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Analysis of the connectivity of *Quercus suber* habitats in Sardinia

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Abstract

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Habitat fragmentation is a serious threat to biodiversity and is increasing exponentially worldwide, interacting with other anthropogenic disturbances and contributing to irreversible effects on ecosystems. A landscape connectivity analysis was carried out on *Quercus suber* populations in Sardinia (Italy) to assess the risk of habitat fragmentation for each area and each island municipality. The *ArcGIS* and *CONEFOR* software were combined to process the available geographical data on the subject and calculate the values of two probabilistic indices, *dPCflux* and *dPCconnector*. These values were analysed, and maps were produced showing the most critical situations in each municipality on the island. The study showed that most of the threatened areas of *Quercus suber* forest were in the northern half of the island. In these areas, where *Quercus suber* is an important economic resource, better planning would help to drastically reduce the problem within a few years, for example, by encouraging local farmers to plant new *Quercus suber* in specific corridors now occupied by open pastures.

Keywords: conservation, endangered habitats, habitat connectivity, habitat fragmentation.

INTRODUCTION

The problem of habitat fragmentation, a process that causes changes in landscape patterns over time through habitat loss and reduction, habitat isolation, edge effects, and the creation or expansion of anthropogenic ecosystems, poses a serious threat to biodiversity on the planet and is increasing at an exponential rate worldwide, interacting with other anthropogenic disturbances and contributing to several irreversible effects (Andrén, 1994; Bennett, 1999; D'Angelo et al., 2001; Battisti, 2003).

In woodland ecosystems, this process has been shown to have a damaging, albeit variable, impact on internal biodiversity (Klein, 1989; Sala et al., 2000; Morris, 2010; Schleuning et al., 2011). It also plays a vital role in the nutrient cycling of forests through the modification of animal communities that feed on dead organic matter (Gessner et al., 2010): it has long been documented that in fragmented areas, a significant decrease in the rate of decomposition of dung correlates with a lower abundance and diversity of dung beetles (Klein, 1989). Fragmentation alters key ecological and physiological functions related to plant reproduction, such as interactions with pollinators and seed production (Cunningham, 2000; Aguilar et al., 2006).

In fragmentation studies, graph-based landscape connectivity analysis has been widely used to quantify the degree of fragmentation of habitat (Pascual-

Hortal & Saura, 2006; Galpern et al., 2011). Graphs are composed of nodes, i.e. patches of suitable habitat, connected by links that imply the potential ability of an organism to disperse directly between these two patches (Urban & Keitt, 2001), where no node is visited more than once (Pascual-Hortal & Saura, 2006).

On the island of Sardinia, *Quercus suber* landscapes are essential for conserving biodiversity and represent an important source of local income (Goncalves, 2000; Gil & Varela, 2008). Cork, the product of a secondary meristem, can be harvested every 7–9 years between May and August from plants at least 15–20 years old and can be processed into various goods. *Quercus suber* habitats are also associated with traditional agro-silvo-pastoral practices in "Less Favoured Areas of the European Community" (Commission of the European Communities, 1997), which "represent a sustainable balance between human activities and natural resources and have created landscapes of high heterogeneity and cultural value" (Vogiatzakis et al., 2005).

During the second half of the 20th century, and despite regional legislation aimed at protecting them (Pungetti, 1996), *Quercus suber* habitats have suffered irreversible degradation almost everywhere, including Sardinia (Vogiatzakis et al., 2005). In particular, the main impacts on them are due to grazing (Vogiatzakis et al., 2005; Pampiro et al., 1991; Ruiu et al., 1995), fire (Ruju, 2002), pests (Sechi et al., 2002; Prota et al., 1992; Luciano & Roversi, 2001; Contarini, 2014) and climate change (Lorenz et al., 2000, 2007).

Fragmentation, which is linked to these degradation factors, has never been quantified or considered in the risk assessment and/or general planning of *Quercus suber* populations on the island, even though it is an issue that could be easily analysed by digital means and at a lower cost compared to other methods of analysis that require massive monitoring on the ground. Its assessment, in the form of a georeferenced map or vectorial dataset (e.g., shapefile), could provide a practical starting point for further planning in a specific region or district, and this is what has been achieved in this study.

The research results presented here were obtained by applying graph-based landscape connectivity analysis to quantify the degree of fragmentation of *Quercus suber* populations on the island of Sardinia in relation to wind pollination, the factor most involved in reproductive processes. This study aimed to produce valuable outputs (maps) to be considered and used in future planning at the municipal level on the island. The basic question to be answered was whether it was possible to develop a fully digital method to carry out a preliminary, rapid and inexpensive risk assessment of specific forest communities over a large area, so a relatively large island (Sardinia is 24 100.02 km²) was chosen as the best setting for the sample.

MATERIALS AND METHODS

Study species

Quercus suber L. (Fagaceae), the cork oak belonging to the Fagaceae family, is a sclerophyllous evergreen tree that grows to a height of 20 m. It thrives between 600 and 1 000 mm of annual precipitation, although it is relatively resistant to drought, and between 13° and 18°C of mean annual temperature. It cannot survive below –10ºC. It survives up to 950 m above sea level in Sardinia, 1200 m above sea level in Sicily and 2400 m above sea level in Morocco.

