Landscape planning and defragmentation measures: an assessment of costs and critical issues

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Abstract

Defragmentation, i.e. the systematic action of reconnecting even smaller and more isolated landscape patches, is a major concern for landscape analysists and planners. Landscape fragmentation (LF) can jeopardize both ecosystem continuity and quality. Transport and mobility infrastructures (TMIs) are considered one of the main causes of LF and trigger negative effects, such as death of wild animals killed by vehicular traffic, and decrease of landscape connectivity. The effectiveness of defragmentation actions can be monitored through indices, such as the Infrastructural Fragmentation Index (IFI) and, as a counterpart, the connectivity index (CI). In this paper, we aim at illustrating the effect of defragmentation actions based on the use of wildlife crossing structures (WCSs). WCSs are targeted for the wild boar and ideally located at different linear densities in the fragmented and car accidents very rich landscape unit of Alghero, Sardinia, Italy. Results demonstrate that the higher the WCSs' density the higher the defragmentation effect and that the average cost of defragmentation increases for scenarios with denser WCSs.

Keywords: defragmentation, wild boar, wildlife crossing structures, infrastructural fragmentation index, continuity index.

1. Introduction

In 2000, the Council of Europe adopted the European Landscape Convention (ELC), acknowledging all landscapes as key element for people's quality of life (ELC, 2000). The ELC was also a response to an accelerated transformation of landscapes due to several causes including agriculture, industrial production techniques, town planning, and transport and mobility infrastructures (TMIs). The ELC stresses the importance of landscape protection, management and planning (ELC, 2000). Although the ELC does not directly deal with "ecological coherence and connectivity, it provides an integrated framework that supports actions for such issues through landscape planning and management" (Kettunen et al., 2007). Landscape changes over time and its transformation is closely related to landscape fragmentation (LF), which in turn has some effects on connectivity (LC) (Clevenger and Wierzchowski, 2006). In parallel, the European Commission has developed the Natura 2000 network that stems from the directive about conservation of natural habitats and of wild fauna and flora, better known as Habitats Directive (EC Council, 1992). It is a network of natural sites to ensure the survival of Europe's most valuable and threatened species and habitats and where people and wildlife can live together. Articles 3 and 10 of the Habitats Directive mention necessity of preserving 'ecological coherence', which is related to the connectivity between Natura 2000 sites (Opermanis et al., 2012).

LF can be defined as a dynamic process, where larger landscape fragments (patches) tend to become smaller and more insulated than in their original condition (EEA, 2011). Linear TMIs bring to LF (for a broad discussion about road networks and landscape fragmentation, see Forman et al., 2002), reduce LC, and negatively affect normal animal movements (Bissonette and Adair, 2008), triggering isolation of species and death of animals due to wildlife-vehicle collisions (WVCs) (Spellerberg, 1998). LF is appraisable through indices such as the Infrastructural Fragmentation Index (IFI) (Fabietti et al., 2011; Romano and Paolinelli, 2007; Biondi et al., 2003; Romano and Tamburini, 2001; Romano, 2000). Furthermore, the measurement of IFI considers discontinuities such as bridges and tunnels that could not be designed according to fauna crossing structures (wildlife crossing structures, WCSs) principia. Thus, for some target species such discontinuities could be ineffective.

WCSs can mitigate LF and facilitate wild fauna in crossing roads and railway tracts (Mata et al., 2008). WCSs aim to increase permeability, habitat connectivity, and ecosystems continuity and reducing WVCs (Clevenger and Huijser, 2011), but they can be expensive (White and Moody, 2015) and require an accurate location and sizing. Thus, WCSs could meet three objectives at the same time: reducing LF, increasing LC, and reducing (or avoiding) WVCs.

We are interested in achieving two objectives in response to two research questions (RQ_s, see Table 1). Firstly, we aim to study the effect of WCSs on LF and LC. Secondly, we focus on the cost of defragmentation, i.e. the resource budgeted to reduce LF (or increase LC) by one percent unit. We tailored our study on a specific target species, the wild boar (*Sus scrofa*), one of the main wild species involved in vehicle collision in north-western Sardinia, Italy (Apollonio et al., 2012; RAS, 2016).

Please, place Table 1 about here.

To achieve our objectives, the methodology is applied to the landscape unit (LU) of Alghero (Sardinia, Italy), which has no WCSs and the highest number of car accidents due to wild boars occurred in Sardinia. We discuss the results in the perspective of supporting decision-makers responsible for landscape protection and planning, and interested in wild and human life safeguard and protection policies.

The paper unfolds as follows. In the second section, we report on the state of the art summary about LF, LC, WVCs, and WCSs. In the third section, we introduce the case study by describing the geographical context. In the fourth section, we describe the method proposed in this study. In section five and six, we report on and discuss the results. Finally, in section seven we stress the concluding remarks.

2. State of the art summary

LF has negative effects on biodiversity conservation (Battisti, 2004; Henle et al., 2004; Wilcove et al., 1986). The main effects include decline of population caused by loss of functional connectivity (Harrisson et al., 2012) and of species richness (Collinge, 1996). LF can reduce resilience of habitat and variety of ecosystems, triggering population decline (Kettunen et al., 2007). The main causes of LF include urbanization, deforestation, agricultural land conversion, and TMIs (De Montis et al., 2017; Igondova et al., 2016; EEA, 2011; Battisti and Romano, 2007; Jongman, 2004; Serrano et al., 2002; Saunders et al., 1991). Some policies -including the Convention on Biological Diversity and the Ramsar Convention- have been proposed to maintain ecological coherence and connectivity (Kettunen et al., 2007). Then, the importance of LF and its ecological effects has been acknowledged internationally. Scientific literature on LF is rich and scholars have proposed several measures (or indices). Jaeger (2000) characterizes LF according to a geometric approach, by introducing three quantitative measures: effective mesh size, degree of landscape division, and splitting index. Such measures “are based on the ability of two animals – placed in different areas somewhere in a region – to find each other within the landscape” (Jaeger, 2000) and can be effectively used for all fragmentation phases (perforation, incision, dissection, dissipation, shrinkage, and attrition; for a description of fragmentation phases, see Forman, 1995). Butler et al. (2004) focus on forest fragmentation due to human decisions about land-use and develop a fragmentation index by combining three fragmentation metrics, namely interspersion, percentage non-forest cover, and percentage edge. Such metrics were chosen in order to study fragmentation at regional scale in the Pacific Northwest (western Washington and western Oregon). Li et al. (2009) assess the rates of forest change and fragmentation in Alabama, USA. Forest fragmentation was measured through a forest fragmentation model and four metrics: edge density, mean polygon area, core area index, and largest polygon index (Li et al., 2009). The set of spatial metrics was applied in both federal and non-federal forest by “using the Image Analyzer [...] program” (Li et al., 2009).

