Comparative ecological network analysis: an application to Italy

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## Abstract

Ecological networks (ENs), i.e. compounds of a set of patches interconnected through a set of corridors, are major strategies for counteracting landscape fragmentation in stressed urban, peri-urban and rural domains. They are adopted in many cases worldwide and their success or difficult rooting can be used as a living indicator of the inclination of human settlements to favour the development of green systems. We aim at constructing a network analysis method and testing it to the comparative study of two ENs to be developed in Sassari and Nuoro, Italy. We will study ENs with the same number of nodes, analyse the size of the patches, and scrutinize the main variables expressing the topological and weighted centrality. This approach allows us to locate the hotspots of the ENs, i.e. the places that need to be protected from external negative drivers. Results demonstrate that the method is useful, as it helps finding similarities and dissimilarities in different ecological systems and confirms that network analysis has very good potential when applied in a comparative modality.

**Keywords**: landscape fragmentation; ecological networks; comparative study; complex networks analysis; centrality; peri-urban settlements

## 1. Introduction

The development of human settlements exerts interference over the equilibrium and functional dynamics of the environment and the landscape. The construction of a variety of urban centres (from metropolitan areas to small villages) and of the necessary transport and mobility infrastructures has the direct effect of the interposition of many barriers. These artificial buildings act as interpositions and interrupt the continuity originally observed in natural wide areas. Landscape fragmentation (LF) is the phenomenon, according to which the initial very large parts of habitat (also called patches) are progressively cut and divided in even smaller and more isolated fragments (Fichera et al., 2015). LF has many shortcomings, such as reduced animal mobility and vegetal seed dispersal activity that should be counteracted to achieve healthier landscapes in contemporary peri-urban settlements. A major strategy to diminish LF, i.e. defragmentation, is the design and implementation of structures able to reconnect the patches in larger and more robust ensembles. In this regard, ecological networks (EN) are documented to serve the cause, as they allow the re-joining of the patches through the different parts of an urban settlement from the core to the periphery (Bennett and Mulongoy, 2006). A prominent method to support the design on ENs is the ecological network analysis (ENA), which enables the construction and analysis of ENs starting from their relational and functional properties (Schramski et al., 2004). ENA consist of the application of network analysis to the study of ecological systems. Network analysis is a field of science that studies complex systems by projecting their properties over a graph including individual entities (modelled as nodes) interconnected through links. This prominent research area has revamped in the last twenty years, thanks to an even higher processing power, which enables scientists to investigate very large systems in many fields (including biology, sociology, and engineering) (Albert and Barabási, 2002). Our study is mainly focused on mutualistic webs, like relations within ecosystem services such as pollination and seed dispersal. These are the cases, in particular, of frugivore networks, where plants interact with their animal seed dispersers (Ings et al., 2009). One of the major advantages of network analysis is that it enables the comparison of apparently different systems by adopting very simple metrics, thus it adds a unifying perspective to the study of similarities and differences and their rationales. Many authors used network analysis in comparative approaches for studying ecological systems (see Théau et al., 2015).

In this paper, we aim at applying complex network analyses to support the design of two ENs for the towns of Sassari and Nuoro, Italy. We compare these systems by setting the same number of patches and focusing on naturalistic characterisation and centrality properties. While achieving this objective, we are interested in answering to the following research questions (RQs). RQ1 regards the possibility to compare different ENs in a simple and intuitive way through network analysis. We will develop on the application of a method -namely Comparative Ecological Network Analysis (CENA)- able to model ENs as frugivorous networks and to simplify the study of two (or ideally more) complex ecosystems. RQ2 attains the opportunity to assess the most important patches by means of network analysis. In this respect, we will focus on network centrality and investigate on the vulnerability of the ENs.

This paper unfolds as follows. In the next section, we will summarize the state of the literature on the last advances in the domain of ENs and LF, the application of network analysis to the study of ecological systems, and the adoption of comparative approaches to EN modelling. In section 3, we will recall the main characteristics of the approach adopted and based on complex network analysis and describe the application of the method to the comparison of two ENs in the towns of Sassari and Nuoro, Italy. In section 4, we will report on the results of the application, while in section 5 we will discuss the results and present the conclusions of this paper.

## 2. State of the art summary

### *2.1 Ecological networks and landscape defragmentation*

Urban settlements and their expansion in peri-urban and rural domains often triggers the rise of porosities and fringes, where the original large habitats are divided in several smaller and more isolated pieces. This well-known phenomenon is termed landscape fragmentation (LF) and is associated to a degradation of ecological properties including biodiversity and basic functional mechanisms (Fichera et al., 2015; Romano and Zullo, 2012; Fahrig, 2013; Vizzari and Sigura, 2015). LF is a critical aspect of the human-landscape interplay and must be counteracted through systemic actions designed to defragment the landscape by reconnecting the natural elements in a new evolving ensemble. In this respect, a major strategy adopted implies the development of ecological networks, i.e. systems of individual entities (patches) intertwined in a web of connections depicted by functional relations or associations (Hagen et al., 2012). An EN includes core areas (focal individual part of a landscape), corridors (material and immaterial support to the connection of, or movement between, core areas), and buffer zones (protection areas surrounding the other two types of areas) (Jongman, 1995; Bennett, 2004). The adoption of ENs in landscape policy making and planning has been documented in a lot of examples worldwide (Bennett and Mulongoy, 2006) and in Europe (Bloemmen and van der Sluis, 2004). Italy is also quite active, as regional administrations are responsible of designing, realizing and managing regional ENs (De Montis et al., 2016).

### *2.2 Complex network analysis approach to the study of ecological networks*

In a recent editorial, Guimarães and De Deyn (2016) emphasize that complex problems in a variety of scientific fields have been approached by using the network paradigm (Amaral and Ottino, 2004). Ecological systems are modelled as networks including individual elements interacting through peculiar relations. Thus, the ecological patterns can be described in terms of network structures. The use of network analysis for disentangling ecological systems is certainly not new (see, inter alia, Cohen and Stephens, 1978; May, 1973; Odum, 1975; Galpern et al., 2011). By contrast, the adoption of networks in ecology has recently become pervasive and quickly attained the description of several ecological systems (Guimarães and De Deyn, 2016; Luque et al., 2012; Saura et al., 2011). The principles of complex network theory provide scholars with the idea that a simple graph structure can inform about the ecological and evolutionary processes (Fall et al., 2007; Minor and Urban, 2007; Urban et al., 2009). In this respect, the evidence that complex systems behave according to their inner structure, also called topology (Albert and Barabási, 2002), represents an important starting point. Ings et al. (2009) observe that the availability of high computing software and hardware have made possible the investigation of a variety of systems tackled as biological (e.g. genetic), technological (e.g. Internet) and social (e.g. friendship) networks (Borgatti and Everett, 1997; Strogatz, 2001; Barabási et al., 2002; Dorogovtsev et al., 2003; Kossinets, 2006; Montoya et al., 2006) under innovative and unifying perspectives. According to some scholars (Ings et al., 2009; Montoya et al., 2006; Solé and Montoya, 2001; Dunne et al., 2002), there is increasing interest in more robust cross-comparisons among different network types. As far as ecological systems are concerned, Ings et al. (2009) propose a three-partition into: (i) 'traditional' food webs (FW), (ii) host-parasitoid webs (HPW), and, more recently, (iii) mutualistic webs (MW). This classification was based on the study of the relations within ecosystem services and indicated as: (i) pollination networks through maps of interactions between plants and their animal pollinators; (ii) frugivore networks by scrutinizing the interactions between plants and their animal seed dispersers; and (iii) ant–plant networks by the analysis the food-protection relations between plants and ants. Janssen et al. (2006), who develop on the possibility to compare social and ecological networks and infer common properties in empirical case studies, have proposed another interesting grouping. They distinguish three types of ecosystem networks that are: (i) connected by people via information or physical flows; (ii) disconnected and fragmented by people, and (iii) a connection between people. In a similar way, Hines et al. (2016) recall the tool able to assess ecosystems in a holistic perspective and named them Ecosystem Network Analysis (ENA) (Schramski et al., 2011; Fath and Patten, 1999; Ulanowicz, 2004). ENA is an important part of the new field of network ecology (Borrett et al, 2014) and maps the direct and indirect interactions among all ecosystem components (Schramski et al., 2011; Fath et al., 2007). A prominent stream of tools has been borrowed from the social and economic sciences (Hannon, 1973; Wasserman and Faust, 1994; Borgatti, 2005; Estrada, 2010) and adopted to define and identify key components in ecosystems (Jordán et al., 2007; Estrada and Bodin, 2008; Borrett, 2013). Centrality represents a frequent and relevant focus in many tools (Foltête et al., 2012; Saura and Torné, 2009). Centrality metrics provide information on the ability of each component of an ecosystem network to influence directly and indirectly the rest of the system, and thus measure the functional importance of each piece with respect to the whole ecosystem (Estrada, 2007).

