


Article

Fragmentation and Connectivity of Island Forests in Agricultural Mediterranean Environments: A Comparative Study between the Guadalquivir Valley (Spain) and the Apulia Region (Italy)

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Abstract: Habitat loss and fragmentation are considered some of the main threats to biodiversity. Original forests have suffered an accentuated fragmentation and agricultural homogenization, leaving only some areas of natural vegetation, relegated to strongly anthropized disconnected patches (island forests, IFs) in a hostile matrix. These patches of original vegetation could be the key for the design and management of ecological corridors to promote species migration, an essential strategy for meeting the consequences of Global Change. This study proposes a comparative analysis of the fragmentation and connectivity of IFs of *Quercus* in two typically Mediterranean areas of predominantly agricultural use: the Guadalquivir valley (Spain) and the Apulia region (Italy). A retrospective comparison is also carried out in the Guadalquivir valley. The aim is to develop an objective new methodology to locate the patches of most interest using quantitative and qualitative data. Reference cartography of current island forests of *Quercus* species was developed from several digital sources and validated with orthoimages and field observations. Fragmentation analysis was based on graph structures using the software Conefor 2.6, a reliable tool for assessment of the role of patches in the landscape. Area and distance were used as node and connector values. Dispersion distance was established as 500 m, based on the maximum dispersion of acorns. Results indicate that the Guadalquivir valley has suffered an intensive fragmentation in recent decades. Both the Guadalquivir and Apulia regions host some IFs with the relevant potential to contribute as core habitats in the creation of connections to other natural protected sites. Many residual IFs in the landscape could contribute as stepping stones in the design and management of ecological corridors. Our methodology highlights the value of IFs to develop assessment strategies using homogenized available digital cartography and common criteria for the dispersion distances in graph theory analysis. The application of this new methodology could help in the management of protected sites using highly fragmented areas to allow the species movement through inhospitable landscapes in a unique opportunity to connect the different protected areas.

Keywords: Apulia; Conefor 2.6.; ecological corridors; fragmentation; Guadalquivir valley; island forests; *Quercus*

1. Introduction

The processes of reduction and fragmentation of habitats are considered by the scientific community as one of the main threats to biodiversity [1,2]. This biodiversity loss makes

an ecosystem less resilient, and thus less capable of tolerating disturbances. In addition, it could impact economic processes affecting human well-being, since biodiversity is essential for many elements of ecosystem services [3,4].

Species are distributed according to the spatial variation of the environmental conditions that characterize the habitats they occupy. Natural disasters, such as floods or wildfires, among many other natural phenomena, modify the structure of the territory, creating a heterogeneous landscape. Other environmental variables such as topography, lithology, edaphology, etc., can also contribute to the landscape heterogeneity. However, from a conservationist point of view, it is not this gradual change in the natural landscape which concerns managers, but rather the increasing capacity of human activity to transform the environment. It is seriously affecting the normal functioning of natural systems. Human activity has been modifying land cover for approximately 10,000 years, with early forest clearing for the subsequent installation of crops and pastures. This transformation has been intensified by the industrial revolution since the latter part of the 18th century [5] and the development of heavy machinery, capable of transforming large areas in a short period. Such has been the severity of this influence that Crutzen and Stoermer [5] proposed a new geological era called the Anthropocene, to indicate the power that humanity has had over the basic processes of the biosphere.

In recent decades, this transformation has been very intense in western Europe: the original forests that made up the European landscape have suffered an accentuated fragmentation and agricultural homogenization, leaving only some areas of natural vegetation, relegated to strongly anthropized disconnected patches in a hostile matrix [6–8] sufficiently permeable to allow animal movements or plant dispersion. These losses of forest cover are more common in meadows, valleys and plateaus, as they are accessible areas with higher productivity. In other areas of Western Europe, many sites previously dedicated to agriculture have shown a clear recovery in recent times, so this phenomenon of land use change and fragmentation has not been generalized throughout the continent [9,10]. Such sites are basically ancient agricultural areas of low productivity characterised by a particular relief that makes mechanization difficult, and are consequently less profitable for agriculture.

Fragmentation refers to the progressive change in landscape by which a given habitat, usually forests, is reduced to smaller patches or island forests, enclosed within a hostile matrix with a land use different than the original one. The negative consequences of this change can be summarized as [1,11,12]: (i) a reduction in the amount of available habitat, and therefore, a lower population size of the species; (ii) a decrease in the average size and an increase in the number of habitat fragments; (iii) the isolation of the resulting fragments, limiting the exchange of individuals between separate patches; and (iv) a higher perimeter/surface ratio among the patches and hence greater exposure and permeability to the negative effects of surrounding land uses, known as the edge effect [8].

The results of this fragmentation and isolation are residual areas, generally known as Island Forests (IFs) where the original ecosystem was a forest. According to the theory of island biogeography [13,14], there are unconnected patches of the original habitat (islands) embedded in a matrix (sea) very different from the original one (Figure 1).

The conservation of hedges, fences, boundaries, IFs, etc. in these transformed landscapes is a key factor for the following reasons:

- They favour the maintenance of biological richness and biodiversity. They contribute to the knowledge and characterization of the potential vegetation in those territories with a marked alteration [15].
- IFs are an important core for ecological succession in the recovery of some areas of abandoned cultivation, and/or the creation of ecological corridors allowing species flow through the landscape [16].
- They are patches of mature ecosystems providing heterogeneity and the maintenance of ecological processes in the landscape [17,18], and playing a substantial role in pest control and serving as a refuge for wildlife [19].



Figure 1. Picture of an Island Forest (IF) in the Guadalquivir valley (Spain) in the middle of a hostile agricultural matrix. The structure of this patch is a forest of holm oak trees accompanied by dense scrubland.

Apart from these reasons, there is the need to address a new threat to the biosphere: global change. This proposed human-induced phenomenon is driving species in a process known as poleward (latitudinal) and upward (altitudinal) migration [20,21]. Range shift could be especially severe in overexploited and degraded habitats, as the speed of the shift may be too fast for the dispersal capacity of many species. In this context, high latitude and high mountain forests will be seriously affected due to the absence of available territories into which they can migrate [22]. Stenoic and low dispersal capacity species would require a specific management to face this fast shift [23]. One proposed solution is benign introduction, a particular type of intentional introduction aimed at establishing a new population of an endangered species outside its recorded historical range to favor its conservation without causing ecological damage [24]. Other solutions involve the management of the landscape to facilitate the dispersion of the species by means of landscape corridors [25]. In this strategy, the dispersed elements of the landscape play an essential role.

However, there are no specific criteria for the identification and management of the most significant elements in the landscape when designing an ecological corridor. This study aims to develop an objective methodology to locate patches of key interest, using quantitative and qualitative data. The final goal is to establish a scientific basis for the development of an interconnection strategy based on ecological corridors. This strategy is essential for the proper management of protected sites, including the Natura 2000 Network [26].

2. Materials and Methods

2.1. Study Area

To demonstrate the capacity of this methodology, the study is conducted with the first step in the Guadalquivir Valley (southern Spain, Figure 2A), where a retrospective analysis was carried out. In the second step, the results were compared with an equivalent area in south central Europe: the Apulia region in the south of Italy (Figure 2A). Both areas are widely described as representative of Mediterranean oak forests, with a high degree of deforestation due to conversion into arable land (Figure 2B,C).