TMIs negatively affect ecological systems bringing to loss of habitat and biota (Smith, 2004; Jaarsma and Willems, 2002; Spellerberg, 1998). Negative effects include increased mortality of plants, WVC, and LF. LF is measurable by using several indices proposed in literature, but “few of these are useful for the transportation infrastructures design, as they often operate without considering the effect of each infrastructure or their different typology” (Bruschi et al., 2015). The IFI has often been used to measure LF (De Montis et al., 2017; Bruschi et al., 2015; Fabietti et al., 2011; Mennella et al., 2008; Melis and Puddu, 2008; Battisti and Romano, 2007; Zanon et al., 2007; La Rovere et al., 2006; Romano and Tamburini, 2001) and can be calculated according to different approaches (De Montis et al., 2017). Studies on the IFI have been applied recently. De Montis et al. (2017) study LF caused by TMIs in Sardinia (Italy) and Andalusia (Spain). The authors apply the IFI in six landscape units, obtaining comparable results. Results show that LF tends to be more remarkable in coastal areas than in inland areas. Bruschi et al. (2015) discuss on habitat fragmentation due to TMIs, by measuring the IFI of 24 Italian national parks. They demonstrate that LF is higher in central and southern Italy. Neri et al. (2010) discuss about a methodology for the proper location of environmentally sustainable transport infrastructures in central Italy. They introduce the Ifim, which is referred to a cell of one square kilometre, and is independent from the surface area of the LU. La Rovere et al. (2006) discuss about the integration of eco-biogeographic parameters in spatial planning tools. They focus on TMIs density (length of TMIs per unit of surface area), IFI, urban density (urbanized surface areas per unit of total surface area), and weighted urban density. The study focuses on the abundance of avifauna species in the province of Rome, Italy and reports that avifauna is more susceptible to urbanization than to linear TMIs.

LC is the extent to which landscape structure facilitates or impedes movement through a landscape (Taylor et al., 1993). TMIs have a major impact in landscape composition and configuration and on the flows of matter and energy occurring in the ecosystems (Trocmé et al., 2003). The capability of an ecosystem to preserve its integrity and biodiversity increases with its size, its isolation from human disturbances, and its connectivity with other natural areas, which is influenced by the presence of linear infrastructures (Geneletti, 2004). Increasing the organism’s ability to move through landscape is a key goal for conservation biology, and this has led to a proliferation of connectivity measures (Kindlmann and Burel, 2008). It is frequent to find in the literature indicators that measure the permissiveness of the territory to the organism movements assigning resistance values to the landscape matrix (egs. Marulli and Mallarach, 2005; Gurrutxaga et al., 2011). The indicator CI has been used to measure the effects of TMIs in LC in several studies (Mancebo Quintana et al., 2010, Ortega et al., 2016; De Montis et al., 2017). Its calculation is based in GIS and it is a function of the effective distance. As this kind of connectivity indicators, it computes the minimum distance between two points, separated by a resistance matrix. The resistance matrix models the territory according to a theoretical difficulty encountered by organisms in moving around. It assigns a penalization if there are patches in the landscape that can be considered as obstacles (such as infrastructure, artificial or natural areas that correspond to a different type or category). Then, the spatial configuration of land uses and infrastructure barriers are reflected in the values of CI.

As for WVC, the scientific literature is rich. In particular, some authors focus on wild boar as target species. Sáenz-de-Santa-María and Tellería (2015) study 74,600 WVCs occurred in Spain form 2006 to 2012 and find that the wild boar is the most important cause for human injuries, while wild boar and roe deer are responsible for relevant economic losses. According to a study by Kruuse et al. (2016) on the temporal distribution of 918 WVCs involving wild boars and occurred in Estonia from 2004 to 2013, "the highest risk for collision is in October, November, and December", on Friday, and, in general, after sunset. Similar results have been obtained by Putzu et al. (2014), who studied 1,110 car accidents reports occurred in the province of Cuneo, northern Italy. The authors suggest that such a temporal distribution depend on "complex interaction of phenological, behavioral and human-related reasons" (Putzu et al., 2014). Cserkész et al. (2013) focus on the occurrence of WVCs along fenced roads in Hungary, as the 5% of car accidents still involves wild fauna. They consider six target species, including otter, badger, and wild boar, and argue that population density is a critical issue because "more WVCs occurred in areas where the population density of these species was high" (Cserkész et al., 2013). As regards the wild boar, they point out that the wild boar fatalities were not very often recorded at highways interchanges, but they were frequently reported "near railways that are parallel to highways". In general, they argue that a reduction of WVCs would be possible by preventing wild fauna from crossing transport and mobility infrastructures.

Conservation of biodiversity is positively affected by proper WCSs (van Der Grift and van Der Ree, 2015). WCSs contribute in reducing WVC and their effectiveness increases if combined with fences (Smith et al., 2015). WCSs can be clustered into overpasses and underpasses (van Der Ree et al., 2007). Overpasses include land bridges, overpasses for small roads, canopy bridges, and glider pole, while underpasses include culverts, tunnels, and bridges (van Der Ree et al., 2007). A proper selection of WCS depends on "impacts to be mitigated, the target species, engineering and other location-related constraints and traffic safety considerations" (Smith et al., 2015). Wildlife underpasses "are the most common type of crossing structure" (Smith et al., 2015). High-quality habitat at the entry of the underpass, high values of openness index, and absence of humans are acknowledged as key factors in increasing the effectiveness of WCSs (van Der Ree et al., 2007). Mata et al. (2008) assess the effectiveness of different types of crossing structures along the (four-lane) A-52 highway, in Spain. The highway is entirely fenced along its length and crossed by 4,500 vehicles per day. The crossing structures include wildlife passages, wildlife-adapted box culverts, functional passages, and culverts. According to their results, Mata et al. (2008) argue that crossing structure type and width are critical factors in order to be used by wild fauna. In particular, wild boar uses preferably wildlife overpasses (the most used) and underpasses, and overpasses not specifically designed for wild fauna. Overpasses has been preferred by moose and deer in a study carried out by Iuell et al. (2003) quoted by Langbein et al. (2011, p. 243), but in other studies the "use of overpasses [...] by red, roe and fallow deer was lower than that of underpasses" (Olbrich, 1984, quoted by Langbein et al. 2011, p. 243). Thus, the use of overpasses and underpasses by wild fauna can be variable according to different scenarios and involved species. Discontinuities such as bridges and tunnels are usually built-up to overcome certain types of natural obstacles, or drain downstream waters (bridges). Wild fauna can use such discontinuities to cross TMIs, unless they are obstructed by metal fences or dense vegetation. Scientific literature and national guidelines (SMAFE, 2016; Guccione et al., 2008; Collinge, 1996) report on the minimum requirements of effective WCSs for specific target species. Iuell et al. (2003) quoted by Langbein et al. (2011, p. 242) suggest 40-50 m width (minimum 20 m width in optimal topographic conditions that facilitate the access of wild fauna onto the crossing structure) for overpasses used by red deer and wild boar. However, Langbein et al. (2011) argue that the availability of "some smaller passages which those animals determined to cross can use (such as e.g. seasonal movements of male ungulates into female areas during the rut [...]) may still suffice to bring significant reduction in the frequency of ungulate–vehicle collisions [...]". When improvements of road safety (reduction of WVC) is more important than reducing isolation of wild fauna population, other authors quoted by Langbein et al. (2011, p. 243) suggest for ungulates a minimum width of overpasses ranging from 6 to 12 m. According to Dinetti et al. (2008), the width of overpasses suitable exclusively for wildlife (including large mammal) can vary in the range 4-12 m. According to Spanish technical prescriptions issued by the Ministry of Agriculture, Food and the Environment (SMAFE, 2016), large mammal overpasses designed for wildlife should have 20 m minimum width and width-length ratio greater than 0.8. As regards wildlife underpass, Olbrich (1984) -quoted by Langbein et al. (2011, p. 241)- argues that one of the key factors in using such a type of WCS is the openness, namely the ratio between aperture size (depending on height and breadth) and length. The technical report issued by the Italian National Institute for Environmental Protection and Research (Dinetti et al., 2008) recommends the respect of three conditions for effective underpasses (Figure 1):