### *2.3 Comparative ecological network analysis*

In this paper, by Comparative Ecological Network Analysis (CENA), we refer to the adoption of network analysis for understanding and comparing many complex ecosystems. The literature on CENA includes contributions concerning the use of simple metrics to clarify the similarities and dissimilarities between complex systems. In this respect, Eklöf et al. (2013) consider 200 ecological networks to assess how many dimensions (trait axis) are required to predict whether two species interact. They found that the number of dimensions needed is usually small (<10) and ideally less than five, since the use of simple models facilitates the description and understanding of ecological networks. Joppa et al. (2010) examined 101 networks that consist of mutualists and their resources and parasitoids and their hosts. They investigated the nestedness to describe the presence of different species on different islands. Results clarified how recurrent nested patterns imply that the species composition on islands with fewer species is a proper subset of those on islands with more species. Nor et al. (2017) compare the ecological networks of three large cities in South East Asia: Kuala Lumpur, Jakarta, and Metro Manila. They focused on the potential corridors to connect green space patches for ecological connectivity networks through circuit theory, connectivity and least-cost path analysis. Théau et al. (2015) apply a quantitative evaluation tool to compare different ecological networks constructed according to a variety of approaches to their design. They adopted different existing models to develop several ecological networks for the same region, i.e. the Saint-Francois River watershed in southern Quebec, Canada. The comparative assessment developed in (Théau et al., 2015) was based on a common set of ecological, economic, and social spatial thematic indicators related to the concept of sustainable landscape development (Opdam et al., 2006; Dramstad and Fjellstad, 2011).

## 3. Methods and application to a case study

In this section, we describe the rationale of the analysis developed in this paper by explaining the method selected in sub section 3.1 and detailing its application to the comparison of two ecological systems in subsection 3.2.

### *3.1 Methodology*

The method belongs to the family of comparative ecological network analysis (CENA) tools (Hines et al., 2016). It is based on a framework initially proposed by De Montis et al. (2016) for studying a pilot EN including 236 patches in the town of Nuoro and readdressed in this work to collate two ENs displaying a much larger number (i.e. 1,000) of patches. We develop on the centrality analysis in a comparative perspective by confronting two systems of similar size and characteristics. These systems consist of the ecological networks proposed for the towns of Sassari and Nuoro, in Sardinia, Italy. As proposed by Ings et al. (2009), the selected ENs can be classified as mutualistic webs (MW). In fact, their modelling is tailored on seed dispersal of two Mediterranean vegetal target species (holm oak, *Quercus ilex,* and olive tree, *Olea europaea*) by means of the frugivorous activity and movement of some volatile vector species (including the European jay, *Garrulus glandarius*, and the Common Starling, *Sturnus vulgaris*). In this section, we describe the main pillars of the method adopted.

We define our model using a graph $G = (E, N)$ that comprises a set of nodes $N(G)$ and edges (i.e. links) $E(G)$ connecting the nodes. Nodes stand for patches and edges for mutual relations. The connection between nodes can be unidirectional, if $e_{ij}= e_{ji}$, or directional, otherwise. Connectivity is an important property of graphs, as it allows the movement throughout the nodes. A graph is said to be connected, if every node is reachable from any other node and unconnected, otherwise. The set of the edges connecting two nodes is called path ($l$). The path $l_{ij}$, which connects two nodes i and $j$ with the minimum number of edges, is the shortest path. A mathematical formalization often used for describing an ecological network is the adjacency matrix $A$, where diagonal elements $a_{ii}$ are equal to zero (a patch cannot be connected to itself) and off-diagonal elements $a_{ij}$ are equal to 1, if nodes $i$ and $j$ are connected, and 0 otherwise. In the literature, many measures have been assessed to study complex networks and explain their behaviour. A major issue is the assessment of centrality, i.e. the identification of the patches that play a primary role in the ecological network. Node degree ($k$) counts the number or first neighbours of a node and stands as a simple quantification of the topological importance of patches in the habitat. The higher is the degree $k$ of a node, the higher is the dispersal capacity of the corresponding patch. The degree $k$ for node $i$ obeys to the following equation:

$$k_i = \sum_{j \in \vartheta} a_{ij} \tag{1}$$

where $\vartheta$ is the set of $j$ nodes connected to $i$.

Because we model ecological systems as oriented graphs, one can distinguish between in-degree $k^{in}$ (received dispersal activities) and out-degree $k^{out}$ (forwarded dispersal activities). Both $k^{in}$ and $k^{out}$ are paramount for a habitat life as nodes with high $k^{out}$ ensure dispersal activities today while nodes with high $k^{in}$ are those with highest probability to be colonized and be active part of the network in future. The in-degree is the sum connections onto node $i$:

$$k_i^{in} = \sum_{j=\vartheta} a_{ij} \tag{2}$$

The out-degree is the total number of connections coming from node $i$:

$$k_i^{out} = \sum_{j\in\vartheta} a_{ji} \tag{3}$$

The sum of in-degree $k^{in}$ and out-degree $k^{out}$ is equal to the total degree $k$:

$$k_i = k_i^{in} + k_i^{out} \tag{4}$$

In our case, ENs are represented also as weighted directed spatial networks to consider mostly the intensity of the relation between each pair of nodes (dispersal probability). So, the weight varies depending on the probability that plant seeds are dispersed. We spatially locate each node in its patch's centroid and we use the patch's area as an index of the carrying capacity, habitat quality and productivity (Urban and Keitt, 2001). The dispersal probability is expressed as:

$$p_{ij} = f(\beta, d_{ij}) \tag{5}$$

Where $d_{ij}$ is the distance between the centroids of two patches $i$ and $j$ and $\beta$ is an impedance coefficient which accounts for the impact of space in the propagule dispersal (plant seeds). Dispersal probability can take several forms such as exponential and Gaussian distributions (Clark et al., 1999).

We use the concept of dispersal fluxes to take into consideration the capacity of source patches to "colonize" other patches. The dispersal flux from patch *i* to *j* is:

$$w_{ij} = \frac{ap_i}{ap_{tot}} p'_{ij} \tag{6}$$

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. Furthermore, being the network oriented, $w_{ij} \neq w_{ji}$.