The current distribution of *Quercus suber* includes the coastal areas and islands of the western Mediterranean and the Atlantic coasts of Morocco, Portugal and Spain. In Italy, it occurs along the Tyrrhenian coast, Sardinia and Sicily, and in the southern Adriatic in Apulia. Some scattered populations even occur in the Istrian peninsula of Croatia (Schirone et al., 2015). In the Mediterranean, its presence dates back at least to the Tertiary (Eriksson et al., 2017).

In Sardinia, *Quercus suber* forests cover a total area of 103 597 ha, distributed in 178 (47%) municipalities and six types of plant associations (Camarda et al., 2015). Based on their management, these forests can be divided into grazed, managed and natural stands. In natural stands, cork collection is the main economic activity, and more intervention is needed to ensure regeneration and, in general, forest fire prevention (Seddaiu, 2011).

Data collection

The data processed in the analysis are essentially layers in GIS vector format (shapefiles) obtained from various online sources. The basis for the connectivity analysis was the *Carta della Natura* 1 : 50 000 (Camarda et al., 2015), which contains, in shapefile format, polygons classified by 230 habitats according to the European CORINE biotope system. From this source, a total of 754 *Quercus suber* patches were extracted and used in the analysis (Fig. 1).

Since this analysis is based on habitat fragmentation within the different local administrative units, a polygon layer of the municipalities of Sardinia, updated in 2024, was obtained from the official website of the geographical information repository of the Sardinian Regional Administration (https://www.sardegnageoportale.it).

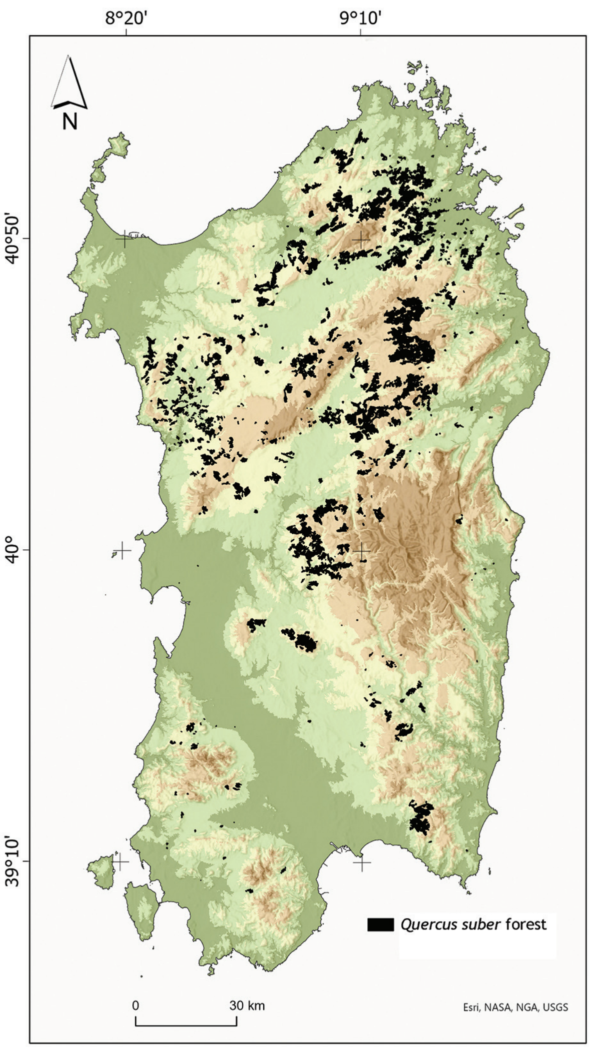

Fig. 1. Distribution of *Quercus suber* habitat patches in Sardinia (after Camarda et al., 2015, modified).

Software

For the study, we used a combination of two software packages: *ArcGIS Desktop v. 10.x* to generate the input files for the fragmentation analysis and *CONEFOR v. 2.6* (Saura & Torné, 2009; http://conefor.org/) to develop the appropriate index values. The PAST software (Hammer et al., 2001) was then used for the statistical analysis of the data.

Data analysis

Graph-based connectivity analysis is usually based on calculating different indices (Bunn et al., 2000; Pascual-Hortal & Saura, 2006). The one chosen for this work is the probability of connectivity (Saura & Pascual-Hortal, 2007; Saura & Rubio, 2010). The probability of connectivity is defined as "the probability that two animals randomly placed in the landscape fall into habitat areas that are reachable from each other (connected), given a set of n habitat patches and the connections between them" (Saura & Pascual-Hortal, 2007). The probability of connectivity increases with better connectivity and ranges from 0 to 1. As a probabilistic index, connectivity is processed by the probability of direct dispersal between two nodes (weighted links).

The values of the connectivity probability index represent the percentage change in connectivity probability caused by removing each element from the landscape (Saura & Rubio, 2010). They can be further divided into sub-indices that consider how a given landscape element (patch or link) can contribute to habitat connectivity and availability in the landscape. In this study, the two sub-indices *dPCflux* and *dPCconnector* were considered. The connectivity probability index is usually used to quantify the habitat fragmentation of specific animal species to determine which fragments should be a conservation priority. In these cases, priority is given to fragments with a high percentage of importance for the nodes within the network (Saura & Pascual-Hortal, 2007). However, in the case of a tree species such as *Quercus suber*, even small fragments (a few individuals) can represent a critical reproductive element; for this reason, in this work, priority was given to small fragments, which are considered the most fragile elements of the system and therefore deserve special attention in terms of conservation.