$$W = \frac{B \cdot H}{A} > 1.5 \qquad (1)$$

$$\frac{H}{A} > 0.1 \qquad (2)$$

$$\frac{B}{A} > 0.1 \qquad (3)$$

where *B* stands for the width, *A* for the length, and *H* for the height of the WCS. *W* is an openness index, which is able to measure the WCS visibility from one side to the other. The higher *W*, the easier is wild fauna crossing. *B* should be larger than 25 m (Dinetti et al., 2008) -or 15 m (SMAFE, 2016)- for large size species.

Please, place Figure 1 about here.

An underpass could be ineffective under some circumstances that determine disturbance of the wildlife: a vehicular traffic larger than 150 vehicles per day or a human usage more frequent than one per day. Underpasses must be located every 1.5 km and a lateral fencing should drive wildlife to the WCS and prevent wild boars from crossing the roadway. The fence should be minimum 1.5 m high and be buried at least for 0.2 m underground, to prevent digging activity by the wild boar (Dinetti et al., 2008).

3. Case study

The target species chosen for this study, the wild boar, is very widespread in Sardinia. As we aim at studying the effectiveness of defragmentation strategies, we are interested in actions reconnecting natural or semi-natural patches and facilitating the movements of the wild boar across TMIs. Although regional administration spends relevant funding to restore damages caused by wild boars in many WVCs, in Sardinia so far there are no WCSs, i.e. discontinuities built-up taking into account defragmentation and perception of wild fauna.

We selected an area suitable for the application of our method by checking the frequency and relevance of WVCs due to wild boars. WVCs frequency depends on the density of wild boars and the intensity of LF. Even though the highest densities are recorded in interior areas of the islands (such as the Gennargentu, with up to 0.15 animals per hectare), the coastal area of Alghero shows the highest percentage (42%) of car accidents due to wild boars occurred in Sardinia (Brugnone and Pittalis, 2008).

Please, place Figure 2 about here.

Because of this emergence, we selected Alghero and set the landscape unit (LU) of that city as the reference territorial unit. Sardinia is divided in 27 coastal LUs by its Regional Landscape Plan (RLP) (RAS, 2006). LUs are designed as geographical areas with similar environmental, cultural, and built-up dimensions, thus they show a certain degree of internal consistency. The LU of Alghero is located as shown in Figure 2, while in Table 2 some relevant features are reported.

Please, place Table 2 about here.

The LU includes five municipalities and Alghero is the main urban centre with about 40,000 residents (ISTAT, 2011). The economy specializes in tourism, agriculture (viticulture and olive oil), and services (University of Sassari and the Scientific and Technological Park of Sardinia).

Please, place Figure 3 about here.

According to the regional land-use map of Sardinia (RAS, 2008), the surface areas occupied by arable and horticultural crops prevails with respect to the other land-use classes (Figure 3), with about 13,000 hectares (ha). Mediterranean maquis and garrigue cover about 21% of the LU (4,368 and 3,938 ha, respectively). The pie chart in Figure 3 shows the percentage share of each land-use class extending more than 1,000 ha. In the study area, the garrigue is usually close or adjacent to the Mediterranean maquis, but it is not directly crossed by TMIs. Remarkable landscape elements consist of the coastal limestone promontories of Capo Caccia, the wide bay of Porto Conte, and the sites of community importance of Punta del Giglio, Lago di Baratz, and Porto Ferro. The LU is fragmented by relevant TMIs, such as highway, roads, and airport. TMIs include national and provincial (two-lane) roads, and local roads, and are particularly thickened in proximity of urban areas (Figure 3). LU Alghero shows a road density equal to 1.15 km of road per km^2 of land area. Road density has been calculated considering extra-urban roads, and excluding rural roads.

4. Methods

In the first part of the study, we measure the effects of WCSs on landscape fragmentation (LF) and connectivity (LC) (RQ_1) and, in the second part, we quantify the average cost of defragmentation measures (RQ_2). We assess the variation of LF and LC according to seven scenarios. As the effectiveness of the reconnection (de-fragmentation) varies with the density of WCSs, we propose, beyond the zero option (building no WCSs), six hypothetic scenarios, where WCSs are ideally located across the roads at regular intervals ranging from 1,000 to 3,500 m (Figure 4).

In the second part of the study, we specify the average cost of defragmentation by assessing what is the cost of a unitary increase/decrease of respectively LC and LF (RQ_2). We repeat the calculations for each scenario considered.

Please, place Figure 4 about here.