As for modelling the weight, De Montis et al. (2016) proposed and applied the following expression

$$w_{ij} = \frac{ap_i}{ap_{tot}} \left(p_{ij,o} + p_{ij,q} * 10^{-3}\right) \tag{7}$$

where *pij,o* and *pij,q* stand for the seed dispersal probability of, respectively, the *O. europaea* and the *q. Ilex*. These probability functions were calibrated in previous studies (Gómez, 2003; Mulas et al., 2003) and adopted by De Montis et al. (2016) and obey to the following logarithmic expressions:

$$p'_{\mathrm{ij,o}} = 2.09 + \frac{7489.42}{\sqrt{2 \times 3.14} \times 0.53 \times d_{\mathrm{ij}}} e^{\frac{-(ln \frac{d_{\mathrm{ij}}}{247.42})^2}{2\times(0.53)^2}} \tag{8}$$

$$p'_{\mathrm{ij,q}} = 2.09 + \frac{7489.42}{\sqrt{2 \times 3.14} \times 0.53 \times d_{\mathrm{ij}}} e^{\frac{-(ln \frac{d_{\mathrm{ij}}}{24.742})^2}{2\times(0.53)^2}} \tag{9}$$

The weighted counterpart of the degree *k* is the strength for the total in-flow ($s^{in}$) and total out-flows ($s^{out}$) from each node. The higher the strength of a node the higher the probability of dispersion from or to the corresponding patch. The corresponding mathematical expressions can be written as follows:

$$s_i^{in} = \sum_{j \in \vartheta} w_{ij} \tag{10}$$

$$s_i^{out} = \sum_{j \in \vartheta} w_{ji} \tag{11}$$

$$s_i = s_i^{in} + s_i^{out} \tag{12}$$

Strength *s* allows one to evaluate nodes' importance according to the strongest direct effects from and to other nodes (Urban and Keitt, 2001). Centrality can also be meant as a relational property involving the relational attitude of the first neighbours. Accordingly, the clustering coefficient measures the fraction of interconnected neighbours of a given node. We expect that the higher the clustering coefficient, the higher is the dispersal capacity of a node because it is well connected to densely interconnected nodes (clusters), instead of being randomly connected to other nodes. The clustering coefficient can better describe how fast dispersal activities propagate across the network. The clustering coefficient (C*C*) for a node *i* in an undirected and un-weighted network reads as follows:

$$CC_i = \frac{2t_i}{k_i(k_i - 1)} \tag{13}$$

where $t_i$ denotes the number of triangles around *i*.

Betweenness centrality (*BC*) is another measure of node centrality, which accounts for the fraction of shortest paths that pass through a given node *i*. A patch with high *BC* is an important intermediary for seed dispersal in ecological networks. In this case, that patch serves as a bridge between clusters of nodes (sub graphs) and -being part of shortcuts- interconnects habitat otherwise disconnected and which would have been doomed to disappear trough time. Freeman (1977) has formalized *BC* as follows:

$$BC_r = \sum_{i,j \in N} \frac{\rho(i,j,r)}{\rho(i,j)} \tag{14}$$

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. The shortest path between two given nodes in the network can be calculated only if the given nodes belong to the same sub graph (if the network is composed of disconnected sub graphs). A common strategy used to find the shortest path between two nodes is the adoption of the algorithm proposed by Dijkstra (1976), a tool which is able to find the path with the least cost.

### *3.2 Application to a case study*

In regional contest of Sardinia, the center of Sassari and Nuoro (Fig. 1) represent, respectively, a medium and small-size urban settlement. Strong relationships between population, culture, history, economy and landscape result as characteristics of the two study areas. The city of Nuoro presents traits of urban ecology quite different as compared to the environment of Sassari.

Please, place Figure 1 about here.

Nuoro has a total area of 192 km$^2$, and a population of about 37,000 inhabitants. The city is surrounded by a rural area strongly linked to agro-pastoral activities that have influenced the peri-urban environmental and landscape context. The development of the peri-uban area is relatively limited and characterized by mild urbanized settlements, as well as by the presence of the industrial area of Prato Sardo, markedly separated from the urban context. Residential development has remained limited to the spontaneous construction of housing units, as the result of individual interests and was rarely accompanied by infrastructures and service equipment. The result is a peri-urban landscape mainly occupied by residences with a marked concentration of urban services in downtown Nuoro. From an environmental point of view, the urban settlement borders with a valley system at the foot of Mount Ortobene Park, which has maintained its natural ecological characteristics, and other partially natural or rangeland areas. The area of the city of Sassari (546.1 km$^2$), with about 129,000 inhabitants, presents situations in which there is an expansion of the city boundaries with the formation of satellite districts that result in settlement forms not circumscribed to a defined perimeter. These have involved a series of changes related to environmental planning. This process evidenced a superposition of three urban layers in a chronological sequence. Firstly, the effects of the settlement pressure of the years 1960-1970 were integrated to the pre-existing agricultural activities and were justified by the attraction of the administrative center of the town. Subsequently, from the end of the 1970s, urban sprawl is still underway and in continuous growth, with the redistribution of large portions of the population and urban settlement outside the historical center of the city (Maciocco, 2013). In a third stage, from the first 1990s, the urban development that firstly affected the flood plains of the main waterways increasingly interested the open spaces of the olive-grooving area. The progressive substitution of the agricultural destination of the areas with the residential function was increased in large part by the greater economic possibilities and by the availability of wider spaces. The result was an urban design that offered a very close relationship with the environmental structure of the landscape. In fact, the nearby settlement areas outside the city are linked to areas of significant environmental values. An example are the horticultural valleys of San Simplicio and Fosso di Sant'Orsola with the Rio di Ottava stream, which flows into it, and the olive-growing area of the urban crown of Sassari, which in the past represented an agricultural element of considerable economic implication for the city (Maciocco, 2013).

From an ecological point of view, we can observe, in both case studies, the possibility of natural dissemination processes of many plant species. The peri-urban areas, in fact, between the urban and rural landscape, present accentuated natural features and represent both a potential source area and a sink receiving strong inputs from the rural area. Consequently, those areas are key to the maintenance and increase of biodiversity through the interconnection of the extra urban environments with the internal natural areas encapsulated in the human settlement. Regional and urban land use plans involve transformations that positively and negatively affect the ecological systems. In this case, coordination is required, as indicated by many examples (Jongman, 2007).

The study started with the identification of two target plant species (*Quercus ilex, Olea europea*). Holm oak and olive tree are considered prevalent in peri-urban ecosystems and in some urban contexts (tree-lined avenues, public and private gardens). For every plant species, one or more animal seed dispersal species was selected based on the realistic possibility to observe them undisturbed in the urban environment. For the holm oak, the most active vector in the seeds dispersion is the European jay (*Garrulus glandularius*) (Gómez, 2003; Pons and Pausas, 2007). The average dispersion distance of the bird is 250 m, with a recorded maximum of 1000 m. Some rodents like *Apodemus sylvaticus* and *Eliomys quercinus* (Gómez et al., 2008) also contribute but are less effective in the dispersion of the seed. Rodents are also active in the seeds dispersal of *Olea europaea* but the maximum distance of dispersion of these vectors is a few meters. Moreover, rodents are frequently controlled in the urban environment by means of specific poison substances. More efficient as olive seeds disperser are many frugivorous birds, such as the Common Starling (*Sturnus vulgaris*), Song Thrush (*Turdus philomenos*), Blackcap (*Sylvia atricapilla*), Sardinian Warbler (*Sylvia melanocephala*) (Rey and Alcántara, 2000; Alcántara and Rey, 2003). These species eat the fruit and regurgitate stones 20-50 min later with a mean dispersion distance of 100 m (Bass et al., 2006). Even large wild mammals and livestock, such as pigs, sheep, goats and cattle, feed on holm oak and olive trees. However, these vectors effectively disperse only the olive seeds and their presence in the urban environment is occasional. Because of these considerations, we selected the European jay as vector of holm oak seed dispersal and the frugivorous birds as vector of olive seeds (De Montis et al., 2016). The two vectors are presents in the studied urban areas even if their presence was not quantified according to the objectives and theoretical nature of the research.

Physical obstacles of different nature (walls, fences, etc.) interrupt the continuity of each area but are ineffective against the seed dispersal by bird vectors. The characterization of patches was aimed to understand the potential functional links between them to conserve and preserve the biological dynamics at urban and peri-urban scale. Through a direct census on the field and the compilation of descriptive sheets on the individual patches, information was collected regarding the presence/absence, distribution of holm oak and olive trees, and their reproductive maturity. This has contributed to the identification of "source areas", from which the dissemination process, within a distance determined for each vector species, can involve patches in which the target species may be hosted. During the census, the different phases of development of the target species were also detected and based on the level of presence of the plant species (absence, plants renewal, young plants, established plants).

Please, place Table 1 about here.

