari's EN in black.

Figure 5 Comparative spatial resilience analysis of the ecological networks of Nuoro and Sassari under (deterministic 2) PPI attack. In the dashboard, BBLJ indicators are plotted by number of removed nodes. Diagrams are set clockwise starting from top left: Q, A, N, and F(T). All indicators but N are normalized. Curves for Nuoro's EN are marked in green, for Sassari's EN in black.

Figure 1

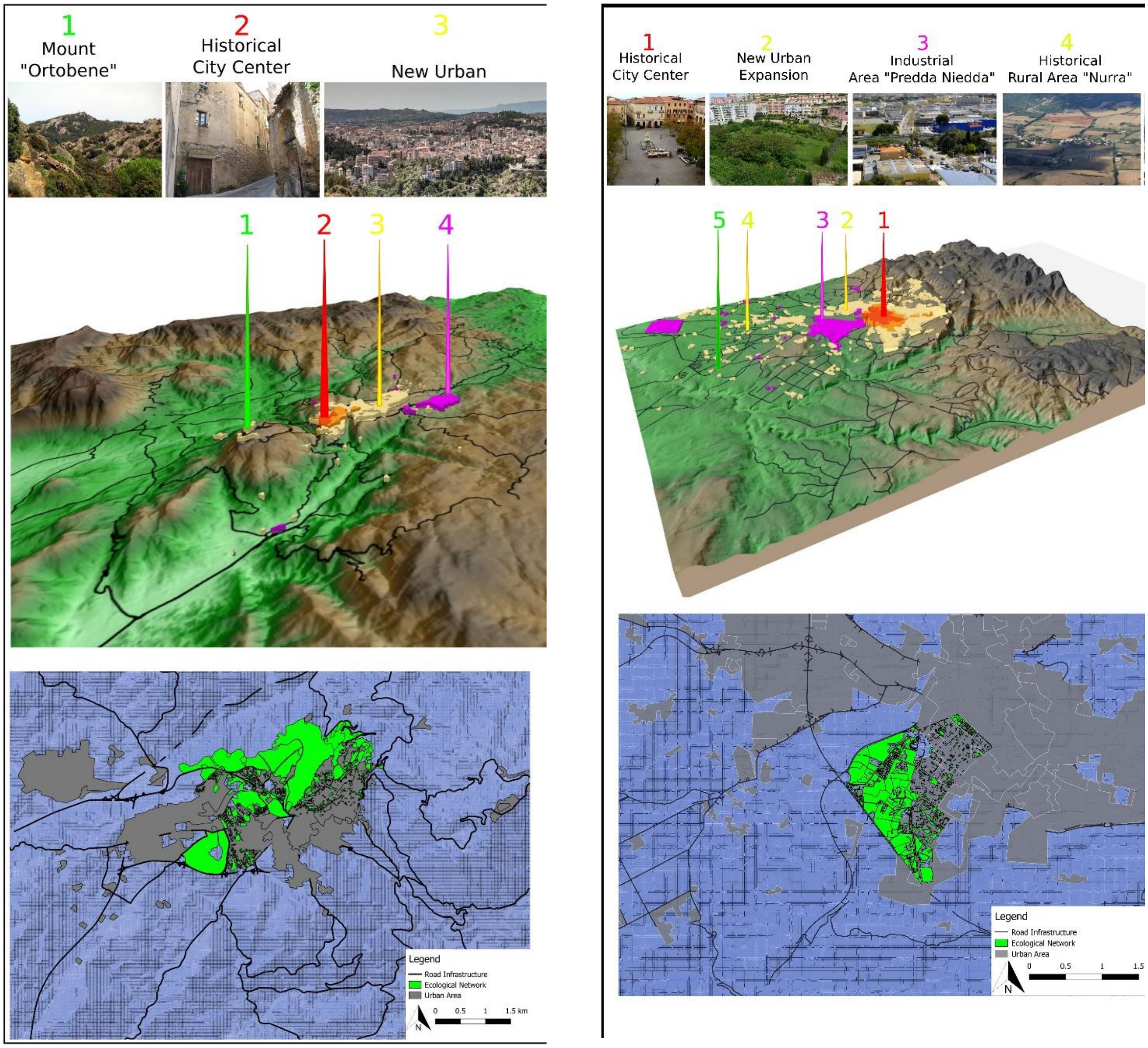

1
Mount "Ortobene"
2
Historical City Center
3
New Urban
1
2
3
4
Legend
Road Infrastructure
Ecological Network
Urban Area
N
0 0.5 1 1.5 km
1
Historical City Center
2
New Urban Expansion
3
Industrial Area "Predda Niedda"
4
Historical Rural Area "Nurra"
5
4
3
2
1
Legend
Road Infrastructure
Ecological Network
Urban Area
N
0 0.5 1 1.5