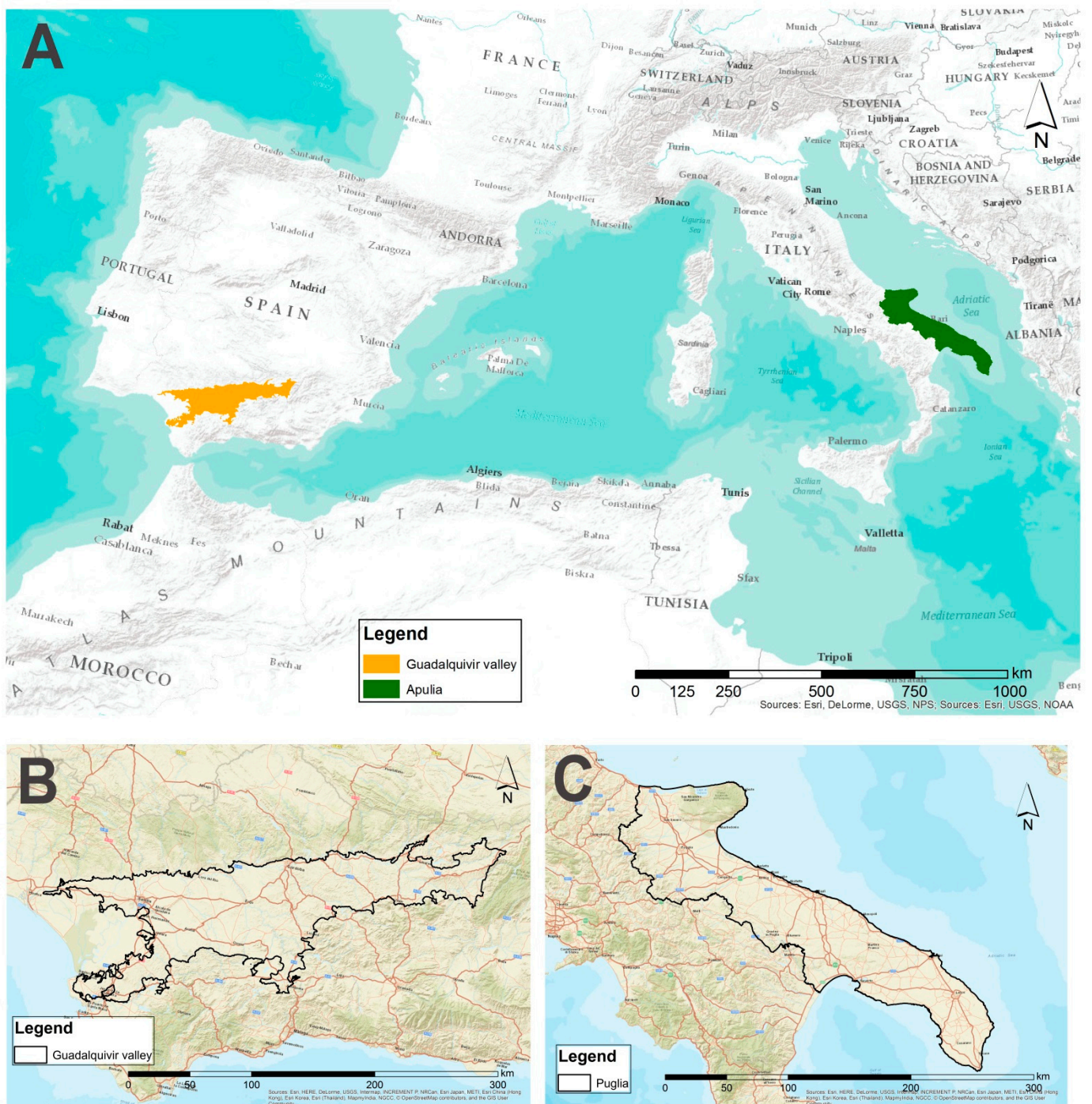


Figure 2. Location of the study area. (A): In orange, the Guadalquivir valley in Spain, in green, the Apulia region in Italy. (B): Detail of the Guadalquivir valley and features of the terrain including Intact Forest Landscape (IFL, ESRI©) in the light green color. (C): Apulia region using the same reference cartography. The absence of nature/native forest in the selected regions is remarkable.

The study areas are both located in the Mediterranean region [27]. The Mediterranean landscape is rich in biodiversity due to its physiographic and climatic diversity, historical dynamics and the coexistence of semi-natural spaces developed for traditional agricultural and livestock purposes together with areas of natural vegetation [28–30]. This is considered an endangered hotspot of biodiversity [31] by the International Union of Conservation of Nature [32,33]. It is an extremely fragile area, vulnerable to Global Change where oak forest decline is leading to pyrophytic shrublands [34]. Fires are natural disturbances in Mediterranean ecosystems and have contributed to landscape dynamics for thousands

of years [35]. However, the Mediterranean Basin is projected to suffer a generalized rise in mean temperatures, and rainfall to undergo irregular patterns [36]. These climatic anomalies [37] have imperilled the current outlook for this fragile ecosystem the worst.

2.2. Reference Cartography

The Spanish study area corresponds to the Guadalquivir valley (Hispalenseac biogeographic sector, Baetic Province, Mediterranean Region). This area pertains to the Guadalquivir basin, a depression filled with the sediments of the surrounding mountain ranges. The valley covers an area of about 17,188 km², or 20% of the area of Andalusia. It is a Mediterranean ecosystem, the main tree species being the holm oak (*Quercus ilex* L. subsp. *Ballota* (Desf.) Samp) and, to a lesser extent, the cork oak (*Q. suber* L.) [15]. The reference cartography for current IFs of the *Quercus* species in the Guadalquivir valley is based on the map developed by Hidalgo et al. [38] This map was derived from several cartographic sources: the MUCVA of 2007 (Mapa de Usos y Coberturas Vegetales de Andalucía, 1:25,000 scale, REDIAM, 2018 [39]), SIOSE Andalusia Cartography at a scale of 1:10,000, updated in 2009, and the Forest Map of Andalusia, at a scale of 1:50,000, from the 3rd National Forest Inventory 1997–2007. This composite map was validated by an intensive field study in which a total of 685 polygons were visited to confirm the accuracy of the obtained cartographic information previously obtained. The polygons were also reviewed with the most recent orthoimages (PNOA, 2018, WMS server [40]). For a retrospective analysis, a digital map (Map of Usage and Vegetation Cover at a scale of 1:33,000, 1956–1957, REDIAM, 2018, [39]) derived from aerial photographs obtained taken in 1956 was used. For validation, all current polygons in our cartography were reviewed and compared with the digital map of 1956.

The Italian zone corresponds to the Apulia administrative Region (Adriatic Province, Mediterranean Region). The study area covers around 19,345 km², slightly larger than the Guadalquivir area. It is known as *La Terra delle Querce* [41], as there is a great diversity of *Quercus* species: *Q. ilex*, *Q. suber*, *Q. cerris* L., *Q. frainetto* Ten., *Q. pubescens* Willd. and *Q. trojana* Webb. However, the National Forest Inventory identifies its forest index as the lowest in the country, with a worrying lack of green areas, especially in the southern part of the region [42]. The digital cartography of these species was derived from several sources [43]: Carta della Natura in Apulia, using CORINE codes at a scale of 1:50,000, developed by ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale), and ARPA Apulia (Agenzia Regionale per la Prevenzione e la Protezione dell’Ambiente della Apulia). The most recent cartography was carried out in 2014 [43]. The composite cartography was validated with the most up-to-date orthoimages available in the WMS server <http://webapps.sit.puglia.it> (last accessed on 15 November 2017). Unfortunately, no historical cartography was available from the Apulia region for retrospective analysis.

In both areas, a 1 km buffer was applied to the forested areas using Geographic Information Systems (ArcGis 10.1, ©ESRI) in order to ensure that these could be considered as isolated. Hence, any IF located in a clear forest domain was filtered out and removed from the digital cartography. By contrast, all IFs surrounded by agricultural matrix remained in the study, as they were clearly identifiable in the landscape. Following the definition of an Island Forest [44], only the polygons with a size between 1 to 1000 hectares and tree cover greater than 50% were selected. In this way, only IFs of sufficient habitat quality were considered. The final result was a digital map of polygons made up of polygons containing *Quercus* species that play an analogous ecological role in the two regions/time slice. In the Italian region, the study excludes short-term plantations of *Quercus* for biomass production in order to focus exclusively on natural forest sites.

2.3. Fragmentation and Connectivity Analysis

The fragmentation and connectivity study was conducted with the Conefor 2.6 tool (<http://www.conefor.org>, last accessed on 15 November 2017). There are many other tools for fragmentation, connectivity studies and ecological corridors design (see <https://>

conservationcorridor.org/corridor-toolbox/programs-and-tools/ for further details, last accessed on 15 August 2021). However, Conefor has been demonstrated to be the most powerful tool for quantifying the importance of habitat areas, i.e., the main goal of our study. This software is free and relatively easy to manage. However, an intensive training course should be carried out to obtain optimum results. This software is based on graph structures [45–47], whereby, in our study, IFs were nodes and the distance between them connectors. Conefor calculates the PC index (Probability of Connection index), which is the probability that two points randomly located in the landscape are connected in a set composed of n patches and their connections [48,49]. The index provides a single value for the entire landscape, and also measures the amount of available habitat in the landscape. This unique value for a given area is useful for comparing different areas or for retrospective analysis. The PC is given by the formula:

$$PC = \frac{\sum_{i=1}^n \cdot \sum_{j=1}^n a_i \cdot a_j \cdot p_{ij}}{A_L^2}$$

where, for i to j patches:

n is the total number of patches or nodes in the landscape,

a are the attributes of the patches (area in our study),

p_{ij} is the product of the maximum probability, i.e., the probability of direct and indirect dispersion between patches i to j ,

A_L is the maximum landscape attribute, i.e., summation of the attributes of all the patches in the landscape (total area in our study).