4.1 Landscape fragmentation and landscape connectivity measurement

We measure LF by calculating the IFI according to equation (4), which has been validated and proved useful in previous studies (De Montis et al., 2017; Bruschi et al., 2015; Romano and Paolinelli, 2007; Biondi et al., 2003; Romano and Tamburini, 2001; Romano, 2000):

$$IFI = \frac{\left(\sum_{i=1}^{i=n} L_i \cdot O_i\right) \cdot N \cdot P}{A} \tag{4}$$

where L_i stands for the length in meters of the road or railway trait with the exclusion of discontinuities (viaducts, bridges, tunnels), O_i for a dimensionless occlusion coefficient, A for the extension in squared meters of the landscape unit (LU) area, P for the perimeter in meters of the LU, and N for the number of patches. O_i varies according to the difficulty that the fauna has in crossing the transportation infrastructure (Bruschi et al. 2015): it is equal to 0.30 for municipal and local roads, to 0.50 for national and provincial roads, and to 1.00 for national four (or more) lane roads and railway. As discontinuities we have chosen 25 m width underpasses. Such a width is the minimum suggested for underpasses (Dinetti et al., 2008) and is greater than (or close to) the minimum width of effective overpasses discussed in Langbein et al. (2011). We monitor the variation of IFI values in six hypothetical scenarios with respect to an original current scenario, where no WCSs are present. We suppose to localise WCSs across extra-urban (two-lane) roads, according to fixed distance intervals ranging from 1,000 to 3,500 m. The choice of assessing the IFI according to predetermined and regular distances helps us to understand to what extent the IFI is sensitive to the number of discontinuities.

LC is measured by the connectivity indicator CI_{i} (Mancebo Quintana et al., 2010). The CI_i obeys to the following equation:

$$CI_i^* = \frac{\sum_{j=1}^{n} \frac{A_j}{de_{i,j}}}{2\pi de_{\max}} \tag{5}$$

where CI_{i}^* is the value of the connectivity index for starting pixel i in a scenario *; $de_{i,j}$ is the effective distance between starting point i and destination j; A_j is the area of the destination j that belongs to the same class of natural area as starting point i; and $2\pi de_{max}$ is the maximum possible value of the numerator. Then, for each pixel i in the study zone, it measures the area corresponding to each same type of natural habitat as that of the cell i, divided by the effective distance calculated, in an area of influence. The value obtained is divided by the maximum value that could be achieved, so the range of values for CI_i is between 0 (minimum connectivity) and 1 (maximum connectivity). For the creation of the resistance matrix the greatest friction coefficient is assigned to high-speed railways and motorways depending on the distance between planned fauna-passes. Then, the values for the infrastructures typology are assigned as a percentage of this maximum value. The effective distance is calculated using Dijkstra's algorithm (1959), according to the values assigned in the creation of the resistance matrix, between the pixel and the analogous habitat. The GIS steps used to perform the indicator were programmed in Arc Macro Language for ArcInfo workstation. All the GIS databases must be compiled in raster format with a cell size adequate for the scale of the work. The main steps are summarized as follows: (i) from a GIS land-use layer that distinguishes the different types of natural and artificial zones, the origins and destinations are established: they are the natural areas in the study zone and classified into categories with common characteristics; (ii) maps or resistance matrixes are created for each type of natural land use and considering a GIS network of linear infrastructures in the study zone that distinguishes between the different typologies, according to the process described in the next subsection; (iii) ArcInfo cost-distance function computes the effective distance for each pixel *i* and the Equation 5 is calculated; (iv) as a number of scenarios are considered, this process is repeated in each of them.

Seven scenarios were designed modifying the distance between WCSs in the resistance matrix. In the original scenario 0, it is considered that the distance between WCSs is the maximum length of railways or motorways in the study area. This implies that these types of infrastructures are completely impermeable to fauna. Once this maximum value is stablished, the resistance values for the rest of elements in the landscape matrix are assigned following Mancebo Quintana et al. (2010). The other six scenarios differ from the original one only in the distance between WCSs. The six scenarios were constructed assigning in the landscape matrix a WCSs inter-distance ranging from 1,000 m to 3,500 m.

Finally, LF and LC changes are measured in percentage, as the variation of IFI value and CI average in the LU for each scenario k, with regard to the original scenario:

$$\Delta LF_{0-k}(\%) = \frac{IFI^{0}-IFI^{k}}{IFI^{0}}\ x\ 100 \tag{6}$$

$$\Delta LC_{0-k}(\%) = \frac{AvgCI_{i}^{0}-AvgCI_{i}^{k}}{AvgCI_{i}^{0}}\ x\ 100 \tag{7}$$

Inspired by De Montis et al. (2017), we consider landscape fragmentation and connectivity as dual phenomena, as they usually show inverse trends. In fact, intuition suggests that landscape fragmentation increases while its connectivity decreases. So, the adoption of indexes that assess both the issues may at a first glance result in redundant analyses. When it comes to the actual application of the specific measures adopted though, De Montis at al. (2017) demonstrate that IFI and, respectively, CI exhibit not trivial relations, scale independently from each other, and add different perspectives to the description of the same phenomenon. In addition, they give complementary information about landscape, since IFI assesses fragmentation in landscape units while CI complements this metric at the pixel level.

4.2 Measuring the cost of defragmentation

We calculate the cost of defragmentation taking into account the overall resources needed to build and install WCSs. In particular, we are interested to quantify how much is a unitary percent increase/decrease of, respectively, CI/IFI worth on average. Thus an appropriate measure is the average cost (AVC), which corresponds –for each transition from the original scenario to each of the six scenarios with different linear densities of WCSs- to the ratio between the cost of the WCSs and the corresponding percentage change of CI/IFI. We measure the AVC according to equation (8)

$$AVC = \frac{C_*}{\Delta_*} \tag{8}$$

where C stands for the cost of WCSs in a given scenario * and Δ for percentage increase of defragmentation, with respect to the original scenario (OS) in terms of both decrease of IFI and increase of CI.

5. Results

As for the analysis of the ideal six scenarios, in Table 3 we report on the results concerning IFI, CI, total number of WCSs, and their construction cost.

Please, place Table 3 about here.

We estimate the cost of wildlife underpasses for the Italian market starting from a reference value (110,000- 270,000 euro) calculated for France in 1999 by Dinetti et al. (2008). Applying a conversion tool available at the Italian National Institute for Statistics (ISTAT, 2017) and using an Index of Consumer Prices for Workers and Employees equal to 1.37, we assume a cost ranging from 150,000 to 370,000 euros. In addition, we consider the differences between French and Italian markets and prudentially set the cost at 500,000 euros.

As we expected, a higher spatial frequency of WCSs leads to a proportionally lower fragmentation and higher connectivity. In both the cases, the values follow a similar tendency, with a little difference in the slope, which is lower for the IFI (see Table 3 and Figure 7).

For the LF, the IFI original value is equal to 19,810, while it ranges between 14,469 for scenario 6 (-26.96%) and 10,416 for scenario 1 (-47.42%). The change values do not follow a clear tendency. The percentage increment between scenarios is not constant and it lays on an irregular line: for instance, 0.9% between 3,500 and 3,000 meters of WCS distance; 2.7% between 2,500 and 2,000 meters; and 3.8% between 1,500 and 1,000 meters of WCS distance.