Figure 2

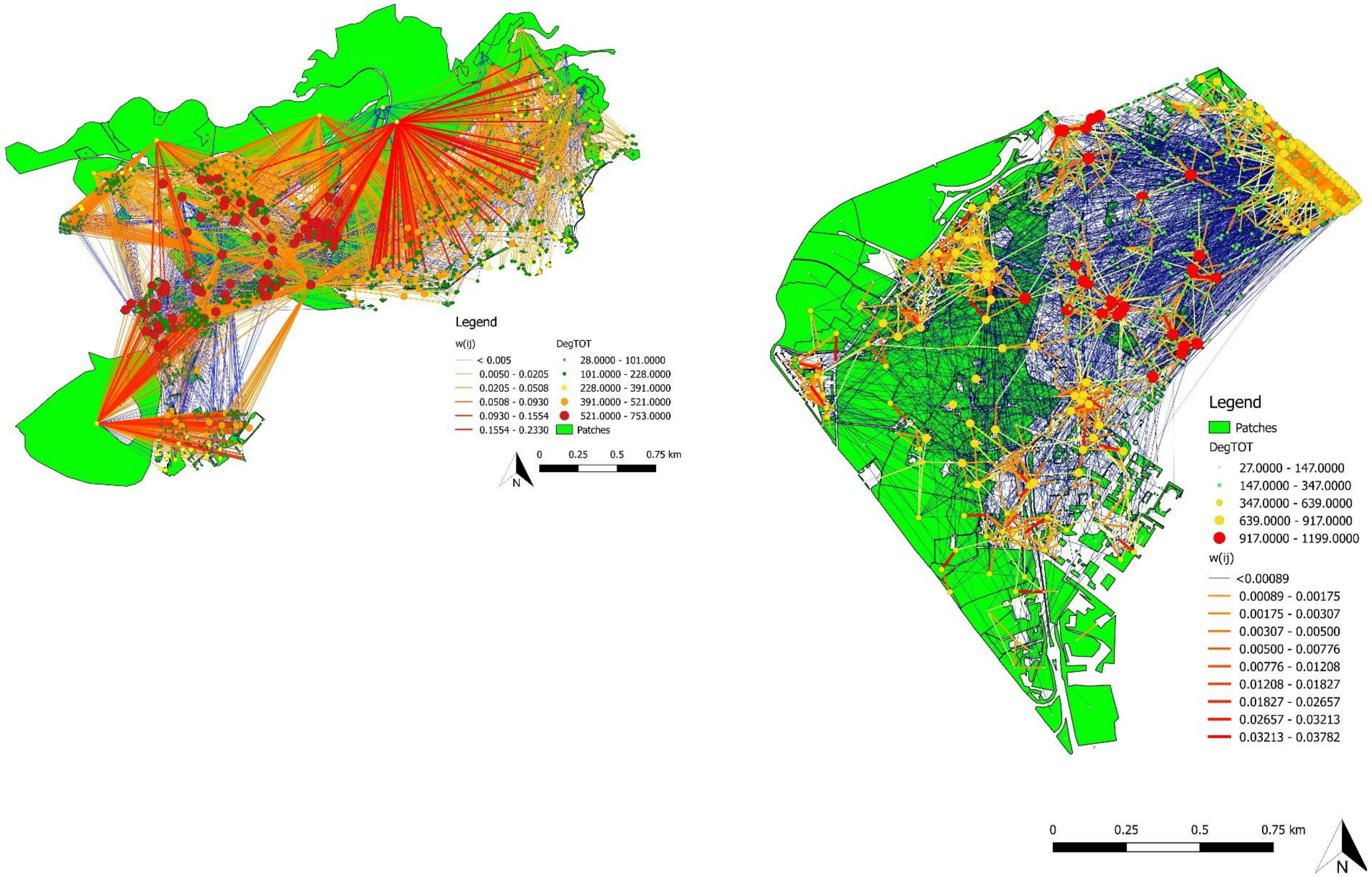

Legend
w(ij)
< 0.005
0.0050 - 0.0205
0.0205 - 0.0508
0.0508 - 0.0930
0.0930 - 0.1554
0.1554 - 0.2330
DegTOT
28.0000 - 101.0000
101.0000 - 228.0000
228.0000 - 391.0000
391.0000 - 521.0000
521.0000 - 753.0000
Patches
0
0.25
0.5
0.75 km
N
Legend
Patches
DegTOT
27.0000 - 147.0000
147.0000 - 347.0000
347.0000 - 639.0000
639.0000 - 917.0000
917.0000 - 1199.0000
w(ij)
<0.00089
0.00089 - 0.00175
0.00175 - 0.00307
0.00307 - 0.00500
0.00500 - 0.00776
0.00776 - 0.01208
0.01208 - 0.01827
0.01827 - 0.02657
0.02657 - 0.03213
0.03213 - 0.03782
0
0.25
0.5
0.75 km
N