The value of p_{ij} is given by the formula:

$$p_{ij} = e^{-d_{ij}/\alpha}$$

where, for i to j patches:

d_{ij} is the distance between nodes i to j ,

α is the dispersion distance of the species,

The threshold of patch connectivity distance is necessary for the calculation of the PC [50]. In our study, the PC value was calculated for all region/time slices using a maximum dispersion distance established as $\alpha = 500$ m, taking the following rodents and birds as the main dispersal vectors of acorns (the fruit of *Quercus* trees): the wood mouse (*Apodemus sylvaticus*) and the Eurasian jay (*Garrulus glandarius*) [51–57]. Due to their nutritional value, acorns are attractive to most of the frugivorous fauna [58]. A minimal part of hidden acorns is not consumed, and they germinate under favourable conditions [54,59,60]. The Eurasian jay plays an important role in the colonization of *Quercus* species. It is responsible for the dispersal of acorns over thousands of meters during the ripening season [53,61] and is the key factor in the regeneration of holm oak forests [55]. However, this bird is very sensitive to landscape fragmentation, tending to disappear in small–medium fragments [62]. Therefore, in highly fragmented areas, the regeneration of oak forests depends almost exclusively on the activity of rodents [63], the field mouse (*Apodemus sylvaticus*, L.) being the main dispersal species in both study areas. It is able to survive in adjacent areas (ecotone) subjected to different management [52,64]. A study on the dispersal and predation of acorns shows that 70% of all fruits collected after the first dispersive movement were dispersed again by rodents at distances exceeding 130 m [65]. These distances also depend on the slope, with downhill displacement increasing hundreds of meters, and uphill displacement rarely reaching 50 m. In conclusion, an average of $\alpha = 500$ m seems to be a reasonable dispersion distance when the probability was set to 0.5 [50], i.e., at least 50% of the acorns are able to reach the distance of $\alpha = 500$ m.

Conefor also estimates the individual contribution of each patch to the connectivity by means of probabilistic models. This contribution is the dPC (differential of Probability of Connection) index, which is the percentage of variation in the PC index due to the

elimination of each patch in the landscape. It summarizes the role of each path in the connectivity of the studied area. The dPC is given by the formula:

$$dPC_k = \frac{PC - PC_{elim}}{PC_k \cdot 100}$$

The value of dPC can be divided into three different parameters (Figure 3) [49]:

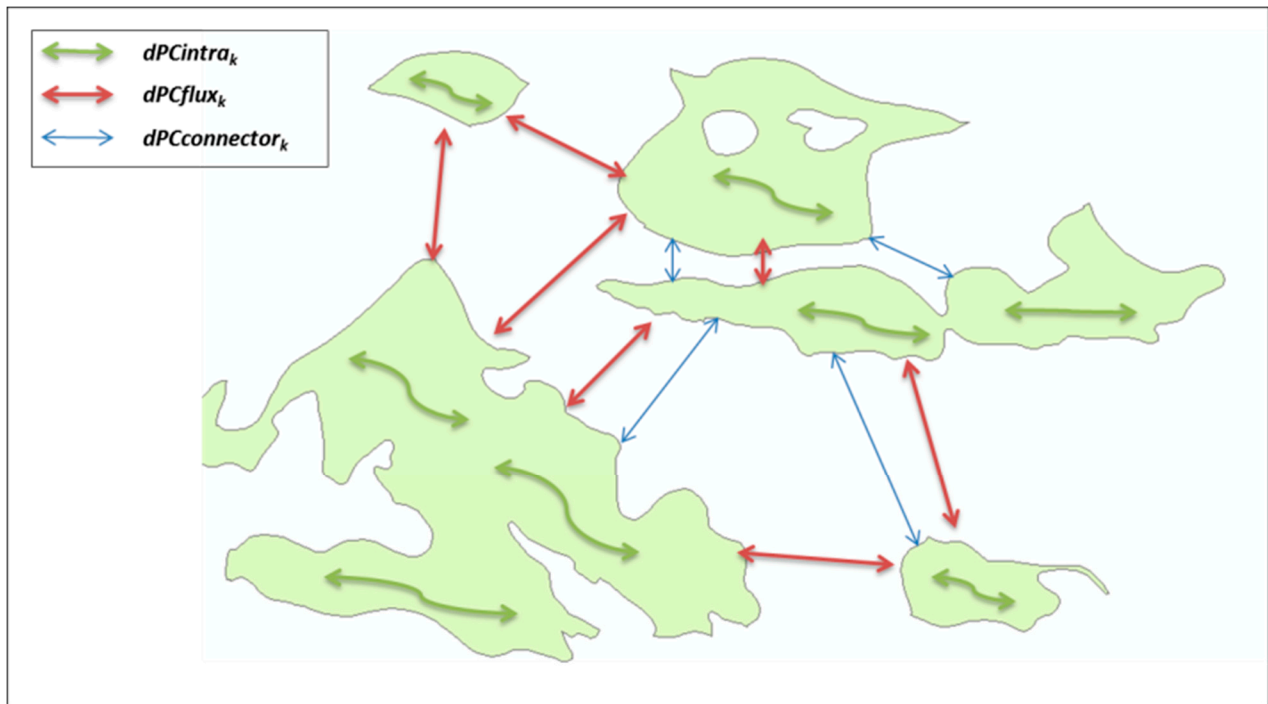


Figure 3. Schematic representation of the three different components of dPC. The value of dPC_{intra} represents the internal connectivity of the patch, dPC_{flux} describes the role of each patch in connecting to surrounding patches (direct connection) and $dPC_{connector}$ describes the role of a patch as a stepping stone (intermediate patch).

$$dPC_K = dPC_{intra} + dPC_{flux} + dPC_{connector}$$






where:


- dPC_{intra} or *intrapatch*: This refers to connections between the resources available within the same patch, i.e., the internal connectivity of each patch. When the attribute used is its area, this factor depends on the patch size, which means that the larger the size, the greater the dPC_{intra} , regardless of the space it occupies in the set of patches. A patch with a high dPC_{intra} value could be considered as a core habitat.
- dPC_{flux} or *interpach*: This represents the direct dispersion flow to the other patches, that is, the flow that occurs between two patches without the need for a third to act as a bridge.
- $dPC_{connector}$ or *stepping stone*: This measures how a patch facilitates dispersion without being the origin or destination of the connection. It is the contribution of each patch as a connecting element or bridge to the other patches of the study area. These elements are known as stepping stones in landscape ecology [66]. Stepping stones are patches of habitat that are smaller than the core habitat patches. The value of $dPC_{connector}$ fluctuates in relation to the position it occupies with respect to the rest of the patches.

Although individual dPC values are of interest in the management of each polygon within the landscape and in the creation of ecological corridors, in our analysis we will show only the sum and mean dPC in order to provide a quick overview of the fragmentation

status of each territory/time slice. Only for particular examples will we show the dPC value for each polygon. In order to facilitate the interpretation of the role of each IF in the landscape, the dPC values have been categorized into 5 intervals (Table 1) using a red-to-green colour scale, in which dark green identifies the most significant IFs in terms of connectivity, and red the most isolated. A qualitative value of connectivity is assigned to each interval using the scale of *low*, *medium low*, *medium*, *medium high*, and *high*. Patches with dPC > 10 were considered as important core areas and sources of species. Patches with dPC < 10 can be considered as stepping stones with a role in connectivity depending on the value assigned in the scale.

Table 1. Classification of dPC values according to intervals and red-to-green colour scale.