Table 3 shows the values of average and changes in CI, and Figures 6 and 7 convey spatial representations by main natural land uses. Figure 5 shows LC situation in the LU Alghero in the original scenario and in the other six scenarios. The situation between reference scenario and the rest of scenarios is quite different. The minimum value is almost the same but the maximum is increased by around a 50%. The overall degree of LC is increased, and two main areas can be identified, as they are divided by the railway layout: the east of the LU Alghero with a relative better starting point situation and the central-western area. In Figure 6, the relative percentage changes can be seen. The maximum changes goes from 98%, in the case of building a fauna pass each 3,500 meters, to 180%, if the fauna passes are located every 1,000 meters. In all the cases, the highest changes are concentrated in the proximity of main roads or railways. In this case, in general, the eastern part of the LU gets lower improvements than the rest. The configuration of landscape matrix with low infrastructures in the east causes that the effect of new fauna passes was reduced, contrary to the rest of the LU. The reason is that it is mainly an agricultural area with scattered natural land uses and a high number of transport infrastructures. Regarding average values (Table 3), the differences from the scenario 0 goes from 43% to 75%. The values show a tendency: the percentage increment between scenarios is higher if the distance of fauna passes is reduced, i.e. 4.4% between 3,500 and 3,000 meters of WCS distance; 6.0% between 2,500 and 2,000 meters; and 9.3% between 1,500 and 1,000 meters of WCS distance.

Please, place Figure 5 about here.

Please, place Figure 6 about here.

Table 3 and Figure 7 (A) allow the reader to evaluate -for transitions from the original to each scenarios- the relation between cost and number of WCSs, and IFI and CI values. Overall a similar tendency emerges: a higher number of WCSs implies lower LF (i.e. smaller IFI values) and higher LC (i.e. larger CI values). Some differences can be observed tough. While IFI values lay on an irregular line, CI values and cost tend to follow a curve showing a smoothly decreasing slope. The results imply that an increment of a unit in the cost of building WCSs provides a similar increment when the number of fauna passes is low; but when the number of WCSs is high, both the reduction of LF and increment of LC scale at a smaller pace. This implies that the impact of WCSs density on the average cost of defragmentation is lower when the number of structures is lower or, in specular terms, that a unit decrease/increase in IFI/CI is more expensive, if WCSs density is higher.

Please, place Figure 7 about here.

This is confirmed if we analyze the AVC of defragmentation, i.e. the cost of a unitary increase/decrease of landscape connectivity/fragmentation (Figure 7, B). The AVC per unit of CI change is always lower than the AVC per unit of IFI. While they are equal respectively to 0.74 and 1.19 MEuro for the transition to the scenario S6 (WCSs located at 3,500 m distance), they remarkably score 1.50 and 2.38 MEuro for the transition to scenario S1 (WCSs located at 1,000 m distance). Hence the AVC of defragmentation sensibly increases when the distance between WCSs is reduced.

6. Discussion

In this section, we discuss the results of this paper, with particular emphasis for the RQs illustrated in the introduction. As for RQ_1, concerning the possibility to measure the effect of WCSs on landscape fragmentation/connectivity, we receive a confirmation of what we expected intuitively: building a denser pattern of WCSs leads to more intense defragmentation. In terms of measures applied in this study, when the number of WCSs per meter increases, IFI decreases and CI increases. The indexes display a percentage variation according to slightly different regimes: the IFI shows a more irregular trend than the CI. In each transition from the original scenario to the six scenarios, the absolute percentage variation of CI is sensibly larger than the one of IFI. The eastern part of LU Alghero shows remarkable positive increase of LC from S1 to S6. Since the LU is mainly characterized by Mediterranean maquis, an increase of the number of WCSs facilitates habitat connection and animal movement. Low values of LC emerge in the western LU, and this depends on its high rate of urbanization (TMIs and urban centres). The city of Alghero and the airport can be considered as the urbanized core of this area, which is surrounded by agricultural productive activities. As for RQ2, concerning the cost of defragmentation actions, we started from an estimate of the cost of the single WCS (500,000 Euros) and obtained a total cost linearly ranging between 32 and 113 MEuros. The regimes of variation for CI and IFI are not linear though, as spatial properties are not uniform throughout the geography of the LU considered in this study. Thus we describe a pattern of AVC of defragmentation that increases remarkably when transitions to denser WCSs are selected. Given the evidently smaller range of variation of IFI with respect to CI, the AVC of a percentage unit of IFI is always larger than the one of CI.

7. Conclusion

In this paper we developed on a research alley beyond the mere assessment of the status quo –i.e. the measurement of the level of landscape fragmentation and connectivity. Instead we approached possible strategies able to counteract fragmentation through actions aimed at reconnecting landscape fragments. In this case, landscape defragmentation actions consist of proper design and location of WCSs (underpasses), which are able to reconnect isolated patches and allow wild fauna to move from habitat to habitat. We tailored our study on a specific target, the wild boar, one of the main species involved in vehicle collision in north-western Sardinia, Italy. Then, we focused on that geographical area and developed our study in the LU Alghero, which is characterized by the highest number of WVCs involving wild boars. But our approach could be applied in any other region, where a high number of vehicle collisions originates from the following conditions: the target species has/have a large home range, the density of transport infrastructures is remarkable, and traffic flow is high. In addition, some operational requirements need to be met: good availability of spatial data on land uses and transport infrastructures, and adequate estimation of the cost of WCSs.

Results demonstrate that it is possible to monitor the effect of different hypothetical patterns of WCSs on landscape fragmentation and connectivity. In addition, the method applied reports on a non-trivial variation of the unitary cost of defragmentation, as the AVC sensibly increases when transition to denser WCSs scenarios are opted. This clearly helps to clarify that defragmentation cannot be considered a zero cost process. By contrast, it needs constant commitment, choice, and design. Furthermore, the indication we extract from this application is valuable for private and public bodies involved in decision-making processes concerning policies for reducing landscape fragmentation. On the other side, some other comments are important on the limitations of this study. We based our study on the analysis of six hypothetical scenarios, where WCSs are planned to be ideally located on regular intervals and according to uniform linear densities. By contrast, a significantly smaller number of underpasses can be effectively realized, as a number of factors hinders the definitive construction of WCSs. First, the orography impedes many times the construction of underpasses unless remarkably higher costs are budgeted. Secondly, the majority of land surface belongs to private owners: on the other side, the construction of underpasses is to be promoted mostly by public bodies interested in wildlife conservation and social and transport security. In this circumstances, expropriation of private land for public interest would be a process complex and probably connected to an increase of costs. As a third point, WCSs should be realized between landscape patches characterized by habitats suitable for the wild boar, i.e. Mediterranean maquis and garrigue. Many localizations ideally designed in our study may not satisfy this criterion. Finally, proper WCS siting should involve detailed spatial information - not always available- on the incidence of WVCs. Planning really effective WCSs involves the analysis of large datasets, concerning traffic, wild fauna, and incidents, and should be prepared preferably at the strategic level, for instance, during strategic environmental assessment processes of transport and mobility plans. Arguments we will be focussing on in future works.