Figure 3

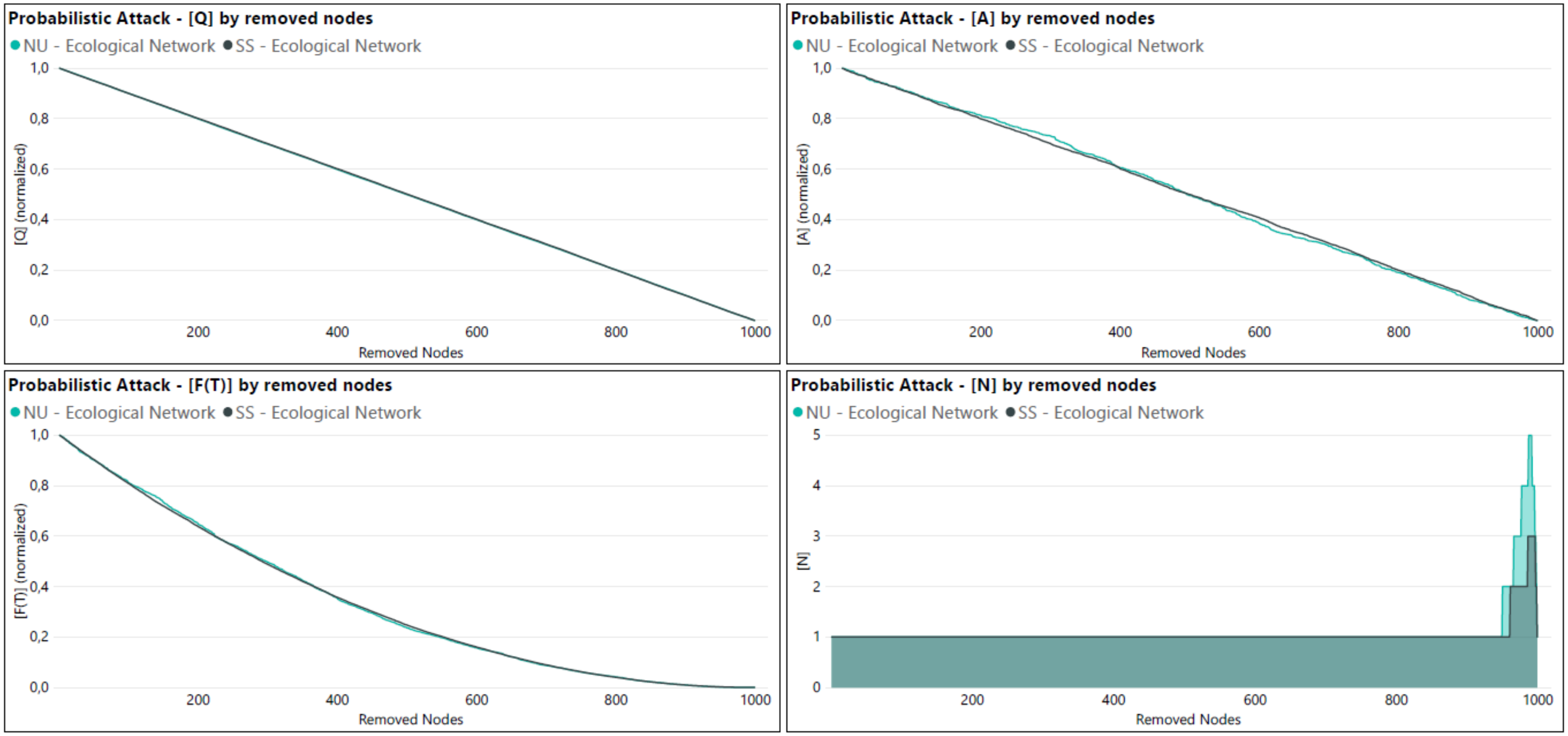

Probabilistic Attack - [Q] by removed nodes
● NU - Ecological Network ● SS - Ecological Network
[Q] (normalized)
1,0
0,8
0,6
0,4
0,2
0,0
200
400
600
800
1000
Removed Nodes
Probabilistic Attack - [A] by removed nodes
● NU - Ecological Network ● SS - Ecological Network
[A] (normalized)
1,0
0,8
0,6
0,4
0,2
0,0
200
400
600
800
1000
Removed Nodes
Probabilistic Attack - [F(T)] by removed nodes
● NU - Ecological Network ● SS - Ecological Network
[F(T)] (normalized)
1,0
0,8
0,6
0,4
0,2
0,0
200
400
600
800
1000
Removed Nodes
Probabilistic Attack - [N] by removed nodes
● NU - Ecological Network ● SS - Ecological Network
[N]
5
4
3
2
1
0
200
400
600
800
1000
Removed Nodes