Intervals	dPC Values	Colour Scale	Connectivity
1	0.0001–0.009		low
2	0.01–0.099		medium low
3	0.1–0.999		medium
4	1–9.999		medium high
5	>10		high



3. Results and Discussion

Island forests were widely distributed in 1956 along the valley, although concentrated in certain specific areas (Figure 4). However, in the present (Figure 5), the number of IFs is clearly lower. Many areas where the forests were well represented have disappeared. Table 2 shows the IF data for *Quercus* trees in both time slices. Of the 975 IFs in 1956, only 706 remain, a total of 206 IF loss in around six decades. This is not the only loss in this process. The total area of IFs in 1956 was 27,832.82 ha, representing 1.62% of the total surface, of which only 11,622.49 ha remains nowadays, a reduction of a 58.24% and with a representation of only 0.62% of the territory. A comparable dramatic reduction over a short period of time has also been reported in Brazilian Cerrado (tropical savannah) where 23.9% of natural patches have been lost in 17 years [16]. In addition, the mean area of the Guadalquivir valley IFs nowadays has shrunk from 28.55 ha to 16.04 ha. This means that those IFs that do remain are now approximately half the size of the originals. Notably, the mean perimeter of IFs has remained pretty much the same since 1956, despite the total number of patch perimeters being higher than today. In short, there is less area but the same perimeter, i.e., one of the main factors contributing to an increase in the edge effect.

With respect to the distribution of IF of *Quercus* in the Apulia region (Figure 6), the surviving IFs in this agricultural area are concentrated in the north, linked to other natural forests of the Meridional (southern) Apennines as a result of a transition landscape. In the south, they spread out to the southeast of Bari in areas which are hard to convert into arable land and therefore permit natural forests to remain. The rest of the IFs are scattered across in the huge territory in a sporadic fashion. Comparing these results with those obtained for the Guadalquivir valley in the present (Table 2), it is notable that there are 340 more polygons in the Apulia region. The total area in Apulia is higher, but the mean area of IFs is lower, i.e., there are more polygons, but they are smaller. This result is coherent with areas subjected to intensive agriculture, a process leading to a drastic erosion of the original natural ecosystem into remnant forests. With respect to the mean perimeter, this is of the same magnitude as the Guadalquivir valley in both periods.

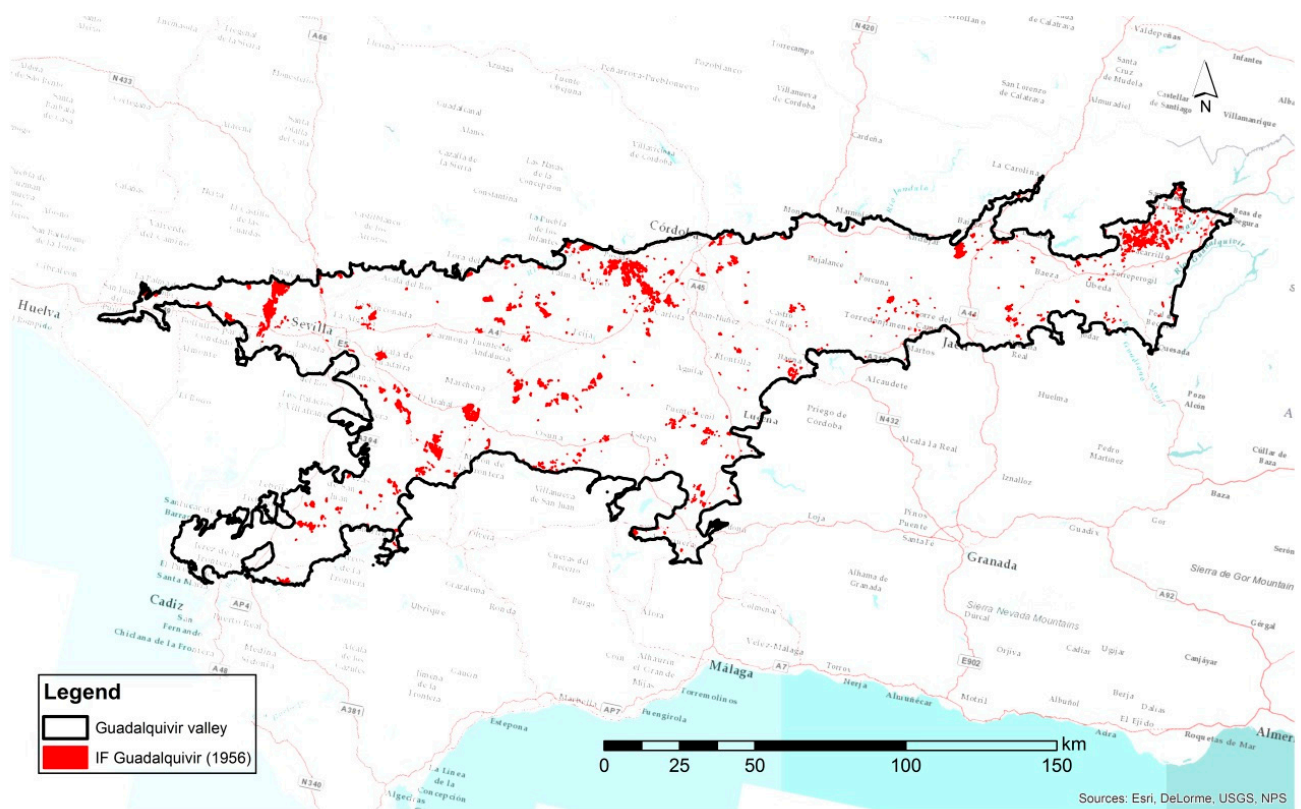


Figure 4. Distribution of IF in the Guadalquivir valley in 1956.

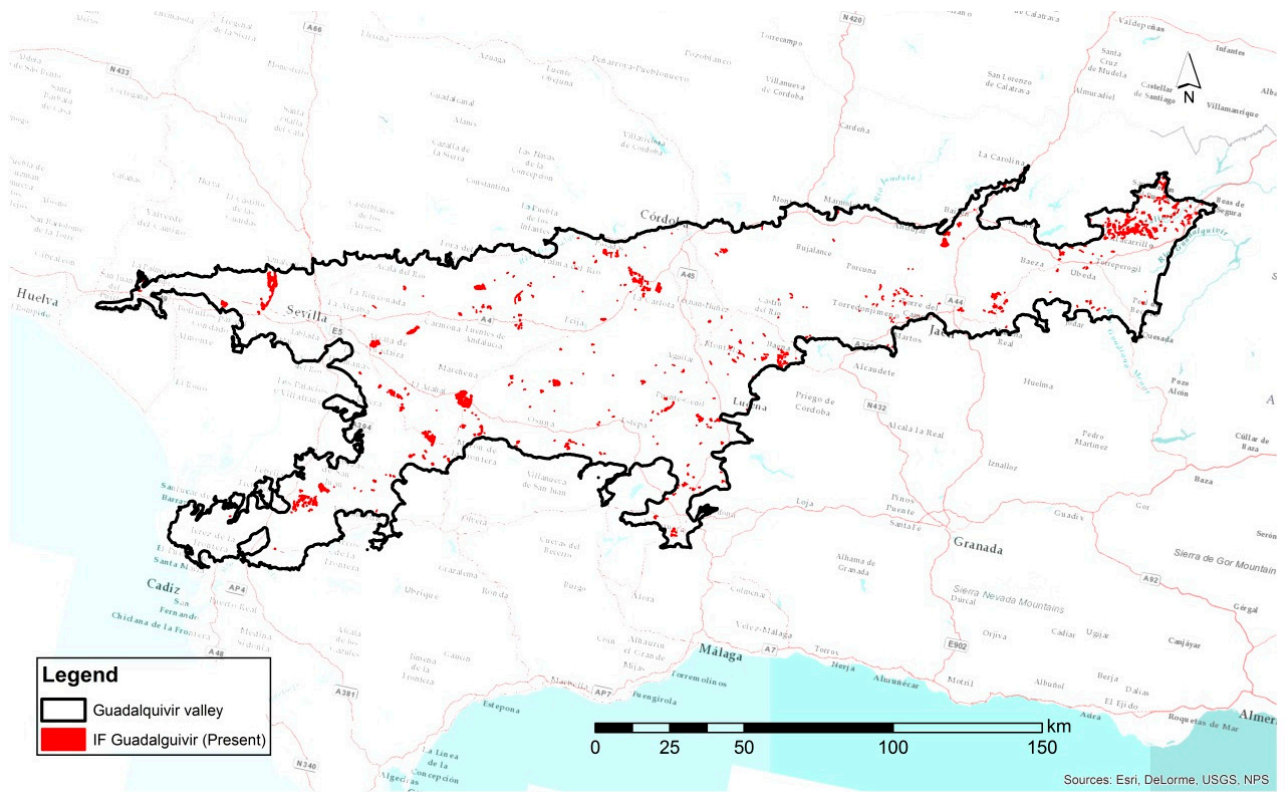


Figure 5. Present distribution of IFs in the Guadalquivir valley.