For this reason, the values *dPCflux* and *dPCconnector*, which measure the connectivity between patches in relation to a given landscape element, were used, with their '0' values expressing zero importance in network connectivity. In particular, the former measures how an element is connected to other patches in the landscape, but not how important that patch is for maintaining connectivity between the rest of the patches, whereas the latter represents the contribution of a patch or link to the connectivity between other habitat patches, as a connecting element or stepping stone between them, and depends only on the topological position of a patch or link in the landscape network. Therefore, using these two sub-indices allows the classification of the patches to be binary since any value × > 0 indicates the positivity of the index. The classification of the patches presented in this work is not based on quantifying the degree of fragmentation of each patch, but rather on the binary value of the presence or absence of one or both indices considered.

At this point, the *CONEFOR Inputs* plug-in (https://www.jennessent.com/ arcgis/conefor_inputs.htm) was used within the same GIS environment to calculate the Euclidean edge-to-edge distances between each of the given patches (polygon features). The output of this process was two different text files for each area considered, one quantifying the distances between each node and the other reporting the importance of each polygon as a 'node' in the network of connections. These two files were then imported into *CONEFOR* v. 2.6, which was used to calculate connectivity indices using the distance and node data. The following parameters were set for the analysis in *CONEFOR*:

1. **Type of connection**. The distance parameter was selected. This was the only choice since the input files were created using the ArcGIS plugin.

2. **Connectivity probability index**. This is the distance threshold and corresponds to the probability. The maximum distance was set at 500 m, corresponding to the maximum dispersal distance of the rarest haplotypes (Eriksson et al., 2013), and such a value corresponds to a probability of 0.01 (1%).

3. **Display deltas**. *dI* (delta) values are percentage values that express the importance of each node in the network. Since the importance of a particular node can be the result of both intrinsic habitat characteristics and topological position within the landscape network, the high *dI* values are usually associated with the higher importance of the node in terms of connectivity between and within patches (Saura & Pascual-Hortal, 2007).

4. **Precision**. The parameter was set to the highest value.

The software produced an output text file containing the *PC_Flux* and *PC_Connector* values for each area and patch (node importance file). The results were analysed and presented for the whole island and each municipality. They were grouped into two categories:

1. **Values per class**. The node importance file was processed to group the dPC values per patch into three classes based on their *PC_Flux* and *PC_Connector* values:

Vulnerable (Class 1). *PC_Flux* = 0 and *PC_Connector* = 0. Patches in this class can be considered particularly vulnerable due to high fragmentation and lack of connectivity.

Insignificant (Class 2). *PC_Flux* > 0 and *PC_Connector* = 0. These patches are connected to others, but their importance to the network is negligible.

Significant (Class 3). *PC_Flux* > 0 and *PC_Connector* > 0. These patches are connected to others and are important in the network.

2. **Distribution of patches per class per municipality**. The distribution of the different classes of patches was analysed and reported per municipality. A list and a map of these patches were produced.

Finally, two maps were produced in shapefile format, one with the polygons of the *Quercus suber* patches and the values obtained after the *CONEFOR* analysis, and one with the polygon layer of the municipalities, completed with the analysis results.

RESULTS

In Sardinia, a total of 754 *Quercus suber* forest patches were identified (Table 1). The average size of a patch was 137 ha, and the area of individual patches ranged from a maximum of 7 428.00 ha to a minimum of 1.02 ha.

The results of the fragmentation analysis for the whole island (Table 1 and Table 2; Fig. 2 and Fig. 3) show that the number of patches belonging to the vulnerable class represents 27% of the total. However, the percentage decreases to 15% of the total area occupied by these patches. Patches classified as insignificant represent 47% of the total number of patches, which is again a significant amount, as they include elements that are connected but have no relative importance in the maintenance of the network. These patches occupy 27% of the total area of *Quercus suber* forests. The remaining patches, classified as significant, occupy most of the area (58%), although their number represents the lower percentage (26%), mainly because they tend to be larger. Their mean area was 305 ha, while those belonging to the insignificant and vulnerable classes occupied a mean area of 80 ha and 75 ha, respectively.

On the island of Sardinia, a total of 74% of *Quercus suber* patches require some intervention to minimise the adverse effects of their fragmentation. These patches represent 42% of the total area occupied by *Quercus suber* habitats.

Considering the general situation of the samples per municipality (Table 3; Fig. 4 and Fig. 5), *Quercus suber* forest patches were recorded in a total of 178 municipalities of the island (47%), and the mean number of patches per municipality was 5.8. In 58 (33%) municipalities, only patches of the vulnerable class were recorded. Patches classified as vulnerable and insignificant were recorded in 26 (15%) municipalities, while patches classified as endangered were found on the territory of 84 (47%) municipalities.

The analysis showed that the highest mean number of *Quercus suber* patches classified as insignificant at the municipal level was 2.5 (Fig. 6), while the mean number of vulnerable and significant patches was below 2 (1.5 and 1.8, respectively). The situation was different when analysing the percentage of patches per class in a municipality. In this case, vulnerable patches represented 45.6% of the total, while insignificant and significant patches represented 33.5% and 20.9%, respectively.