The creation of the ecological network of the two sites required the identification and the classification of patches according to the above-descripted criteria of presence/absence and reproductive maturity of the two target species in urban and peri-urban contexts of the cities of Sassari and Nuoro. In Table 1, we report on the data processed in our experimentation. Geographical information on the localization of the target vegetal species was taken from aero-photogrammetric maps and verified through photo interpretation of satellite images and detailed field surveys. These elements were key to the definition of the boundaries of the patches. Satellite orthophotographs were geo-referenced according to the Monte Mario/Italy zone 1 projection (EPSG code: 3003).

Information on land use pattern characterizing the patches of our ENs was extracted from the zoning cartographic elaboration included in the main land use planning tool, i.e. the Municipal Master Plan (MMP) of Sassari and Nuoro. The MMP refers to the complete municipal territory and constitutes the main regulation of the right of transforming the environment and landscape. The zoning consists of the subdivision of the territory in homogeneous areas, to which a single functional destination is attributed with a letter coding: A, B, and C for historic, completion and expansion residential areas, D for industrial production, E for agricultural production, F for tourism, G for general service delivery, and H for environmental protection. Datasets are available from the Autonomous Region of Sardinia through the geoportal and the archive of MMPs (see the links reported in Table 1).

## 4. Results

In this section, the results of the application are presented in two sub-sections. The first one presents the preliminary analyses of the size, naturalistic characteristics and land-use attributes of the patches. The second sub-section deals with the resulting metrics of the complex network analysis.

### *4.1 Preliminary analyses*

In the cities of Nuoro and Sassari, the extension of the patches varied in the transition from the peri-urban context to the urban context (Table 2). In both the cases, the greatest percentage of green areas is attached to the class of small size patches, but Sassari shows by far a higher figure (48.5%), because of the presence of a variety of small urban gardens. Much lower values were found for the remaining size classes with slightly larger figures reported for Nuoro. The largest patches were observed for both the towns in not negligible shares and usually correspond to peri-urban areas, where agricultural areas are intertwined with zones in the past devoted to the cultivation of the olive tree.

Please, place Table 2 about here

In Tables 3 and 4, the results of the naturalistic characterization of the patches showed a homogeneous distribution of the target species.

Please, place Tables 3 and 4 about here.

In both the towns, the two target species were absent in a very important share of patches (more than 50%). Significant values were reported for the patches, in which there are established plants of olive trees in the absence of holm oaks (12.7% for Nuoro and 16.9% for Sassari). The patches in which there were established plants of holm oak in the absence of olive trees represented the 12.1% for Nuoro and the 16.0% for Sassari. We generally observed a greater human control over cultivated and spontaneous vegetation in Sassari. In this town, we observed patches in which the presence of the olive tree was typical of areas characterized by semi-natural zones. In these environments, we also observed processes of settlement of a diversified and specialized flora (degraded urban areas). Few olive trees were present in private and public gardens, characterized by artificial and homogeneous environments. In these contexts, the regular care taken by private individuals prevented the growth of the olive tree renewal. Regarding the distribution of holm oak, the species occurred on public areas (schools, public parks or sports facilities) where vegetation referred to very anthropized environments, parking lots, flowerbeds, road trees and in uncultivated marginal areas. It should be noted the poor renewal of the holm oak, probably due also in this case to the periodic treatments carried out by the gardeners. In the case of Nuoro, urban parks are characterized by the presence of holm oak and olive trees. In the past, these species have been used in urban green. In fact, there are numerous road trees, in which the holm oak appears. In the case of Nuoro, there is also a greater wealth of the target species within the selected patches, due to less anthropic control, facilitating the renewal process of the olive tree and the holm oak. In this situation, it is more evident, compared to Sassari, a direct correlation between the absence of holm oak and the dominance of olive tree. While the holm oak is found at the stage of young and established plants, a renovation is very difficult for the olive tree, which instead asserts itself in the absence of the holm oak. This evolution is expected, according to the ecological successions.

In Table 5, we report on a comparative analysis of the land use patterns affecting the ecological network in the two towns, as per the zoning of the correspondent MMP.

Please, place Table 5 about here

While in Nuoro the patches fall mostly (roughly 72%) in the completion (B) and expansion (C) residential zones, in Sassari they correspond broadly (roughly 51%) to neighbourhood (S) and general (G) service delivery zones. In both the towns, a very small share of patches was found in the most aggressive industrial (D) and in the environmentally protected (H) zones.

The analysis of the distribution of the target species showed the presence of monumental plants in the patches of interest for the functioning of the ecological network. These patches were found in areas of historical-cultural importance of the city of Sassari, such as the area of the public gardens or the rows of holm-oaks around the public schools. The olive-growing areas have been incorporated by urban expansion and represented areas of transition towards the countryside. In these interface situations, peri-urban green areas represented a link between rural areas and the green elements of urban patches. Through natural dissemination processes, the peri-urban area, between the urban and rural landscapes, presenting accentuated natural features, represented a source area receiving strong inputs from the rural area. Among the species present in the area, the olive tree was predominant. The presence of holm oak was low and was favoured by natural dissemination from adjacent rural areas. Within the urban area, there were some semi-natural contexts. These areas, representing natural urban gaps, sometimes left abandoned, were easily colonized by natural vegetation. These areas, without a specific function, had a high degree of floristic richness with species typical of natural environments. In the case of Nuoro, inside the city there are no abandoned areas that allow the uncontrolled spread of the target species. However, even in the case of Nuoro, the dissemination process is favoured by the presence of a natural plant community close to the city and by the strong presence of target species that allow the spread of seeds. The numerous urban parks keep within them numerous examples of holm oak and olive trees that were used in the past, together with other species, in the urban green.

### *4.2 Complex network analyses*

As for the results of the complex network analysis, in Tables 6 and 7 we report on topologic and centrality issues.

Please, place Tables 6 and 7 about here.

As Table 5 reports, both the ENs include the same number of patches (the nodes of the graph). By contrast, the patches show different ecological properties leading the ENs to display different topological -i.e. relational- properties. In Nuoro, a slightly larger number of patches act as source and target thus is active, with respect to the capacity to colonize other habitat areas. Counterintuitively, we observe a much larger number of edges *E* in Sassari. The ecological network of Sassari is 1.5 times denser compared to the one of Nuoro. This is confirmed by a shorter figure of the average shortest path length <*l*>, in the case of Sassari. The same holds for the average spatial distance between centroids <*d*>, which is slightly shorter in the case of Sassari. In Table 6, we report on three relevant measures of topological centrality. Because of the different density, the average total degree <*k*>, i.e. the number of connections of each node is in Sassari on average roughly 1.5 times larger than the one of Nuoro. As for the local connectivity of the nodes measured by the average clustering coefficient <C*C*>, the interconnectedness is slightly larger for the case of Sassari. A different picture emerges, when we observe the average betweenness centrality <*BC*> -a powerful measure of the global centrality of the nodes. This figure is much larger for the case of Nuoro. In Figures 2 and 3, we include the spatial analysis of clustering coefficient and betweenness centrality. These analyses are key to the detection of the most central and critical patches of the ecological networks.

Please, place Figures 2 and 3 about here.

The inspection of the visual representations in Figures 2 and 3 reveals that the patches showing the highest C*C* are frequent and located in peripheral areas in both the cases, while the patches with the largest values of *BC* are much rarer in the two towns and occupy more central places. Figures 2 and 3 also report on the spatial pattern of the weights, whose value depends on the probability of seed dispersal throughout the patches.  In Table 8, the analyses of the average weight and strength are reported.

Please, place Table 8 about here.

The average value of the weight <*w*> is 20 times larger for Nuoro: a clear signature of a correspondingly higher capacity of that ecological network to diffuse seeds and thus to colonize patches. This is confirmed by the analysis of the average strength <*s*>, which shows in Nuoro a value more than 10 times higher than the corresponding figure of Sassari. This is due to the presence in Nuoro of large patches with a good seed dispersal capacity, i.e. nodes with links featured with a high weight (see Table 1). The other way around, the EN of Sassari includes in higher frequencies small patches.