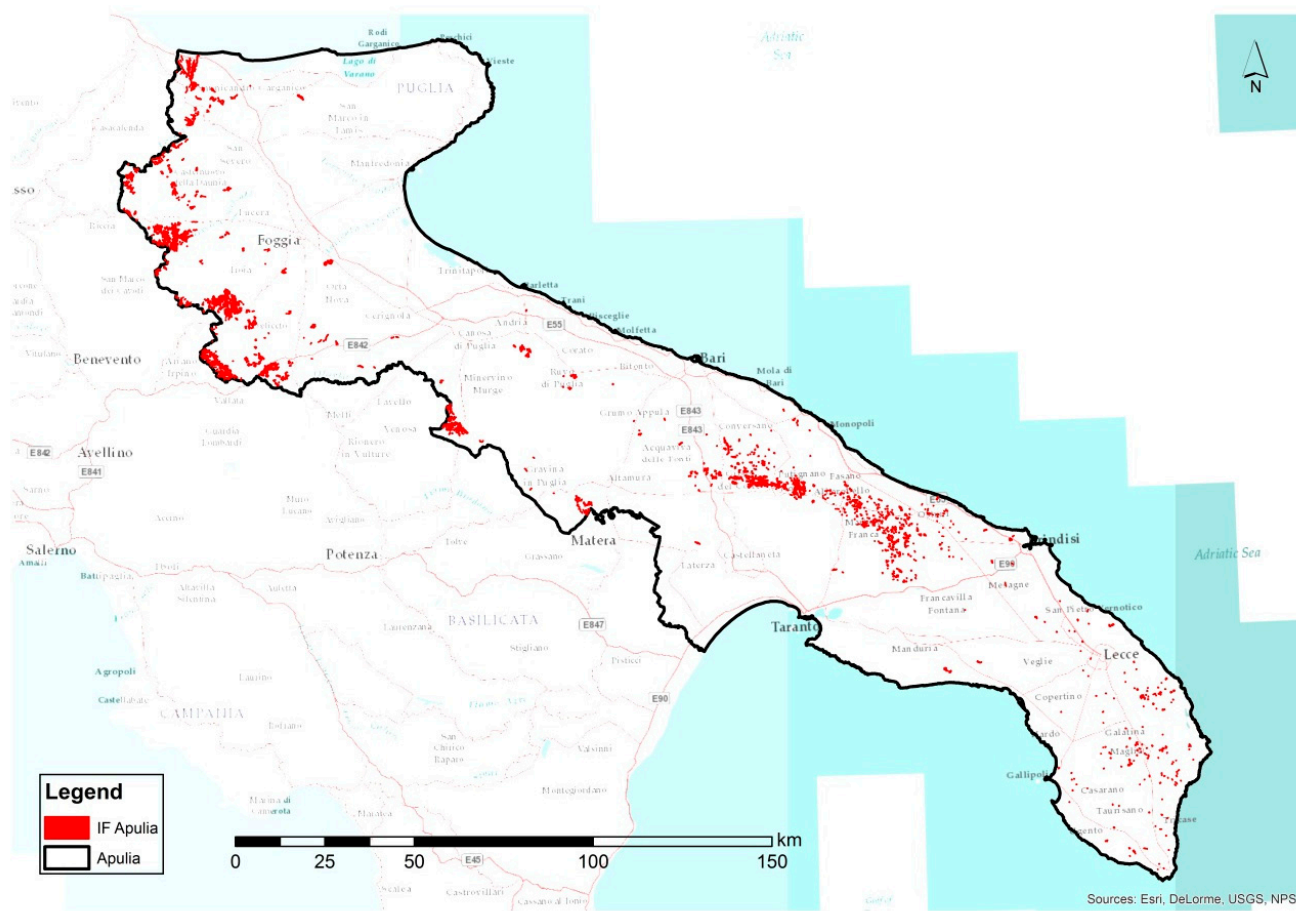


Figure 6. Present distribution of IF in the Apulia region.

Table 2. Area, number of polygons, total area of Island Forests (IFs), mean area, perimeter and mean perimeter of the study regions.

Study Area/Time Slice	Total Area (km ²)	n° Polygons	Total IF Area (ha)	Mean Area (ha)	Total Perimeter (m)	Mean Perimeter (m)
Guadalquivir 1956	17,188	975	27,832.82	28.55	2,681,335	2311
Guadalquivir (present)	17,188	706	11,622.49	16.04	1,789,746	2535
Apulia (present)	19,345	1046	13,327.64	13.07	2,527,263	2416

Concerning the results of the fragmentation analysis obtained by the Conefor software (Table 3), PC values indicate the present situation with respect to connectivity for each territory/time slice. The best result (4670.62) was obtained in the Guadalquivir valley in 1956. This value of PC has declined to 1987.64 (57.44%) in approximately 6 decades. It means that the probability of connection of two isolated patches in the landscape has been reduced by more than a half. This retrospective analysis has proved to be a useful tool for quantifying the functional connectivity changes in the landscape of this region. The applied methodology allows us to understand the recent changes in a given area using quantitative data. Similar results have been obtained in other retrospective studies conducted in other parts of the world [67] where global connectivity (PC value) has progressively decreased over recent decades.

Table 3. Results of the fragmentation analysis. Values for PC (Probability of Connection), dPC and mean, with the three components of dPC (dPC_{intra}, dPC_{flux}, and dPC_{connector}).

Area/Time Slice	PC	Σ dPC/Mean dPC	Σ dPC _{intra} /Mean dPC _{intra}	Σ dPC _{flux} /Mean dPC _{flux}	Σ dPC _{connector} /Mean dPC _{connector}
Guadalquivir 1956	4670.62	192.29/0.19	40.17/0.04	119.65/0.12	32.46/0.03
Guadalquivir (present)	1987.64	176.42/0.24	45.84/0.06	108.30/0.15	21.89/0.03
Apulia (present)	2470.88	193.12/0.18	39.56/0.03	120.87/0.12	33.49/0.03

Comparing the results of present status in the Guadalquivir and the Apulia regions, the PC values for both are similar, albeit slightly higher in Apulia, possibly due to the higher number of polygons. It is interesting to point out that there are many areas in Apulia without any Ifs, but the presence of more polygons across the region makes it as connected as the Guadalquivir valley, where the polygons are more evenly distributed. As this study demonstrates, although PC values are intrinsic to a given territory, comparative analyses can be particularly useful, in terms of both in different territories and in time.

With respect to dPC values, i.e., the contribution of each polygon to the connectivity, the total for the Apulia region is similar to that of the historical situation in the Guadalquivir valley, while the present Guadalquivir situation is slightly lower. This indicates that there are fewer polygons in the Guadalquivir valley nowadays with a lower degree of connectivity and explains the lower PC values in this region. However, the mean value in this area is higher than in the other region/time slices, possibly due to the higher contribution of the surviving IF polygons. Differentiating between the component of dPC (dPC_{intra}, dPC_{flux} and dPC_{connector}), the values for dPC_{intra} are higher in the present Guadalquivir. It means that internal connectivity is more important than the other parameters. By contrast, the values of dPC_{flux} and dPC_{connector} are lower, which account for the low value of the overall dPC. This is to say, when the role that an IF plays in connectivity is low, only internal connectivity gains importance. This explains the lower values for dPC_{flux} and dPC_{connector} in this area in comparison to the other region/time slices.

Detailed analysis of the contribution of each IF to the connectivity in the selected areas/time slices was carried out in various representative areas, where we used the standardization of the values for dPC described in the materials and method section. The value of dPC, unique for each element in the territory, has proved to be a powerful tool for connectivity analysis [68,69].