The mean area of significant *Quercus suber* patches in all municipalities was 337 ha, while the mean area of insignificant patches was 158 ha, and that of

Table 1. Basic statistics of the *Quercus suber* forest patches in Sardinia

Groups of patches	Total number	Percentage of the total number
Vulnerable patches	205	27%
Insignificant patches	352	47%
Significant patches	197	26%
Total number	754	100%

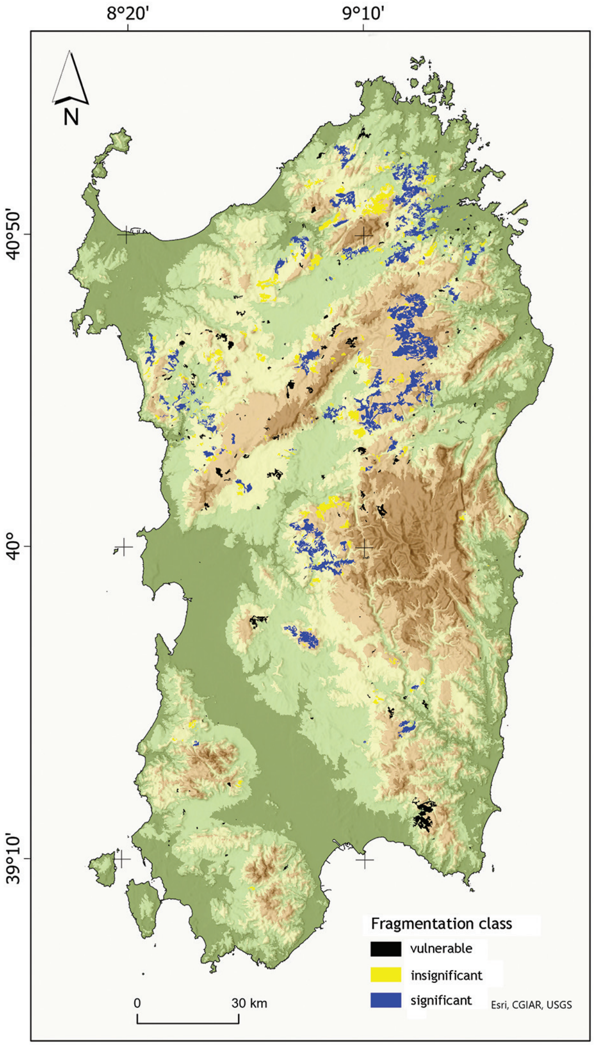

Fig. 2. Distribution of *Quercus suber* patches by class.

Table 2. Basic statistics of the area occupied by *Quercus suber* forests in Sardinia

Groups of patches	Total area (ha)	Percentage of the total	Mean area (ha)	Minimum area (ha)	Maximum area (ha)
Vulnerable patches	15 356.60	15	74.91	1.13	2 861.03
Insignificant patches	28 216.44	27	80.16	1.02	3 295.09
Significant patches	60 024.43	58	304.69	1.06	7 427.69
All patches	103 597.00	100	137.00	1.02	7 428.00

vulnerable patches was 86 ha. Considering the percentage of area occupied by each class of patches, a different regularity was found: the largest part (43%) of the total area was occupied by vulnerable patches, followed by the area occupied by significant (30%) and insignificant (27%) patches.

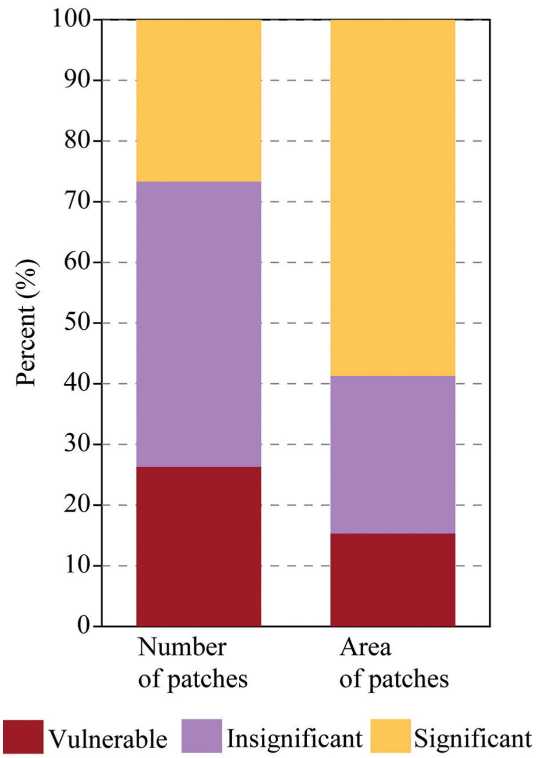

Fig. 3. Distribution of percentage of patches by classes of total number of patches (left) and percentage of area occupied (right).