## 5. Discussion and conclusion

In this paper, we have applied complex network analysis to the study of ENs in two towns of Sardinia, Italy. We contributed to the research stream of works concerning the individuation of the key functional elements of an EN (Hagen et al., 2012; Jongman, 1995; Bennet, 2004), by focusing on systems including material punctual elements (patches) and immaterial linear connections (seed dispersal trajectories) between them.

Drawing from the contributions on the application of network analysis to the study of ecological systems (Cohen, 1978; Galpern et al., 2011; Luque et al., 2012; Saura et al., 2011), we obtained useful indications concerning diverse aspects of network centrality as relevant issues with respect to their design and implementation. While the ENs have been designed to include the same number of patches, their relational structure -i.e. topology- and weight distribution -i.e capacity to colonize- lead to the emergence of not trivial differences. These are explained by the ecological and functional properties of the patches, with respect to their ability to contribute to seed dispersal. In this respect, our paper presents another test of functional properties -namely seed dispersal capacity through vector volatile species- studied in other works (Gómez, 2003; Pons and Pausas, 2007; Gómez et al., 2008; Rey and Alcántara, 2000; Alcántara and Rey, 2003; Bass et al., 2006).

Both ENs presents roughly the same number of active patches. Nevertheless, their spatial pattern leads to different collective network properties. This is clearly another confirmation of past studies concerning the evidence that topology -i.e. the pattern of connection between the nodes- matters (Albert and Barabási, 2002; De Montis et al., 2016; Amaral and Ottino, 2004; Minor and Urban, 2007). In Sassari the EN is 1.5 times denser -i.e. with more edges- than in Nuoro. Similarly, in Sassari the shortest path length is on average smaller than in Nuoro. Another sign of this structural difference comes from the analysis of the average total degree that for the EN in Sassari is 1.5 times higher than in Nuoro. This implies that in Sassari the EN locally displays a stronger attitude to seed dispersal. This result is not confirmed, when we consider more global measures of network centrality. Typically, the analysis of the betweenness centrality (*BC*) reveals that on average in Nuoro the EN has a greater presence of shortcuts and critical bridges between the patches than in Sassari. This usually implies a higher resilience in front of random attacks but -as counterpart- also higher vulnerability in presence of attacks directed just to the high *BC* patches. This result is in line with other investigations on the role of high BC nodes (De Montis et al., 2016; Freeman, 1977; Dijkstra, 1976). As confirmed in the case of the analogous smaller EN investigated in Nuoro by De Montis et al. (2016), high *CC* patches are often located in peripheral neighbours of the ENs while high *BC* ones in the central zones. The first result is the sign of the existence of a green belt of well-clustered patches, while the second signals the presence in the core of the network of highly interconnected patches acting globally as bridges between many couples of patches and, thus, deserving major protection policies.

The analysis of the weighted network adds new information: average weight and strength are much greater in Nuoro. As observed in other studies (Albert and Barabási, 2002), the introduction of the weight -i.e. a measure of the probability of seed dispersal between the patches- uncovers opposite evidence, with respect to the analysis of pure topological centrality (provided by the average total degree).

The achievement of these results is meaningful, since we have demonstrated critical issues related to the RQs posed in the Introduction. With reference to RQ1 concerning the comparative study of different ENs in a simple and intuitive way, we have demonstrated how Comparative Ecological Network Analysis (CENA) is able to provide researchers with straightforward tools. As other essays have demonstrated (Eklöf et al., 2013; Joppa et al., 2010; Nor et al., 2017; Opdam et al., 2006; Dramstad and Fjellstad, 2011), starting from the representation of the functional characteristics -i.e. presence of vegetal target species and potential seed dispersal- CENA can support the designer with crucial indications for the construction and management of the different ENs selected. As for RQ2 on the opportunity to assess the most central and critical patches, we have demonstrated how CENA is able to provide the analyst with relevant measures of topological and weighted centrality. The richness of the indications drawn from the analysis of centrality confirms the need to take into account different aspects and measures (Foltête et al., 2012; Saura and Torné, 2009; Estrada, 2009). Thus, we have studied topological centrality at both the local and the global level and obtained not trivial indications. The *BC* provides us with a powerful indication of the most critical patches of the ENs: special protection should be reserved to those habitats, as their disappearance can undermine the stability of the whole system. The same contradictory indication emerges, when we confront the pure topological with the weighted local centrality measures -i.e. the degree with respect to the strength.

The results obtained are relevant and demonstrate that our approach can be added to other similar works reported in the literature (Eklöf et al., 2013; Nor et al., 2017). In addition, we have developed on the work by De Montis et al. (2016) by considering a greater -i.e. with a larger number of patches and edges- EN for the town of Nuoro and proposing a comparison of that EN with a completely new and similar one studied for the town of Sassari. On the other side, some issues remain open and deserve further investigation. A major usefulness of the approach proposed by De Montis et al. (2016) consists of the resilience analysis. This analysis can be applied in a comparative perspective to ascertain the capacity to react to external shocks consisting in fatal attacks addressed randomly or deterministically. The results indicate the most critical patches of the ENs and the interaction of the whole systems with land use regimes ruled by municipal planning tools. We will be working on this issue in the next future.

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## 6. References

1. Albert, R., Barabási, A.L. 2002. Statistical mechanics of complex networks. Rev. Mod Phys. 74(1), 47–97. http://doi.org/10.1103.

2. Alcántara, J.M., Rey, P.J. 2003. Conflicting selection pressure on seed size: evolutionary ecology of fruit size in a bird-dispersed tree, Olea europaea. J. Evol. Biol., 16, 1168–1176. https://doi.org/10.1046/j.1420-9101.2003.00618.x.
3. Amaral, L.A.N., Ottino, J.M. 2004**.** Complex networks: Augmenting the framework for the study of complex systems. Eur. Phys. J. B. 38(2), 147–162. http://doi.org/10.1140/epjb/e2004-00110-5.
4. Barabási, A.L., Jeong, H., Neda, Z., Ravasz, E., Schubert, A., Vicsek, T. 2002**.** Evolution of the social network of scientific collaborations. Physica A, 311, 590–614. https://doi.org/10.1016/S0378-4371(02)00736-7.
5. Bass, D.A., Crossman, N.D., Lawrie, S.L., Lethbridge, M.R. 2006. The importance of population growth, seed dispersal and habitat sustainability in determining plant invasiveness. Euphytica, 148, 97–109. http://doi.org/10.1007/s10681-006-5944-6.
6. Bennett, G. 2004. Guidelines on the application of existing international instruments in developing the Pan-European Ecological Network (Nature and Environment Series, No. 124). Council of Europe Publishing, Strasbourg.
7. Bennett, G., Mulongoy, K. 2006. Review of experience with ecological networks, corridors and buffer zones (Technical Series, No. 23). Secretariat of the Convention on Biological Diversity, Montreal.
8. Bloemmen, M. and van der Sluis, T. (Eds.) 2004. European corridors – examples studies for the Pan European Ecological Network (Alterra Report N° 1087). Wageningen, Alterra.
9. Borgatti, S.P. 2005. Centrality and network flow. Soc. Networks, 27, 55–71. https://doi.org/10.1016/j.socnet.2004.11.008.
10. Borgatti, S.P., Everett, M. G. 1997. Network analysis of 2-mode data. Soc. Networks, 19(3), 243–269. http://doi.org/10.1016/S0378-8733(96)00301-2.
11. Borrett, S.R. 2013. Throughflow centrality is a global indicator of the functional importance of species in ecosystems. Ecol. Indic., 32, 182–196. https://doi.org/10.1016/j.ecolind.2013.03.014.
12. Borrett, S.R., Moody, J., Edelmann, A. 2014. The rise of Network Ecology: maps of the topic diversity and scientific collaboration. Ecol. Model., 293, 111–127. https://doi.org/10.1016/j.ecolmodel.2014.02.019.
13. Clark, J.S., Silman, M., Kern, R., Macklin, E., Hille Ris Lambers, J. 1999. Seed dispersal near and far: patterns across temperate and tropical forests. Ecol., *80*, 1475-1494. https://doi.org/10.1890/0012-9658(1999)080[1475:SDNAFP]2.0.CO;2.
14. Cohen, J.E., Stephens, D.W. 1978. Food webs and niche space. Princeton University Press, Princeton. ISBN: 9780691082028.
15. De Montis, A., Caschili, S., Mulas, M., Modica, G., Ganciu, A., Bardi, A., Ledda, A., Dessena, L., Laudari, L., Fichera, C. R. 2016. Urban-rural ecological networks for landscape planning. Land Use Policy, 50, 312–327. http://doi.org/10.1016/j.landusepol.2015.10.004.
16. Dijkstra, E.W. 1976. *A Discipline of Programming.* Prentice Hall, New York. ISBN: 013215871X.
17. Dorogovtsev, S.N., Goltsev, A.V., Mendes, J. F. F., Samukhin, A.N. 2003. Spectra of complex networks. Phys. Rev. E., 68(4 Pt 2), 046109(1-10). http://doi.org/10.1103/PhysRevE.68.046109.
18. Dramstad, W.E., Fjellstad, W.J. 2011. Landscapes: bridging the gaps between science, policy and people. Landsc. Urban Plan., 100, 330–332. https://doi.org/10.1016/j.landurbplan.2011.02.003.
19. Dunne, J.A., Williams, R.J., Martinez, N.D. 2002. Food-web structure and network theory: the role of connectance and size. P Natl. Acad. Sci. USA, 99, 12917–12922. https://doi.org/10.1073/pnas.192407699.