The first analysis compared the IFs in a selected area of the Guadalquivir valley in 1956 and the present day (Figure 7). Figure 7A shows the area located to the southwest of the city of Córdoba (Spain). The occurrence of IFs is abundant and the value of dPC of the main patches corresponds to the highest connectivity interval. In at least one patch (the largest, in the southeast, and rounded in shape) there is a good well-defined core habitat. In the second image (Figure 7B), the situation in the present time is radically different. Only a few patches remain and only one has the maximum value for connectivity as described in Table 1. The large patch with an excellent core habitat in 1956 has been reduced to several isolated patches where the values of dPC have been reduced to medium–low values of connectivity. The cause of this degradation of the original IFs is the intensive transformation of land use in this fertile agricultural area. Although the creation of ecological corridors could improve the connectivity of this over-occupied landscape, the possibilities are now more limited than in 1956; success is far from guaranteed, and the cost effectiveness of the implementation of such a project could well be minimal. Further, landscape connectivity is lost when the threshold dispersion distance ($\alpha = 500$ m) is surpassed, or the remaining IFs fall (low dPC_{intra}) below a threshold [16]. Unfortunately, many missing areas detected in 1956 are now impossible to recover because they are highly profitable arable land and reversion is only possible through means beyond our control. Only abandoned arable land provides opportunities for passive rewilding [57] or ecological restoration.

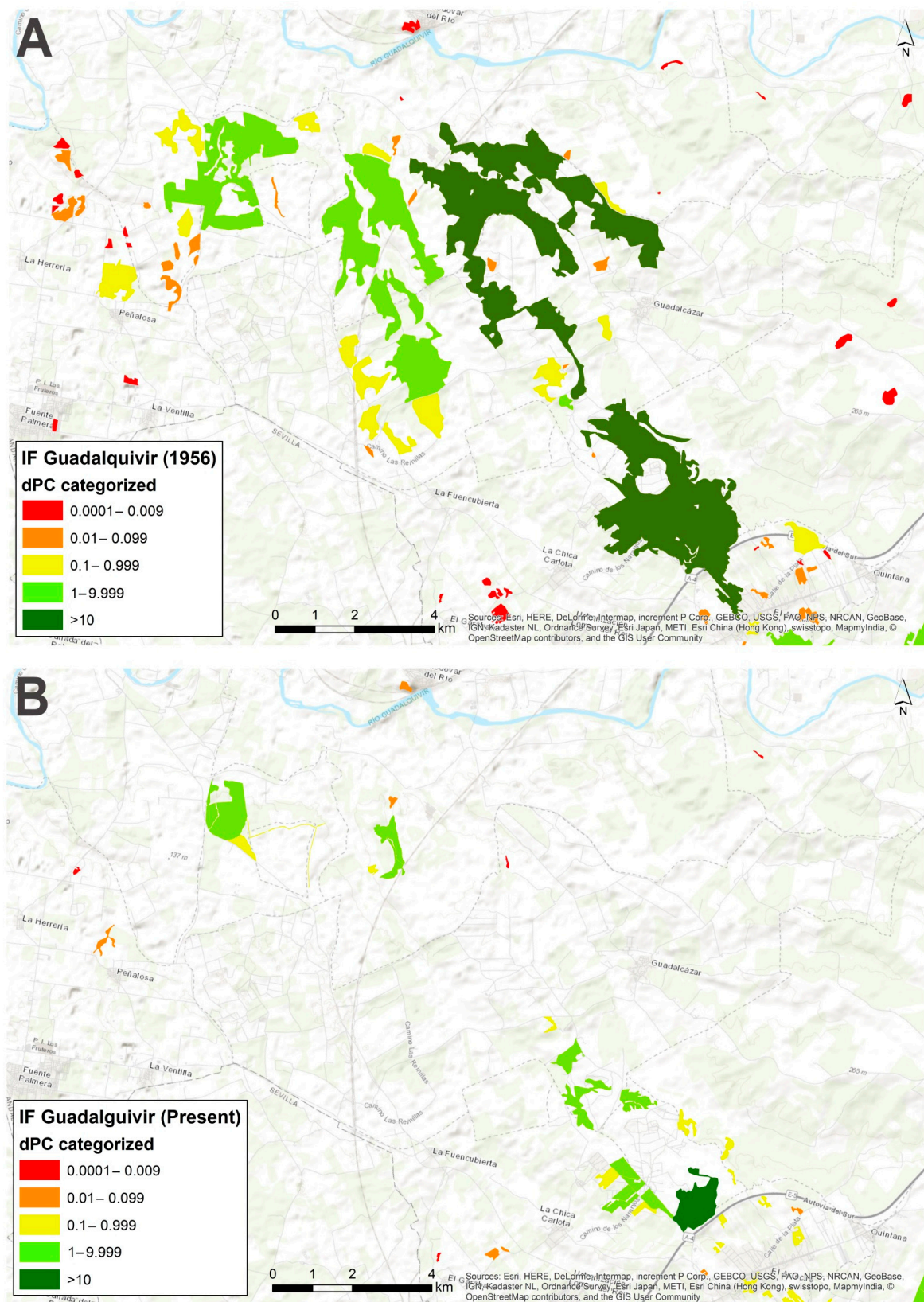


Figure 7. A comparative analysis of fragmentation status in an area located to the southwest of the city of Córdoba (Spain). (A): IFs in 1956 with high values of dPC. (B): Present situation of IFs. Only a few patches remain, and fragmentation has increased.

Further comparison between historical (Figure 8A) and present day (Figure 8B) in an area of the Guadalquivir valley shows that the situation has improved. A set of isolated patches with low values of dPC are now better connected. New IFs have arisen due to the introduction of *Quercus* trees (holm oak) for livestock purposes or on abandoned farmland. Although the area needs proper management to promote the connectivity, the improvement in dPC values of the present IFs guarantees the success of the promotion of ecological corridors. These areas provide opportunities for passive rewilding of areas where habitat removal has ceased, as demonstrated for *Quercus robur* L. in England [57].

Two representative areas of the Guadalquivir valley today are compared in Figure 9. The first (Figure 9A) to the east of the village of Arahál (province of Seville, Spain) shows a well-defined core habitat with a scant edge effect and with a significant role in the connectivity (high dPC value). These well-preserved areas are important sources of seed (acorns in our study) and other plants or animals to be dispersed to adjacent IFs. In this case, an interesting synergic consequence could result: the greater the dispersion of the vector species (wood mouse in our case), the greater the dispersion of acorns and ultimately of the forests [58,64]. The second image (Figure 9B) is an area close to Villadonpardo (province of Jaen, Spain) with dispersed IFs playing a minimal role in the total connectivity (low dPC value). The presence of dispersed IFs with low dPC values indicates that the possibility of connection is limited, and the area requires a specific management to promote the dispersion of the species.

Similar results are shown in Figure 10 for the Apulia region. The first image (Figure 10A), corresponding to the area of Volturino (Foggia, Italy), shows a well-defined core habitat patch (dPC > 1) where the maintenance of the biodiversity is guaranteed. Surrounding this core are many other polygons of interest in the creation of ecological corridors in the form of stepping stones (dPC < 1) to promote connectivity. By contrast, the second image (Figure 10B), located in Ceglie Messapica (Brindisi, Italy), shows a highly fragmented area where the role of IFs plays a less significant role in terms of connectivity. The presence of numerous IFs with medium–medium-low dPC values makes this area of interest for ecological restoration as they play an important part in acting as stepping stones [66,70] to connect other core habitats or the surrounding protected sites.

In summary, the new methodology applied has proven to be a powerful tool for analyzing the status of fragmentation in a given area. The abundant available digital cartography in combination with specific software (GIS and Conefor) work well in tandem to tackle the tangled problem of habitat fragmentation [71]. Although the digital cartography used in this study entails a lot of effort to obtain high-quality data, the methodology is feasible and easily improved by using the most recent techniques in GIS and automatic teledetection.

One of the main problems when managing the landscape is the scarcity of objective criteria for the selection of suitable areas to create corridors or to invest in ecological restoration. These activities are easily carried out in natural or semi-natural protected sites, where the management falls on the corresponding administration. In the case of highly anthropogenically modified landscapes, as described in this study, the survival of IFs is not guaranteed, and the promotion of connectivity is more limited. This is the reason why a classification system of the remnant habitat patches (Island Forests in this study) is absolutely essential before the establishment of ecological corridors or activities of ecological restoration [69]. The new methodology proposed in this study is based on quantitative and objective criteria to obtain this classification system before landscape management.