Figure 4

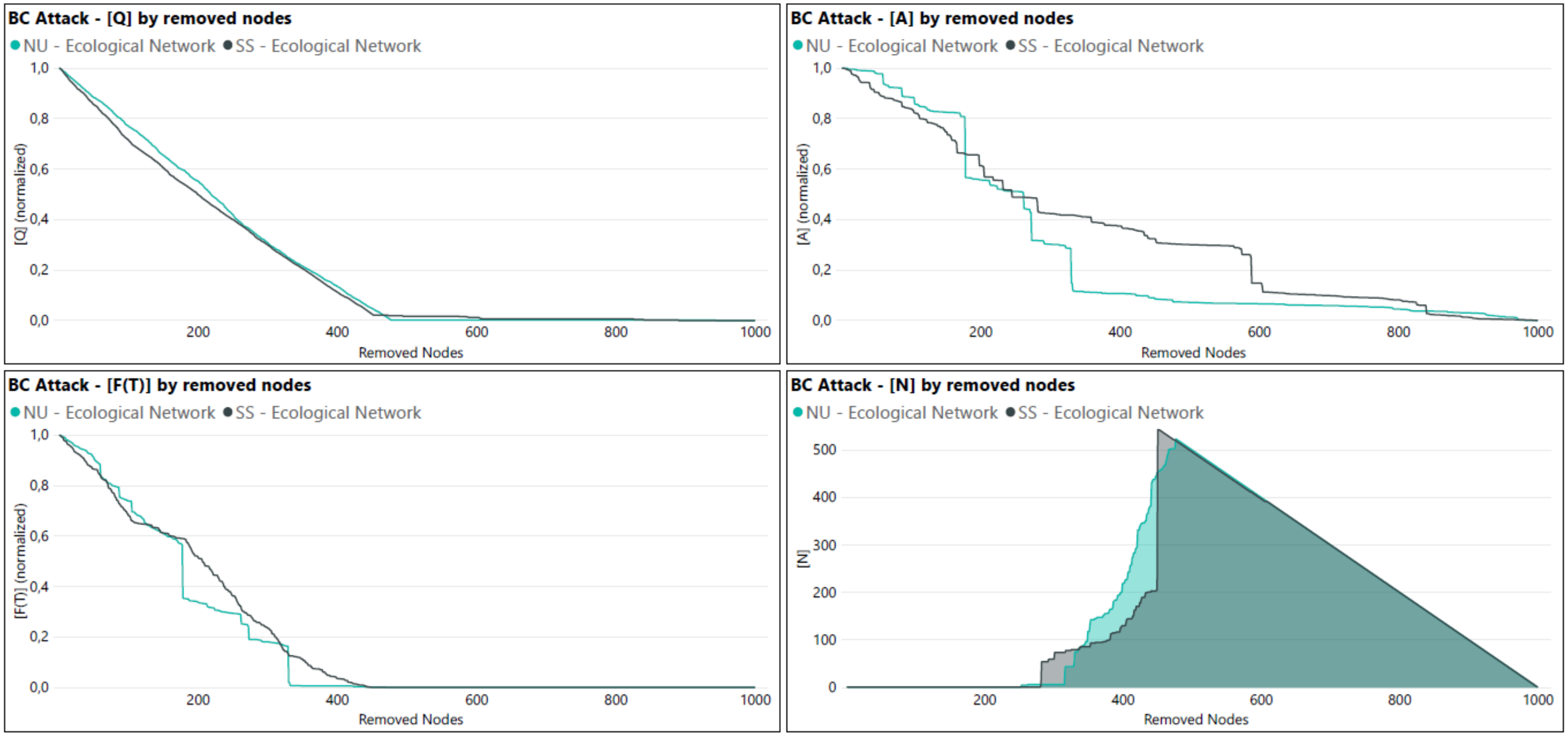
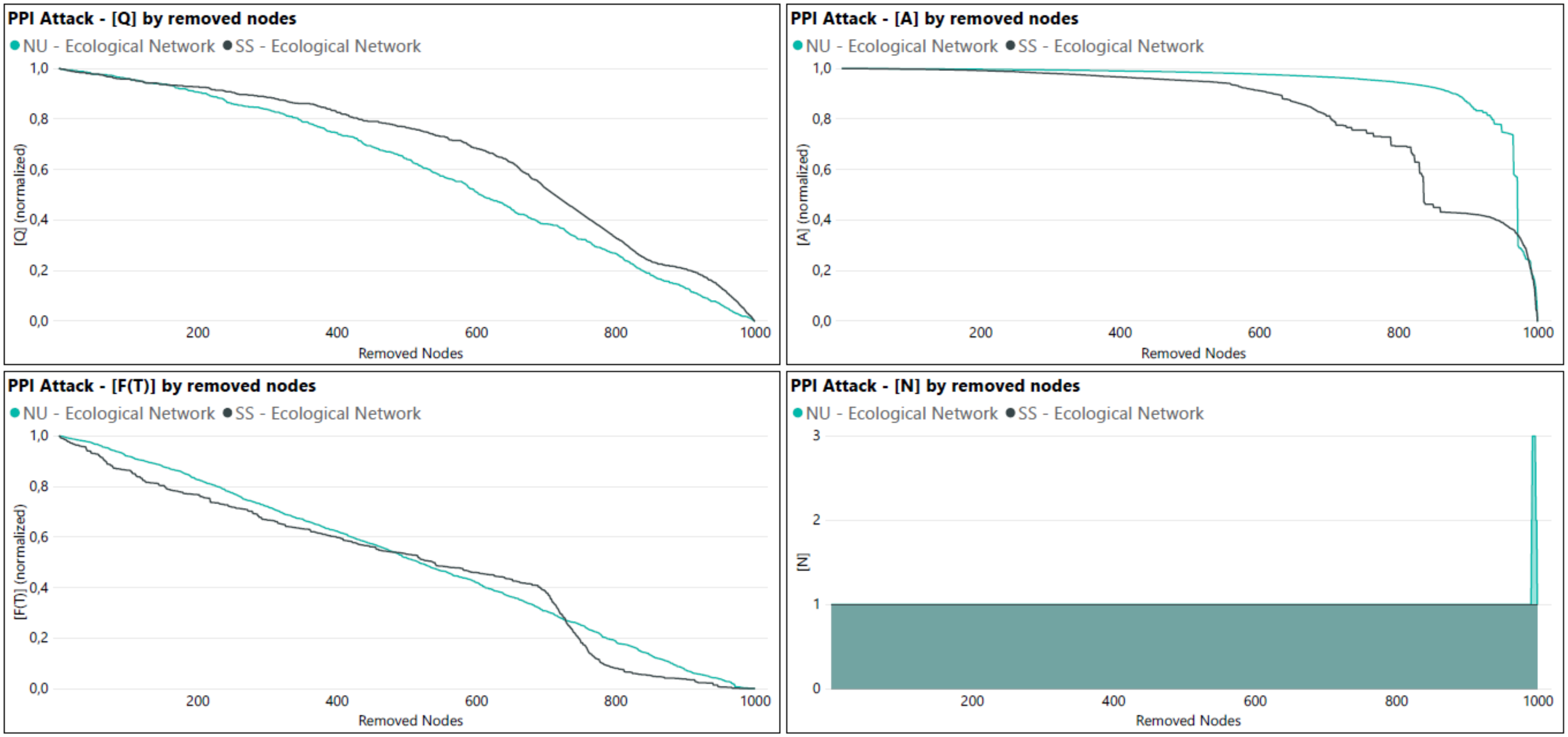

BC Attack - [Q] by removed nodes
● NU - Ecological Network ● SS - Ecological Network
[Q] (normalized)
1,0
0,8
0,6
0,4
0,2
0,0
200
400
600
800
1000
Removed Nodes
BC Attack - [A] by removed nodes
● NU - Ecological Network ● SS - Ecological Network
[A] (normalized)
1,0
0,8
0,6
0,4
0,2
0,0
200
400
600
800
1000
Removed Nodes
BC Attack - [F(T)] by removed nodes
● NU - Ecological Network ● SS - Ecological Network
[F(T)] (normalized)
1,0
0,8
0,6
0,4
0,2
0,0
200
400
600
800
1000
Removed Nodes
BC Attack - [N] by removed nodes
● NU - Ecological Network ● SS - Ecological Network
[N]
500
400
300
200
100
0
200
400
600
800
1000
Removed Nodes

Figure 5



PPI Attack - [Q] by removed nodes

PPI Attack - [A] by removed nodes

PPI Attack - [F(T)] by removed nodes

PPI Attack - [N] by removed nodes