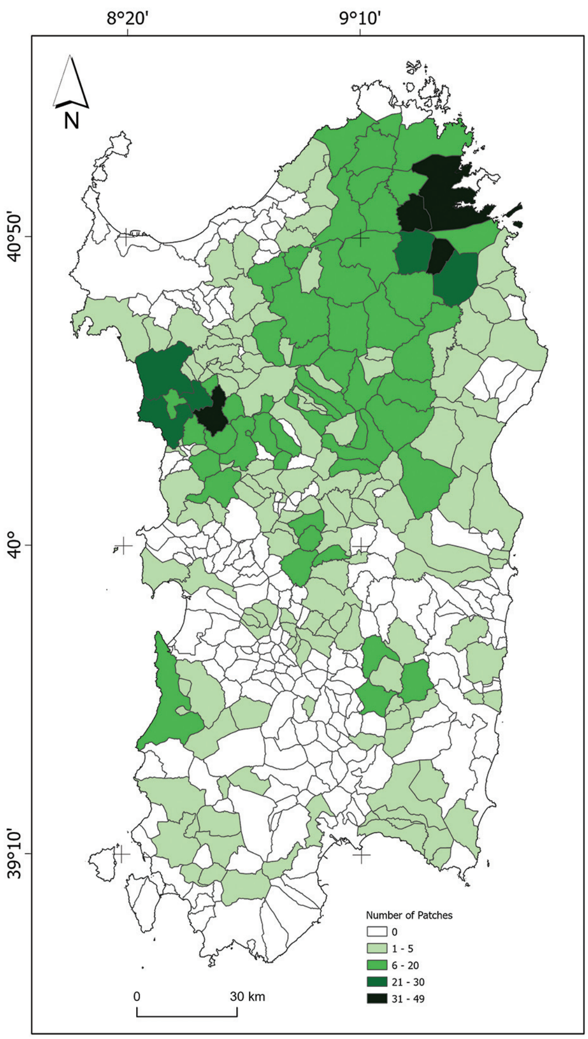

Fig. 4. Number of *Quercus suber* patches per municipality.

Table 3. Summary of the characteristics of *Quercus suber* patches at the municipal level (minimum, maximum and mean ± standard deviation, SD)

Values per municipality	Minimum	Maximum	Mean ± SD
Number of all patches	1	49	5.81 ± 7.14
Number of vulnerable patches	0	12	1.50 ± 1.54
Number of insignificant patches	0	22	2.54 ± 3.59
Number of significant patches	0	20	1.77 ± 3.24
Percentage of vulnerable patches	0	100	45.53 ± 41.23
Percentage of insignificant patches	0	100	33.54 ± 31.22
Percentage of significant patches	0	100	20.90 ± 25.06
Area of all patches (ha)	0.03	5 230.51	582.02 ± 896.27
Area of vulnerable patches (ha)	0	1 607.21	86.27 ± 172.74
Area of insignificant patches (ha)	0	3 122.23	158.52 ± 316.72
Area of significant patches (ha)	0	5 056.78	337.22 ± 755.27
Percentage of vulnerable patch area	0	100	42.67 ± 44.88
Percentage of insignificant patch area	0	100	27.05 ± 34.95
Percentage of significant patch area	0	100	30.27 ± 37.70
Percentage of all patch area	0	49.00	7.61 ± 8.97
Area in municipalities with only vulnerable patches	0.13	1 607.21	125.83 ± 250.92

These results showed more threatened patches (classified as vulnerable and insignificant) than significant patches. A mean of four endangered patches (belonging to the classes of endangered and insignificant patches) was recorded in each municipality. In contrast, a mean of 1.8 patches classified as significant was recorded, and they occupied a larger area of all *Quercus suber* forests (in ha and as a percentage). The analysis of only vulnerable patches, which were recorded in 75% of the municipalities, with a mean of 1.5 patches per municipality (Fig. 6 and Fig. 7), showed that the mean percentages were consistently higher than the absolute values in a municipality, both in terms of area and number of patches.

Analysis at the level of individual municipalities

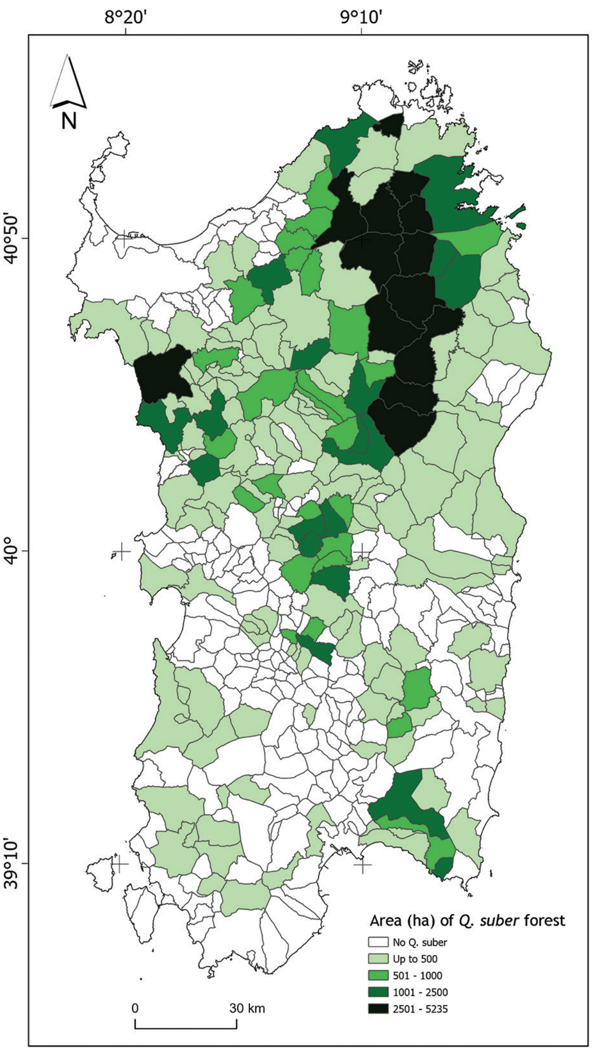

Fig. 5. Area occupied by *Quercus suber* patches per municipality.