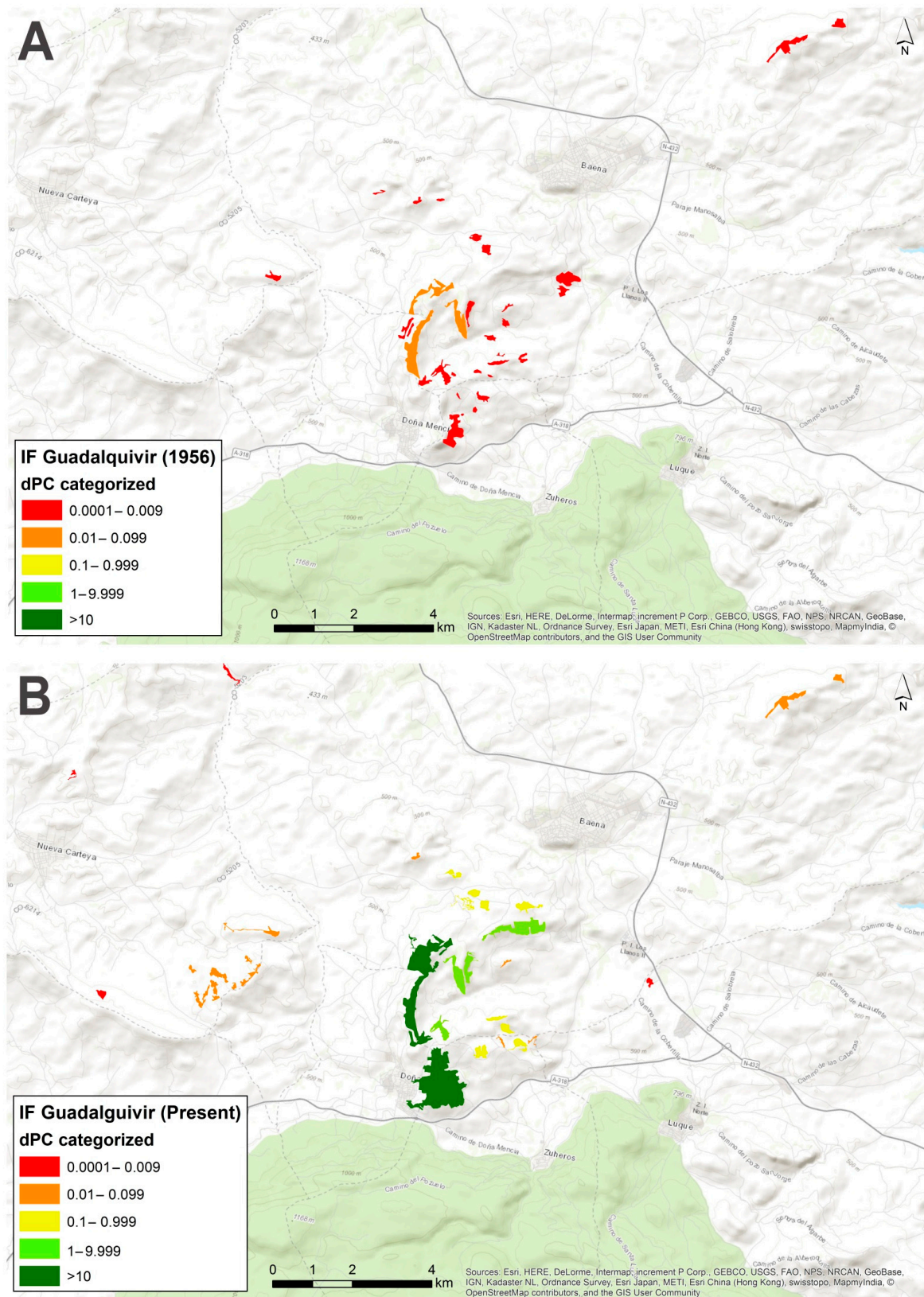


Figure 8. A comparative analysis of the fragmentation status in an area located to the southwest of the village of Baena (Córdoba, Spain). In this case, the situation in the present day (B) has improved with respect to 1956 (A).

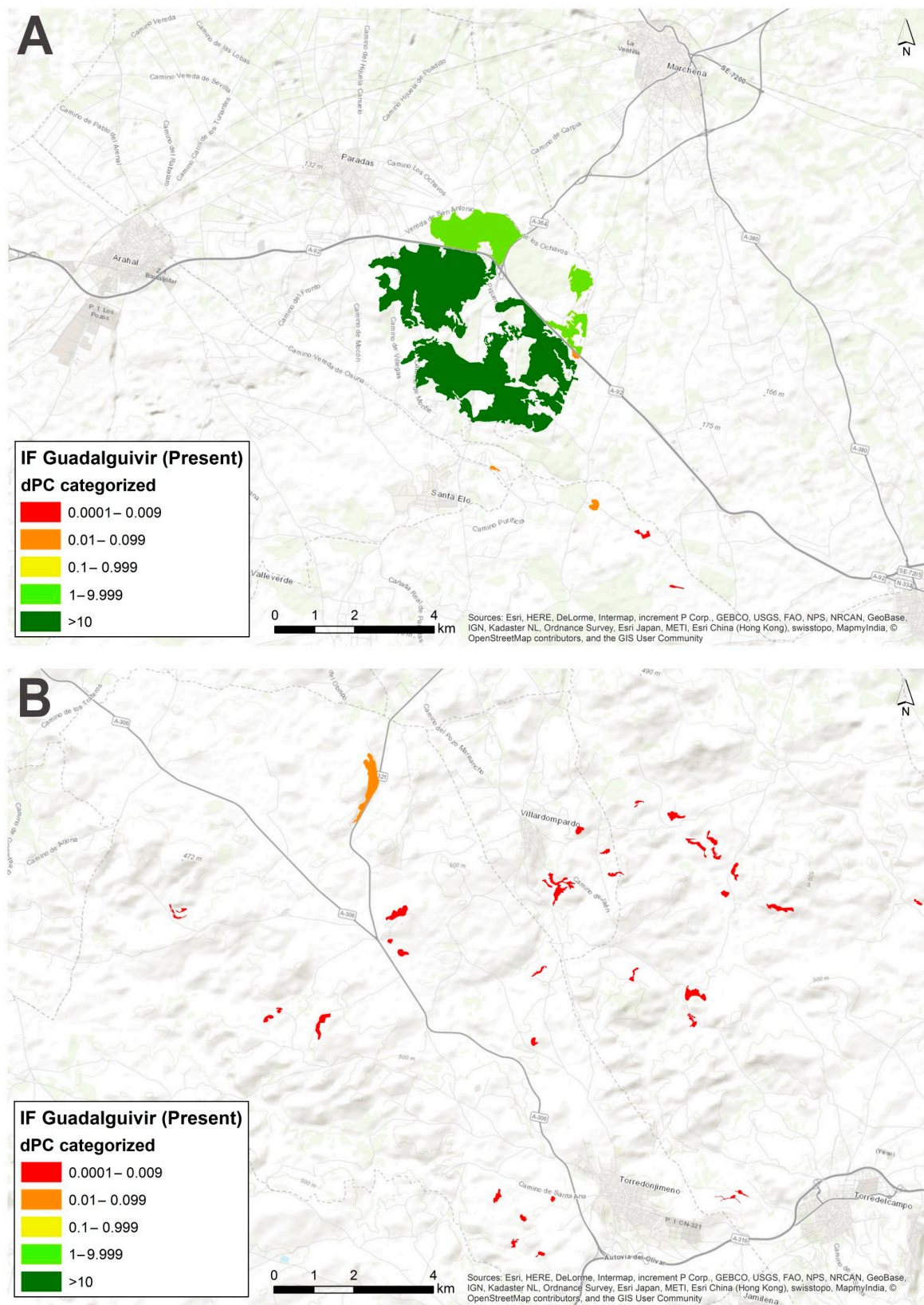


Figure 9. Two examples in the Guadalquivir valley. The IFs are standardized according to dPC values as described in Table 1. (A) shows a well-defined core habitat with high dPC value to the east of the village of Arahal (Seville, Spain). In (B) is a highly fragmented area in the surroundings of Villadonpardo (Jaen, Spain) with low–medium-low values of dPC.