20. Eklöf, A., Jacob, U., Kopp, J., Bosch, J., Castro-Urgal, R., Chacoff, N. P., Dalsgaard, B., de Sassi, C., Galetti, M., Guimarães, P.R., Lomáscolo, S. B., Martín González, A. M., Pizo, M. A., Rader, R., Rodrigo, A., Tylianakis, J.M., Vázquez, D.P., Allesina, S. 2013. The dimensionality of ecological networks. Ecol. Lett., 16(5), 577–583. http://doi.org/10.1111/ele.12081.
21. Estrada, E. 2007. Characterization of topological keystone species: local, global and "meso-scale" centralities in food webs. Ecol. Complex., 4, 48–57. https://doi.org/10.1016/j.ecocom.2007.02.018.
22. Estrada, E. 2010. Generalized walks-based centrality measures for complex biological networks. J. Theor. Biol., 263, 556–565. https://doi.org/10.1016/j.jtbi.2010.01.014.
23. Estrada, E., Bodin, O. 2008. Using network centrality measures to manage landscape connectivity. Ecol. Appl., *18*, 1810–1825. https://doi.org/10.1890/07-1419.1.
24. Fahrig, L. 2013. Rethinking patch size and isolation effects: the habitat amount hypothesis. J. Biogeogr. 40, 1649–1663. https://doi.org/10.1111/jbi.12130.
25. Fall, A., Fortin, M.J., Manseau, M., O'Brien, D. 2007. Spatial graphs: Principles and applications for habitat connectivity. Ecosystems, 10, 448-461. http://doi.org/10.1007/s10021-007-9038-7.
26. Fath, B.D., Patten, B.C. 1999. Review of the foundations of network environ analysis. Ecosystems, 2, 167–179. https://doi.org/10.1007/s100219900067.
27. Fath, B.D., Scharler, U.M., Ulanowicz, R.E., Hannon, B. 2007. Ecological network analysis: network construction. Ecol. Model., 208, 49–55. https://doi.org/10.1016/j.ecolmodel.2007.04.029.
28. Fichera, C. R., Laudari, L., Modica, G. 2015. Application, validation and comparison in different geographical contexts of an integrated model for the design of ecological networks. Journal of Agricultural Enginering, 46(2), 52–61. http://doi.org/10.4081/jae.2015.459.
29. Foltête J.C., Clauzel C., Vuidel G. 2012. A software tool dedicated to the modelling of landscape networks Environ Modell Softw, 38, 316-327. https://doi.org/10.1016/j.envsoft.2012.07.002.
30. Freeman, L.C. 1977. A set of measures of centrality based on betweenness. Sociom., 40, 35-41. https://doi.org/10.2307/3033543.
31. Galpern, P., Manseau, M., Fall, A. 2011. Patch-based graphs of landscape connectivity: A guide to construction, analysis and application for conservation. Biol Conserv, 144, 44-55. http://doi.org/10.1016/j.biocon.2010.09.002.
32. 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.
33. Gómez, J.M., Puerta-Piñero, C., Schupp, E.W. 2008. Effectiveness of rodents as local seed dispersers of Holm oaks. Oecologia, 155, 529–537. https://doi.org/10.1007/s00442-007-0928-3.
34. Guimarães, P.R., De Deyn, G.B. 2016. Ecological networks: Assembly and consequences. Oikos, 125(4), 443–445. http://doi.org/10.1111/oik.03436.
35. 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. Adv. Ecol. Res., 46, 89-210. https://doi.org/10.1016/B978-0-12-396992-7.00002-2.
36. Hannon, B. 1973. The structure of ecosystems. J. Theor. Biol., 41, 535–546. https://doi.org/10.1016/0022-5193(73)90060-X.

37. Hines, D.E., Singh, P., Borrett, S. R. 2016. Evaluating control of nutrient flow in an estuarine nitrogen cycle through comparative network analysis. Ecol. Eng., 89, 70–79. http://doi.org/10.1016/j.ecoleng.2016.01.009.
38. Ings, T.C., Montoya, J.M., Bascompte, J., Blüthgen, N., Brown, L., Dormann, C.F., Edwards, F., Figueroa, D., Jacob, U., Jones, J.I., Lauridsen, R.B., Ledger, M.E., Lewis, H.M., Olesen, J.M., van Veen, F.J., Warren, P.H., Woodward, G. 2009. Ecological networks--beyond food webs. J. Anim. Ecol., 78(1), 253–69. http://doi.org/10.1111/j.1365-2656.2008.01460.x.
39. Janssen, M.A., Bodin, Ö., Anderies, J. M., Elmqvist, T., Ernstson, H., McAllister, R.R.J., Olson, P., Ryan, P. 2006. Toward a network perspective of the study of resilience in social-ecological systems. Ecology and Society, 11(1). http://doi.org/10.5751/ES-01462-110115.
40. Jongman R. 2004. The context and concept of ecological networks. In: Jongman, R., Pungetti, G. (Eds.), Ecological Networks and Greenways Concept, Design and Implementation. Cambridge University Press, Cambridge, pp. 7–33. ISBN: 9780521827768.
41. Jongman, R.H.G. 1995. Nature conservation planning in Europe: developing ecological networks. Landscape Urban Plan., 32(3), 169-183. https://doi.org/10.1016/0169-2046(95)00197-O.
42. Joppa, L.N., Montoya, J.M., Solé, R., Sanderson, J., Pimm, S.L. 2010. On nestedness in ecological networks. Evol. Ecol. Res., 12(1), 35–46.
43. Jordán, F., Benedek, Z., Podani, J. 2007. Quantifying positional importance in foodwebs: a comparison of centrality indices. Ecol. Model., 205, 270–275. https://doi.org/10.1016/j.ecolmodel.2007.02.032.
44. Kossinets, G. 2006. Effects of missing data in social networks. Soc. Networks, 28, 247–268. https://doi.org/10.1016/j.socnet.2005.07.002.
45. Luque, S., Saura, S., Fortin, M.-J. 2012. Landscape connectivity analysis for conservation: insights from combining new methods with ecological and genetic data. Landscape Ecol, 27, 153-157. http://doi.org/10.1007/s10980-011-9700-5.
46. Macciocco G. 2013. Città di città. Il piano territoriale di coordinamento della provincia di Sassari. Milano: Franco Angeli,. ISBN: 9788820427610.
47. May, R.M. 1973. Stability and Complexity in Model Ecosystems. Princeton University Press, Princeton. ISBN: 9780691088617.
48. Minor, E.S., Urban, D.L. 2007. Graph theory as a proxy for spatially explicit population models in conservation planning. Ecol Appl, 17, 1771-1782. http://doi.org/10.1890/06-1073.1.
49. Montoya, J.M., Pimm, S.L., Solé, R.V. 2006. Ecological networks and their fragility. Nature, 442, 259–264. https://doi:10.1038/nature04927.
50. 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], Proceedings of the III National Congress SISEF “Alberi e Foreste per il Nuovo Millennio [Tree and Forests for the New Millennium]”,Viterbo, Italy, 15-18 October 2001, 159-165.
51. Nor, A.N.M., Corstanje, R., Harris, J.A., Grafius, D.R., Siriwardena, G.M. 2017. Ecological connectivity networks in rapidly expanding cities. *Heliyon*, 3(6). http://doi.org/10.1016/j.heliyon.2017.e00325.
52. Odum, E.P. 1975. Ecology, the link between the natural and the social sciences. Holt, Rinehart and Winston, New York. ISBN: 0030047714.
53. Opdam, P., Steingröver, E., Van Rooij, S. 2006. Ecological networks: a spatial concept for multi-actor planning of sustainable landscapes. Landscape urban Plan., 75,322–332. https://doi.org/10.1016/j.landurbplan.2005.02.015.