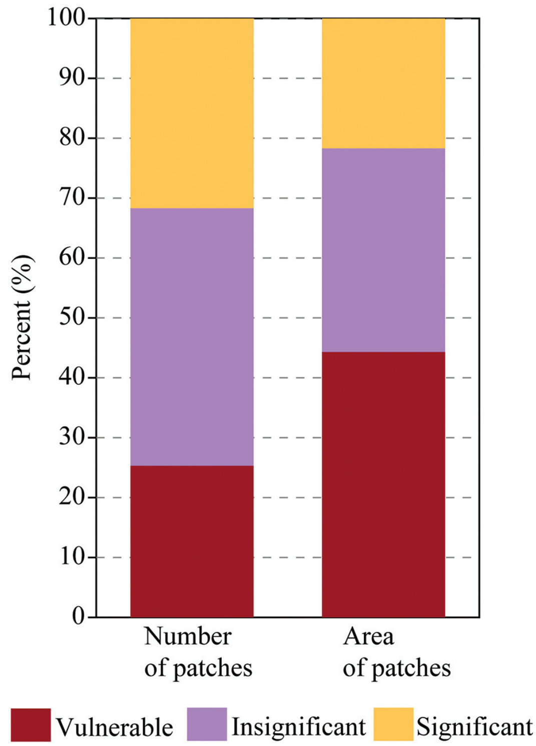

Fig. 6. Mean number and percentage of patches by class per municipality.

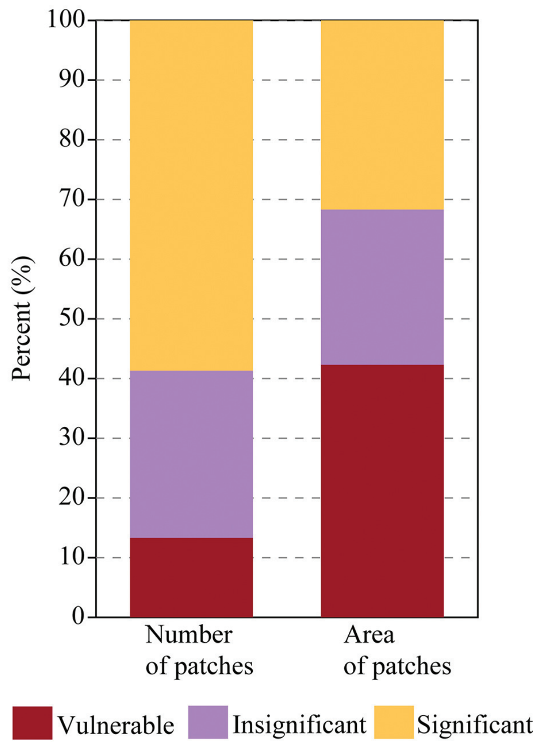

Fig. 7. Mean area occupied by each class of patches in a municipality (ha and %).

showed that those with the highest number of patches (more than 20) were in the northern half of the island, mainly in the north-east (Fig. 8). These municipalities were as follows: Olbia (49 patches), Telti (40), Pozzomaggiore (33), Bosa (30), Monti (26), Villanova Monteleone (24), Padru (23), Padria (22). The municipalities with the largest area occupied by *Quercus suber* (at least 2 500 ha and a percentage of the municipal territory ranging from 13% to 45%) were in the northern part of the island: the municipalities of Alà dei Sardi, Berchidda, Bitti, Buddusò, Calangianus, Monti, Nuoro, Orune, Telti, Tempio Pausania, Sant'Antonio di Gallura and Villanova Monteleone (Fig. 9, Table 4).

The analysis of habitat fragmentation showed that the municipalities in the northeastern part of the island had the highest number of threatened patches. In contrast, the municipalities in the extreme south and the mid-north of the island had the highest number of patches classified as vulnerable.

The most fragmented patches of *Quercus suber* forest (Fig. 8) were found in the municipalities of Olbia (34 patches), Telti (20), Pozzomaggiore (18), Villanova Monteleone (15), Loiri Porto San Paolo and Bosa (14), Padria, Sindia, Monti and Berchidda (13), Nuoro and Padru (11). In each of these municipalities, in the northeast and northwest of the island, more than ten patches classified as vulnerable and