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List of Table captions.

Table 1 Research questions investigated in this paper.

Table 2 LU Alghero: geographical and statistical data (source: RAS, 2008; Apollonio et al., 2012; RAS, 2016; Brugnone and Pittalis, 2008).

Table 3 Absolute value and percentage variation of IFI and CI for the transition to each scenario. Figures are paralleled by wildlife crossing structures costs.

Table 1

RQ_s	**Description**
RQ_1	Can we measure the effects of WCSs on LF and LC?
RQ_2	How much is defragmentation worth?

Table 2

Data	**Value**
Area (ha)	39,050
Perimeter (m)	171,743
Mediterranean maquis and garrigue (ha)	8,306
Wild boar density (wild boars per 100 ha)	6-10
Max wild boar density (wild boars per 100 ha)	10-15

Table 3

			Scenarios (S)											
			S1		S2		S3		S4		S5		S6	
WCS every (m)			1000	Δ_{0-1000}	1500	Δ_{0-1500}	2000	Δ_{0-2000}	2500	Δ_{0-2500}	3000	Δ_{0-3000}	3500	Δ_{0-3500}
WCSs number			226	-	150	-	115	-	91	-	72	-	64	-
WCSs cost C (x10^6€)			113	-	75	-	57.5	-	45.5	-	36	-	32	-
Original scenario (OS)	IFI	19,810	10,416	-47.42%	11,164	-43.64%	12,325	-37.78%	12,869	-35.04%	14,287	-27.88%	14,469	-26.96%
	CI	0.0122	0.0214	75.27%	0.0203	65.94%	0.0194	58.59%	0.0187	52.59%	0.0181	47.52%	0.0175	43.12%

List of Figure captions.

Figure 1 Layout and elevation of an exemplary wildlife underpass. A, B, and H stand for length, width, and height of the WCS (Dinetti et al., 2008). In brown, lateral wooden panels for reducing traffic disturbance. Informational image by Antonio Ledda.[1]

Figure 2 Geographical context. A: in dark grey, the island of Sardinia, Italy; B: in dark grey, location of the study area in northern Sardinia; C: the study area, LU Alghero.

Figure 3 LU Alghero: urbanized areas and TMIs (A), and main land-use classes (B).

Figure 4 Hypothesis of WCSs location every 1,000 m (A), 1,500 m (B), 2,000 m (C), 2,500 m (D), 3,000 m (E), and 3,500 m (F).

Figure 5 Landscape connectivity in LU Alghero for the seven scenarios.

Figure 6 Landscape connectivity change (%) in LU Alghero of each scenario with respect to original scenario 0.

Figure 7 A: relation between average change of IFI and CI and WCS cost. B: average cost of defragmentation referred to unitary decrease/increase of IFI/CI.

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[1] Trees, source: http://www.cadtutor.net/download/raster/tree-images-elevation.php; wild boar: momentbloom, source: vecteezy.com.