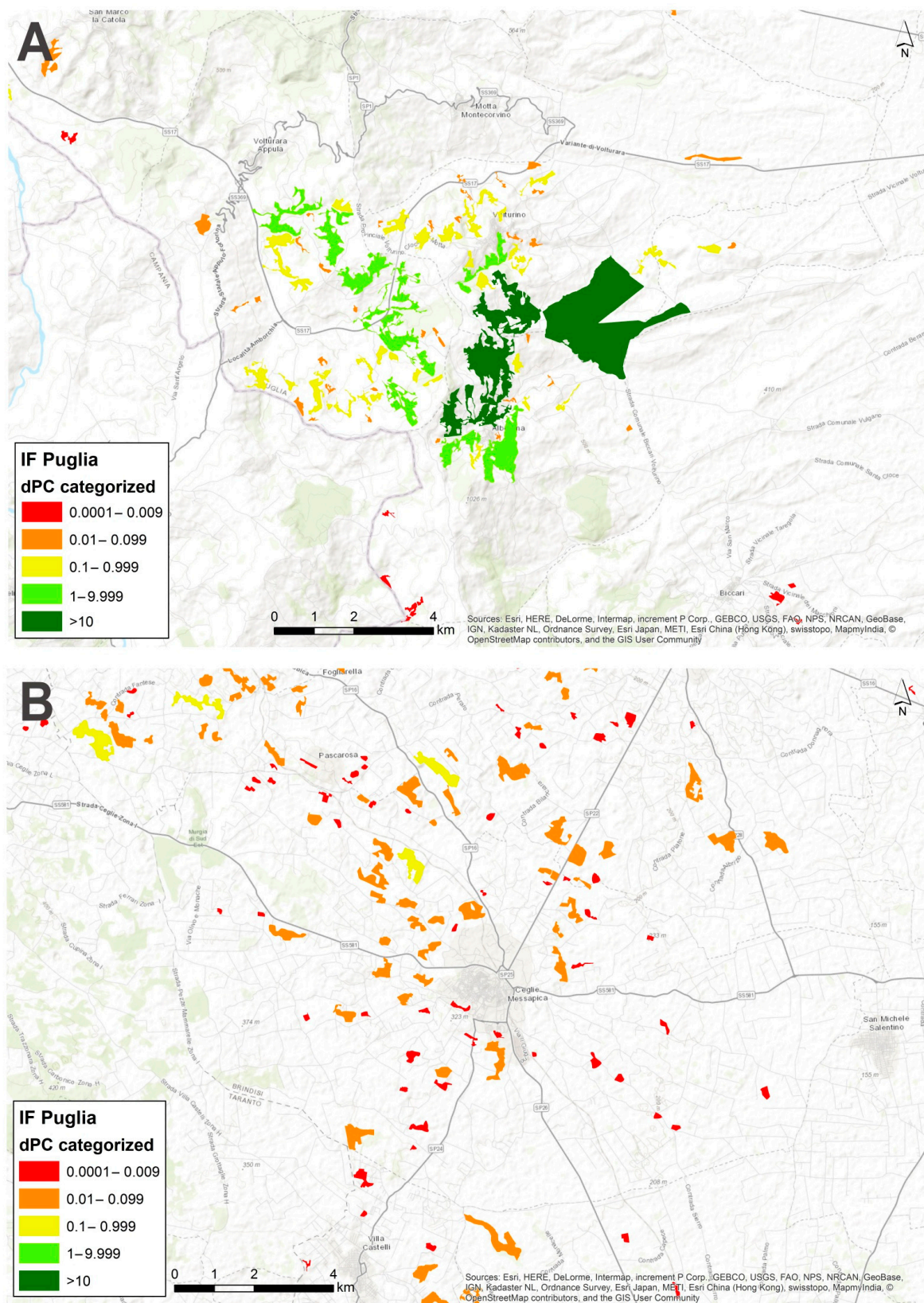


Figure 10. Two examples in the Apulia region. The first one (A) shows a well-defined core habitat in the area of Volturino (Foggia, Italy). The second (B) is an area in the surroundings of Ceglie Messapica (Brindisi, Italy) with many unconnected fragmentary IFs.

Although habitat fragmentation, along with its consequences, is a well-known phenomenon [8], there is a lack of information on highly fragmented habitats where IFs are scarce. However, the role of these disperse elements in the landscape has been gaining importance in recent times due to their function as a base for ecological corridors in modern conservation biology. This is one of the main objectives of the Natura 2000 network [26], the creation of a coherent protection network in the European Union. In this context, the highly anthropized areas are often the only possibility for connecting different elements of this network (Special Areas of Conservation) that are usually dispersed and unconnected within the territory of the member states.

Our results in the Guadalquivir valley demonstrate that this area has been more strongly anthropized in recent decades, with land use change being the main reason for the loss of IFs [72]. These results demonstrate the considerable increase in the fragmentation of the remnant IFs in the valley, an increase in the edge effect, and a limited connectivity between the remaining patches. This change in land use toward arable land has been common in Western Europe since the mechanization of agriculture, and also frequent in many other areas of the world. However, land use change and fragmentation have not been generalized throughout this territory as many areas unsuitable for agriculture have shown a clear recovery in recent times [9,10]. The reason is well known: those areas with clear agricultural or livestock potential have been subjected to intense pressure, whereas areas with less potential to support fertile crops have been abandoned and ecological succession has enhanced these areas in terms of biodiversity. These areas join the remnants of original habitat (IFs), and along with fences, hedges, and other boundaries entail new opportunities for species dispersion. The permeability of the matrix could be easily improved with a proper management of these dispersed elements as they are the only possibility for promoting the connectivity of the landscape structure [73]. Further studies for the implementation of habitat or landscape corridors are needed after the assessment of stepping stones and core habitats identified in this study.

The applied methodology in our study has been applied to many other species where the dispersion capacity of the species is well known, especially in animals [74]. In the case of habitats/ecosystem, it is necessary to establish several dispersion distances to reflect the different distances of various taxa. In these cases, the analysis is carried out with several estimated dispersion distances [67]. It is also possible to test several distances in order to select the most suitable distance for the whole habitat [75]. However, the implementation of an analysis with a different set of distances makes the results difficult to apply and possibly unsuitable for managers. In our case, a single genus (*Quercus*) with the same dispersion strategy (zoochory) and similar life form (mesophanerophytes, [76]) is proposed as the main species for the analysis. Fortunately, the main climatic trees of the Mediterranean basin are oaks. Some of them are evergreen, other marcescent, but they occupy the same ecological niche in each territory/ecosystem. As they are the main element of the Mediterranean forest vegetation, our study could be representative of the whole habitat using a single dispersion distance. An alternative method is to reduce this distance to encompass the species with moderate dispersion abilities. This conservative point of view has also been successfully applied for *Quercus* [48] in an attempt to assess how the *montado* availability/reachability varies for species with different moving abilities, considering a final distance of $\alpha = 200$ m instead $\alpha = 500$ as in our study. In other cases, the maximum dispersion threshold is calculated using a distance based on the average for multiple species susceptible to fragmentation [16]. In any case, we can conclude that our methodology is easily applicable to other regions/areas with forest species different than oaks (*Quercus*). In these cases, dispersion distances should be adapted to other forest species. With respect to shrublands, it is also possible to develop a fragmentation status analysis as demonstrated for environmentally certified forests exploitation [75].

The results of the comparison between the Guadalquivir valley and the Apulia region demonstrate that the proposed methodology is suitable for international studies. This fact is essential for the management of protected border sites that need common strategies for

the interconnection of habitats and species. Connectivity programs usually fail when some elements of the landscape transcend the borders between countries, as strategies are developed independently under the domain of the respective administration in each separate territory. A common methodology, using the same compatible cartography, is more coherent and applicable, and hence more likely to mitigate the effect of habitat fragmentation.

4. Conclusions

Habitat loss and fragmentation is still one of the main threats to biodiversity, and species displacement capacities should be enhanced to meet the challenges of the projected Global Change. This is particularly evident in developing countries, where the use of heavy machinery has intensively transformed many natural areas into fertile arable land during the 20th century. As demonstrated in this study, the result is a highly fragmented landscape with residual dispersed elements in the territory, with a limited capacity to implement ecological corridors. This transformation is especially dramatic in extremely vulnerable areas such as the Mediterranean basin where the adaptation (migration) of species could be more difficult. Strategies directed toward the promotion of species migration are needed, and common methodologies should be developed to mitigate the impacts of global change on biodiversity. Our study highlights the value of Island Forests to develop assessment strategies using homogenized available digital cartography and common criteria for the dispersion distances in graph theory analysis. The application of this new methodology could help in the management of protected sites, such as the Natura 2000 Network, using highly fragmented areas to allow species movement through inhospitable landscapes in a unique opportunity to connect the different protected elements of the Network.

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