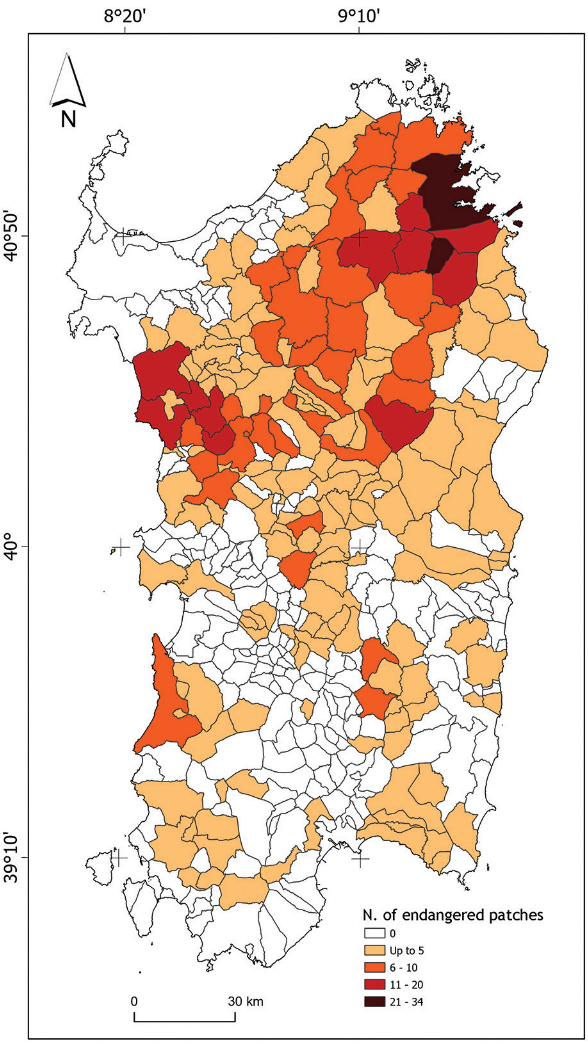

Fig. 8. Number of threatened patches of *Quercus suber* forest per municipality.

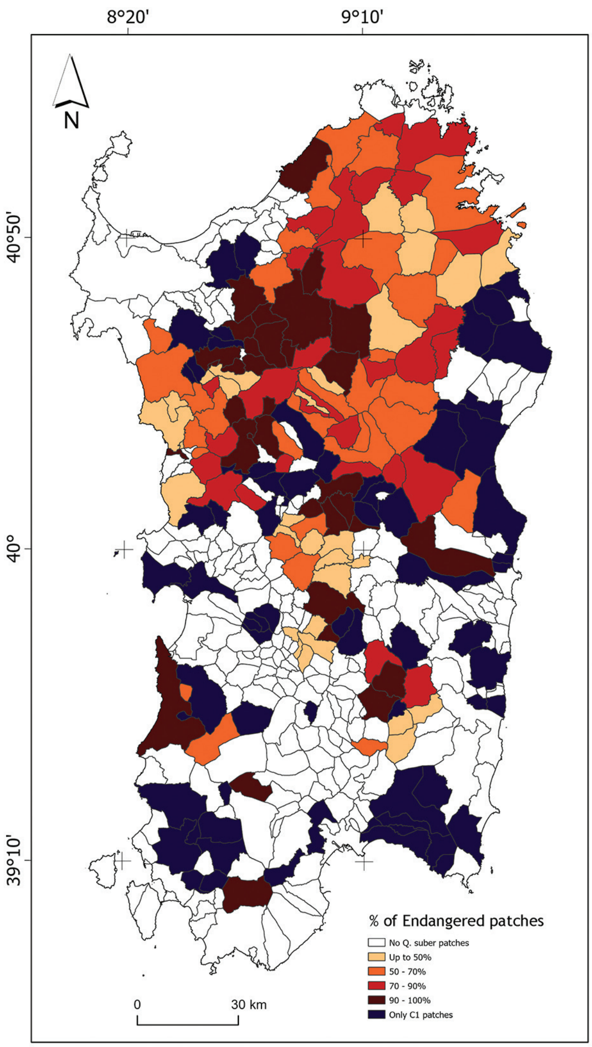

Fig. 9. Percentage of threatened *Quercus suber* forest patches (patches belonging to the vulnerable and insignificant classes) in a municipality.

Table 4. Municipalities with the largest areas of *Quercus suber* forests (more than 2 500 ha)

Municipality	Area (ha)	Total area (ha)	Percentage area (%)
Bitti	21 580	5 231	24
Buddusò	18 610	4 054	22
Calangianus	12 561	4 031	32
Sant'Antonio Di Gallura	8 214	3 716	45
Alà Dei Sardi	18 839	3 379	18
Monti	12 333	3 151	26
Orune	12 859	2 998	23
Telti	8 470	2 801	33
Villanova Monteleone	20 224	2 758	14
Nuoro	19 217	2 699	14
Tempio Pausania	21 130	2 656	13
Berchidda	20 184	2 598	13