Figure 1

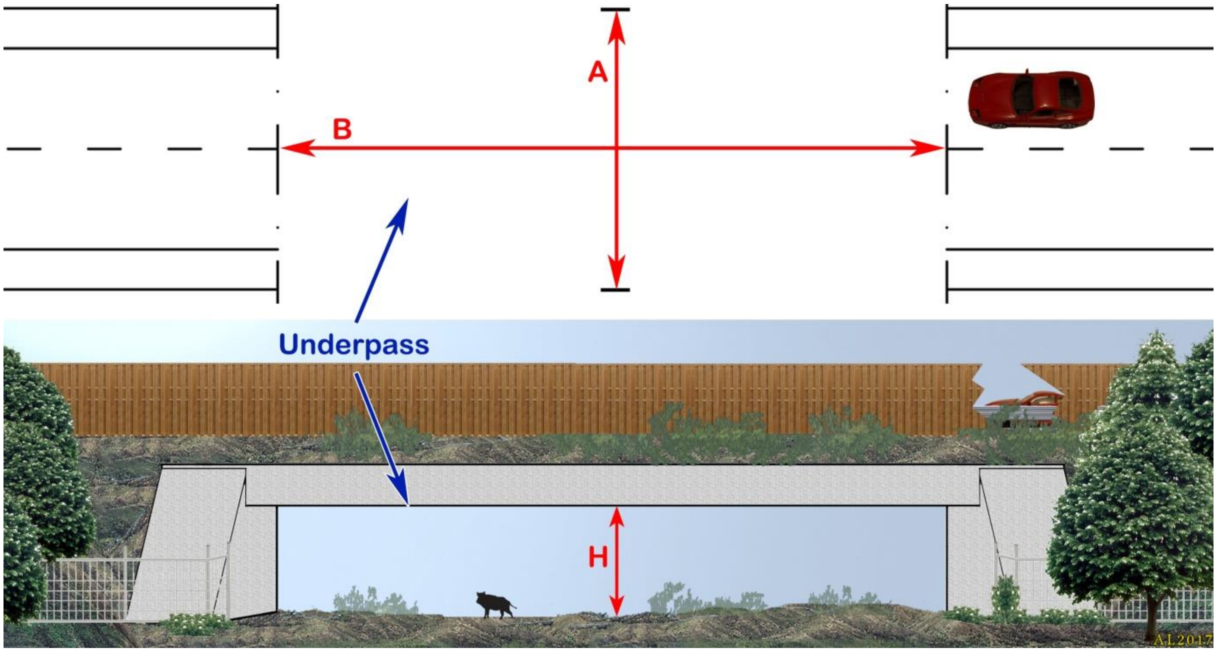


Figure 2

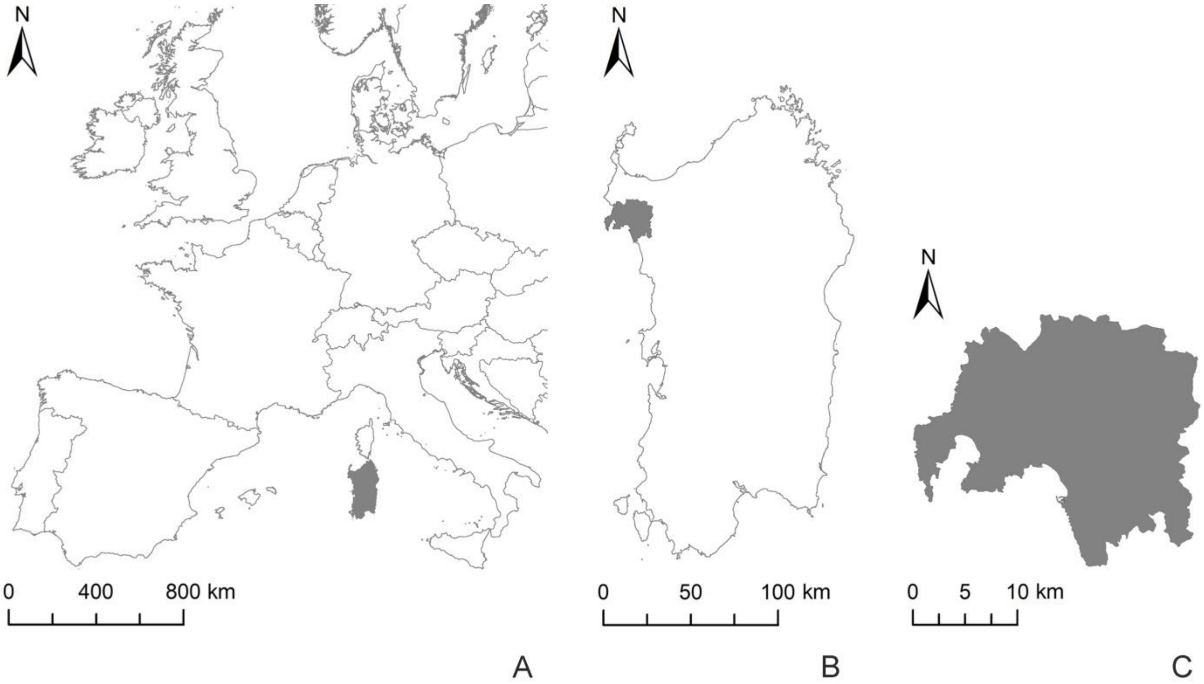


Figure 3

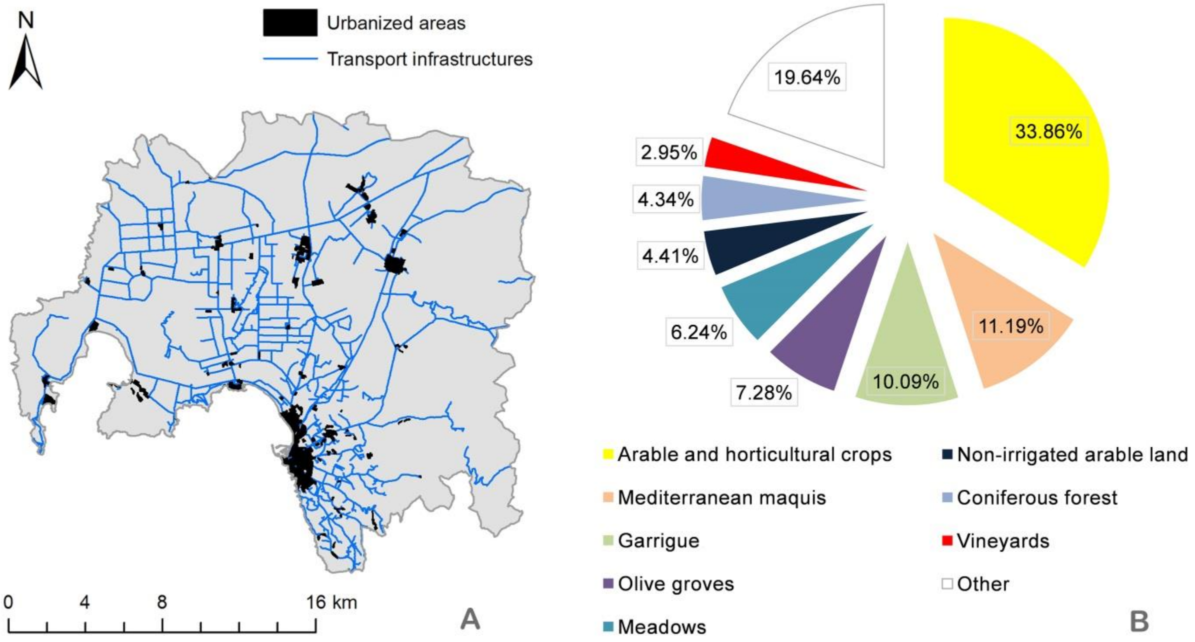

N
Urbanized areas
Transport infrastructures
0
4
8
16 km
A
19.64%
33.86%
2.95%
4.34%
4.41%
6.24%
11.19%
7.28%
10.09%
Arable and horticultural crops
Non-irrigated arable land
Mediterranean maquis
Coniferous forest
Garrigue
Vineyards
Olive groves
Other
Meadows
B