54. Pons, J., Pausas, J.G. 2007. Acorn dispersal estimated by radio-tracking. Oecologia, 153, 903–911. https://doi.org/10.1007/s00442-007-0788-x.
55. Rey P.J., Alcántara, J.M. 2000. Recruitment dynamics of a fleshy-fruited plant (Olea europaea): connecting patterns of seed dispersal to seedling establishment. J. Ecol., 88, 622–633. https://doi.org/10.1046/j.1365-2745.2000.00472.x.
56. Romano B., Zullo F. 2012. Landscape fragmentation in Italy. Indices implementation to support territorial policies. In: Campagna M., De Montis A., Isola F., Lai S., Pira C., Zoppi C. (Eds.) Planning Support Tools: Policy analysis, Implementation and Evaluation, Franco Angeli, Milano, pp. 399-414. ISBN: 9788856875973.
57. Saura, S., Estreguil, C., Mouton, C., Rodríguez-Freire, M. 2011**.** Network analysis to assess landscape connectivity trends: Application to European forests (1990-2000). Ecol Indic, 11, 407-416. http://doi.org/10.1016/j.ecolind.2010.06.011.
58. Saura, S., Torné J. 2009. Conefor Sensinode 2.2: a software package for quantifying the importance of habitat patches for landscape connectivity. Environ Modell Softw, 24, 135-139. https://doi.org/10.1016/j.envsoft.2008.05.005.
59. Schramski, J.R., Kazanci, C., Tollner, E.W. 2011. Network environ theory, simulation and Econet© 2.0. Environ. Modell. Softw. 26, 419–428. https://doi.org/10.1016/j.envsoft.2010.10.003.
60. Solé, R.V., Montoya., J.M. 2001. Complexity and fragility in ecological networks. P. Roy. Soc. B-Biol. Sci., 268, 2039–2045. https://doi.org/10.1098/rspb.2001.1767.
61. Strogatz, S.H. 2001. Exploring complex networks. Nature, 410, 268–276. https://doi.org/10.1038/35065725.
62. Théau, J., Bernier, A., Fournier, R. A. 2015. An evaluation framework based on sustainability-related indicators for the comparison of conceptual approaches for ecological networks. Ecol. Indic., 52, 444–457. http://doi.org/10.1016/j.ecolind.2014.12.029.
63. Ulanowicz, R.E. 2004. Quantitative methods for ecological network analysis. Comput. Biol. Chem., 28, 321–339. https://doi.org/10.1016/j.compbiolchem.2004.09.001.
64. Urban, D.L., Keitt, T. 2001. Landscape connectivity: a graph-theoretic perspective. Ecol., 82, 1205-1218. https://doi.org/10.2307/2679983.
65. Urban, D.L., Minor, E.S., Treml, E.A., Schick, R.S. 2009. Graph models of habitat mosaics. Ecol Lett, 12, 260-273. http://doi.org/10.1111/j.1461-0248.2008.01271.x.
66. Vizzari, M., Sigura, M. 2015. Landscape sequences along the urban–rural–natural gradient: A novel geospatial approach for identification and analysis. Landscape Urban Plan. 140, 42–55. https://doi.org/10.1016/j.landurbplan.2015.04.001.
67. Wasserman, S., Faust, K. 1994. Social Network Analysis: Methods and Applications. Cambridge University Press, Cambridge. ISBN: 9780521387071.

List of table captions.

Table 1

| Data | Resolution/Scale | Year | Projection | Source | Link |
|---|---|---|---|---|---|
| Satellite orthophotographs | 0.80 m x 0.80 m per pixel | 2013 | EPSG code: 3003 (Monte Mario / Italy zone 1) | Sardinia Geoportal, Autonomous Region of Sardinia | http://www.sardegnageoportale.it/webgis2/sardegnamappe/?map=base |
| Regional technical aero-photogrammetric map | 1:10,000 | 2000 | | Sardinia Geoportal, Autonomous Region of Sardinia | http://www.sardegnageoportale.it/areetematiche/cartatecnicaregionale/ |
| Zoning, Municipal Master Plan of Sassari | 1:4,000 | 2014 | | Official bulletin of the Autonomous Region of Sardinia (BURAS) n. 58, 11 December 2014 | http://webgis.regione.sardegna.it/puc_serviziconsultazione/ElencoComuni.ejb |
| Zoning, Municipal Master Plan of Nuoro | 1:5,000 | 2015 | | BURAS n. 11, 12 March 2015 | http://webgis.regione.sardegna.it/puc_serviziconsultazione/ElencoComuni.ejb |

Table 2

| **Town** | **Percentage share of patches by surface area (m$^2$)** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **0-100** | **101-250** | **251-500** | **501-750** | **751-1000** | **More than 1000** | **Total** |
| Nuoro | 33.7% | 25.3% | 16% | 6.8% | 2.9% | 15.3% | 100% |
| Sassari | 48.5% | 21.5% | 10.5% | 4.4% | 1.7% | 13.4% | 100% |

Table 3

| **Nuoro** | | ***O. europea*** | | | |
|---|---|---|---|---|---|
| | | **Absence** | **Plants renewal** | **Young plants** | **Established plants** |
| ***Q. ilex*** | **Absence** | 52.1 | 3.9 | 2.6 | 12.7 |
| | **Plants renewal** | 3.6 | 3.3 | 0.1 | 0.8 |
| | **Young plants** | 1.8 | 0 | 0.6 | 0.1 |
| | **Established plants** | 12.1 | 0.5 | 1.4 | 4.4 |

Table 4

| **Sassari** | | ***O. europea*** | | | |
|---|---|---|---|---|---|
| | | **Absence** | **Plants renewal** | **Young plants** | **Established plants** |
| ***Q. ilex*** | **Absence** | 53.60 | 2.5 | 2.5 | 16.9 |
| | **Plants renewal** | 0.2 | 0.1 | 0.1 | 0.6 |
| | **Young plants** | 0.3 | 0 | 0.1 | 0.4 |
| | **Established plants** | 16.0 | 0.2 | 0.1 | 6.4 |

Table 5

| **Town** | **Percentage share of patches by land use** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **A** | **B** | **C** | **D** | **E** | **F** | **G** | **H** | **S** | **Total** |
| Nuoro | 8.2% | 61.8% | 10.4% | 0% | 2.8% | 0% | 3.5% | 0.1% | 13.2% | 100% |
| Sassari | 9.5% | 3.25% | 1.5% | 0.4% | 0% | 0% | 26.8% | 4.6% | 24.7% | 100% |

Table 6

| **Town** | **N** | | | **E** | **<*l*>** | **<*d*> (km)** |
|---|---|---|---|---|---|---|
| | **Total** | **Source and target** | **Target** | | | |
| Nuoro | 1000 | 478 | 522 | 102654 | 2.39 | 0.58 |
| Sassari | 1000 | 458 | 542 | 154574 | 1.96 | 0.53 |

Table 7

| **Town** | **<*k*>** | **<C*C*>** | **<*BC*>** |
|---|---|---|---|
| Nuoro | 102.65 | 0.61 | 0.00065 |
| Sassari | 154.57 | 0.64 | 0.00043 |

Table 8

| **Town** | ***<w>*** | ***<s>*** |
|---|---|---|
| Nuoro | 0.00060 | 0.062 |
| Sassari | 0.00003 | 0.005 |

List of figure captions.