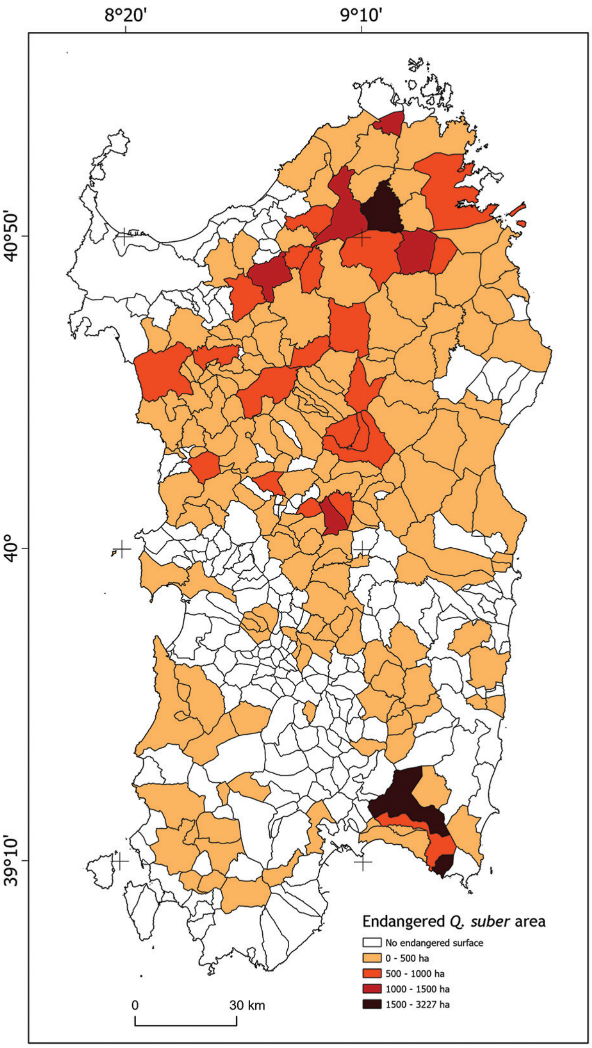

Fig. 10. Area occupied by vulnerable patches of *Quercus suber* forest per municipality.

insignificant were recorded. The analysis of the percentage of threatened *Quercus suber* forest patches (Fig. 9) showed that these habitats were most threatened in 58 municipalities since they contained only patches classified as vulnerable. These municipalities were distributed all over the island.

The analysis of the area occupied by endangered and most valuable *Quercus suber* forests (more than 1 000 ha), including vulnerable and insignificant patches (Fig. 10), showed that they were recorded in the municipalities of the south-east (Sinnai municipality), central (Austis) and northern (Calangianus, Chiaramonti, Monti, Tempio Pausania municipalities) parts of the island. In the southern municipality of Sinnai and the neighbouring municipality of Maracalagonis, there are some large patches of *Quercus suber* forest, presumably relatively healthy habitats. Still, they seem very isolated from the rest of the habitats. Therefore, these patches cannot contribute effectively to the rest of the network.

The southern part of the island, although it contains large areas of *Quercus suber* forest, is mainly characterised by small patches scattered across the landscape. Sites in the southwestern part of the island, in the municipalities of Assemini, Carbonia, Guspini, Iglesias, Narcao and Villamassargia, must be considered particularly threatened due to their high degree of isolation. In these areas, *Quercus suber* is not as important for the local economy as it is in the northern regions, so the risk of more significant fragmentation is higher.

The analysis of *Quercus suber* forest habitats in Sardinia showed that 74% of the patches on the island (42% of the total surface occupied by *Quercus suber* forest) need some intervention to solve the problems caused by fragmentation. In 47% of the municipalities, at least part of the *Quercus suber* patches were threatened, while 33% (58 municipalities) were characterised by only vulnerable patches with a high degree of fragmentation. Most of the threatened *Quercus suber* patches were in the island's northern half. In this region, where *Quercus suber* is an important economic resource, better planning would help to drastically reduce the problem within a few years, for example, by encouraging local farmers to plant new *Quercus suber* in specific corridors now occupied by open pastures. Scattered patches of *Quercus suber* forests still exist in the southern half of the island.

However, in some cases of considerable size, they are generally small, and their isolation even more threatens their existence.

DISCUSSION

This study attempts to provide a rapid method for analysing habitat fragmentation issues, as this information is a basis for conserving forest habitats. The CONEFOR software was used to calculate two indices, *PC_Flux* and *PC_Connector*, for each patch of *Quercus suber* forest on the island of Sardinia. The analysis results were classified according to the presence or absence of a value for one or both indices. The lack of values represents a certain degree of fragmentation. The output of the analysis consists of two shapefiles and eight maps.

The methodology presented in this study is essentially binary. Typically, percentage values of the importance of individual patches in the network are interpreted according to context. For example, a fragmentation value of 20% could be very significant in one situation and insignificant in another. The method used here has the advantage of being quick and extremely inexpensive in identifying a major threat to *Quercus suber* forest communities. Habitat fragmentation could indirectly increase the risk level of the other threats to the habitat. The method can be applied to any forest community, with adjustments for the type of tree species pollination, and can be easily integrated with other necessary variables.

A problem in applying the methodology was related to the specific geographical distribution of the studied habitat, which in the case of Sardinia was very heterogeneous, especially in the southern part of the island. This led the algorithm to consider large forest patches as particularly vulnerable due to their isolation from the rest of the network. This is exactly what it is supposed to do, but these patches' actual vulnerability is debatable. The analysis has identified the general extent of the problem across the island, specifically in those municipalities where the risk of fragmentation is high. In general, the results indicate that the percentage of fragmented *Quercus suber* patches is high (74% of them needing some intervention) and that these habitats are more concentrated in those regions of the island where *Quercus suber* has high economic importance, for example, in the northeastern region of Sardinia.

The degree of habitat fragmentation should be carefully considered in future planning, and this could be done quickly using a fragmentation map. Such a map could and should also consider the factors affecting the favourable status of *Quercus suber* populations, such as grazing, fire and pests, for each municipality. This will require further work to collect and collate data on these threats across the island, but it will also provide a high-quality mapping base for future planning at a regional level.

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Author contributions. All research was performed, data analysed, and text written by the author.

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