Figure 1. Geographic representation of the case study: location of Sassari and Nuoro in Sardinia (A), and Google satellite images of Sassari (B) and Nuoro (C).

Figure 2. Network representation of the ecological networks of Sassari (A) and Nuoro (B): analysis of the clustering coefficient and of the weights.

Figure 3. Network representation of the ecological networks of Sassari (A) and Nuoro (B): analysis of the betweenness centrality.

Figure 1

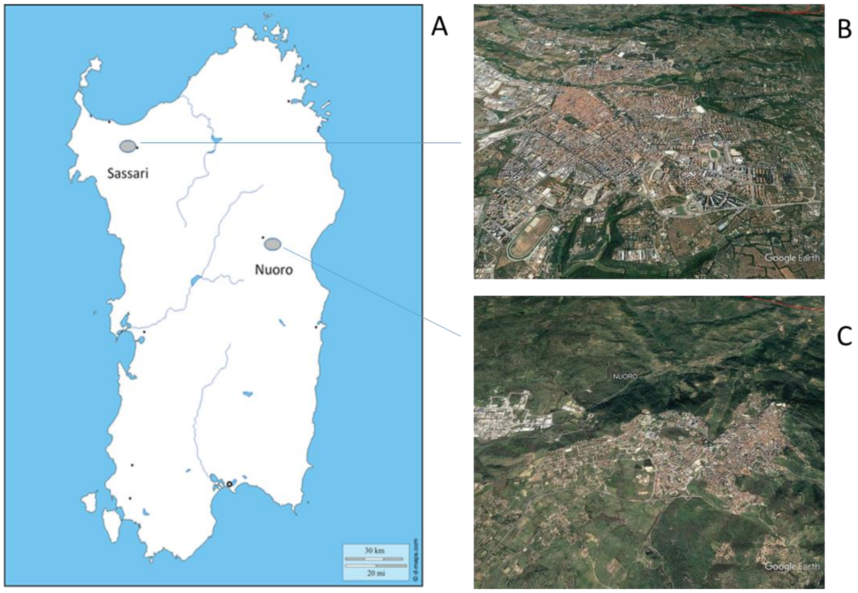

A
B
C
Sassari
Nuoro
30 km
20 mi
© d-maps.com
NUORO
Google Earth
Google Earth

Figure 2

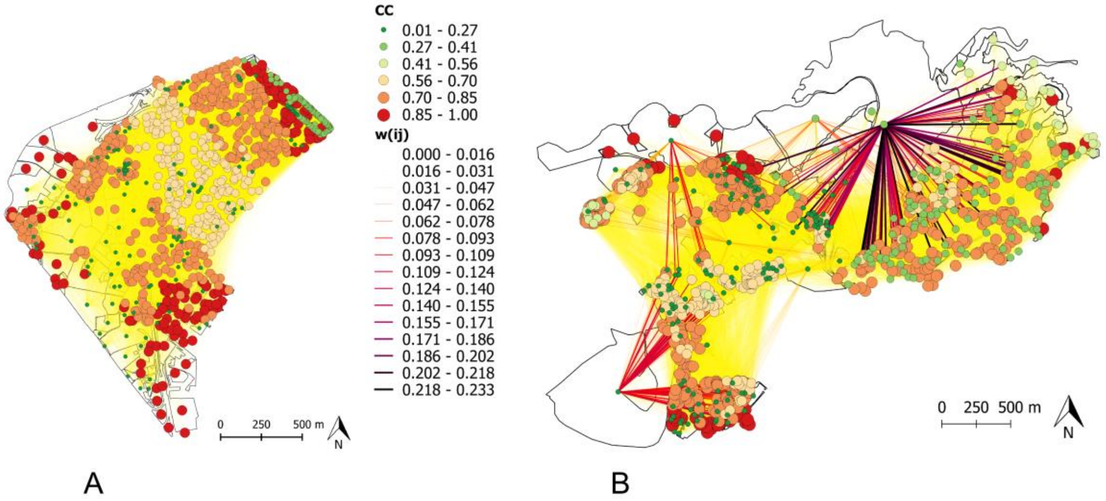
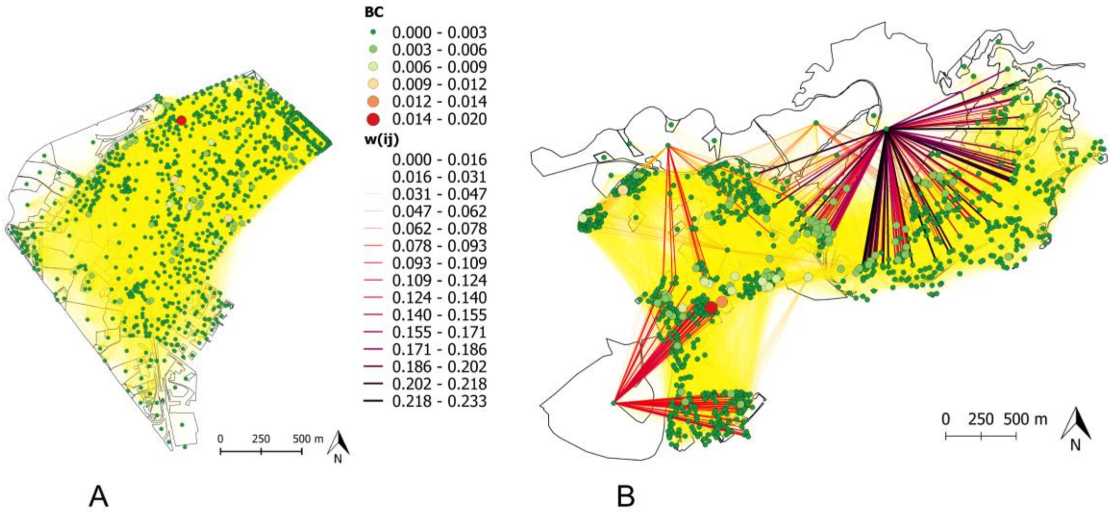

cc
0.01 - 0.27
0.27 - 0.41
0.41 - 0.56
0.56 - 0.70
0.70 - 0.85
0.85 - 1.00
w(ij)
0.000 - 0.016
0.016 - 0.031
0.031 - 0.047
0.047 - 0.062
0.062 - 0.078
0.078 - 0.093
0.093 - 0.109
0.109 - 0.124
0.124 - 0.140
0.140 - 0.155
0.155 - 0.171
0.171 - 0.186
0.186 - 0.202
0.202 - 0.218
0.218 - 0.233
0 250 500 m
N
A
0 250 500 m
N
B

Figure 3


BC
0.000 - 0.003
0.003 - 0.006
0.006 - 0.009
0.009 - 0.012
0.012 - 0.014
0.014 - 0.020
w(ij)
0.000 - 0.016
0.016 - 0.031
0.031 - 0.047
0.047 - 0.062
0.062 - 0.078
0.078 - 0.093
0.093 - 0.109
0.109 - 0.124
0.124 - 0.140
0.140 - 0.155
0.155 - 0.171
0.171 - 0.186
0.186 - 0.202
0.202 - 0.218
0.218 - 0.233
0 250 500 m
N
A
0 250 500 m
N
B