Figure 4

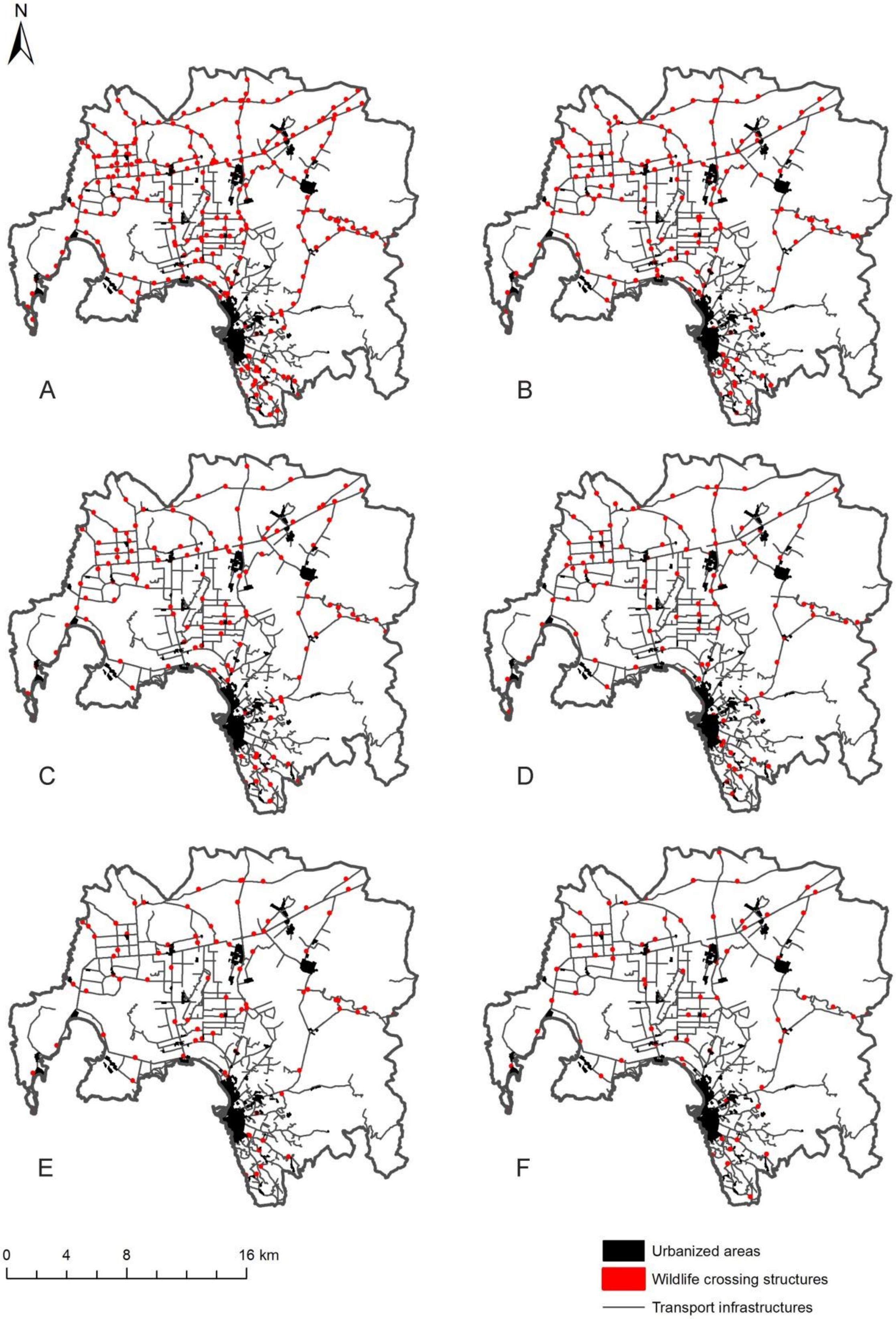

N
A
B
C
D
E
F
0
4
8
16 km
Urbanized areas
Wildlife crossing structures
Transport infrastructures

Figure 5

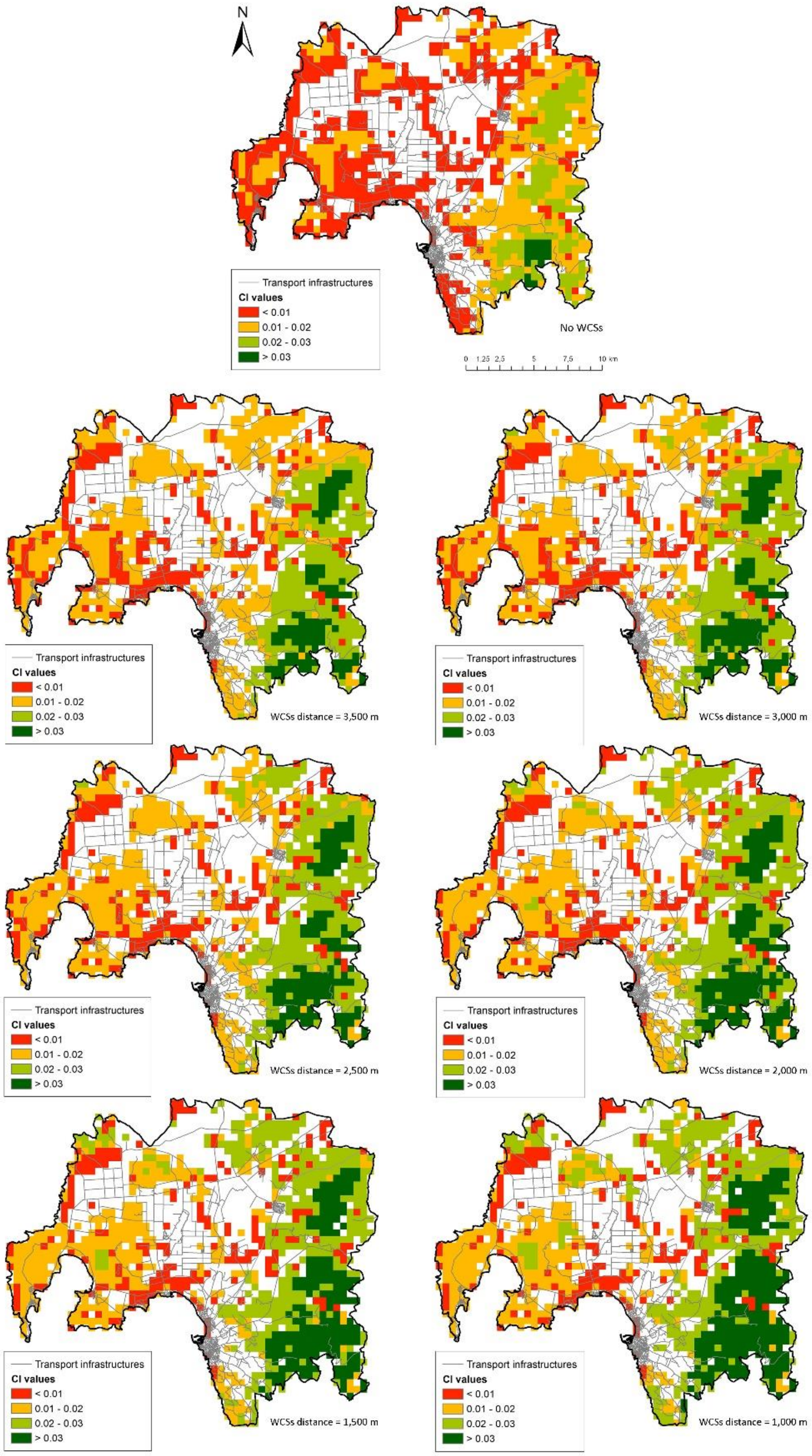

N
Transport infrastructures
CI values
🟥 < 0.01
🟧 0.01 - 0.02
🟩 0.02 - 0.03
🟩 > 0.03
No WCSs
0 1.25 2.5 5 7.5 10 km
WCSs distance = 3,500 m
WCSs distance = 3,000 m
WCSs distance = 2,500 m
WCSs distance = 2,000 m
WCSs distance = 1,500 m
WCSs distance = 1,000 m

Figure 6

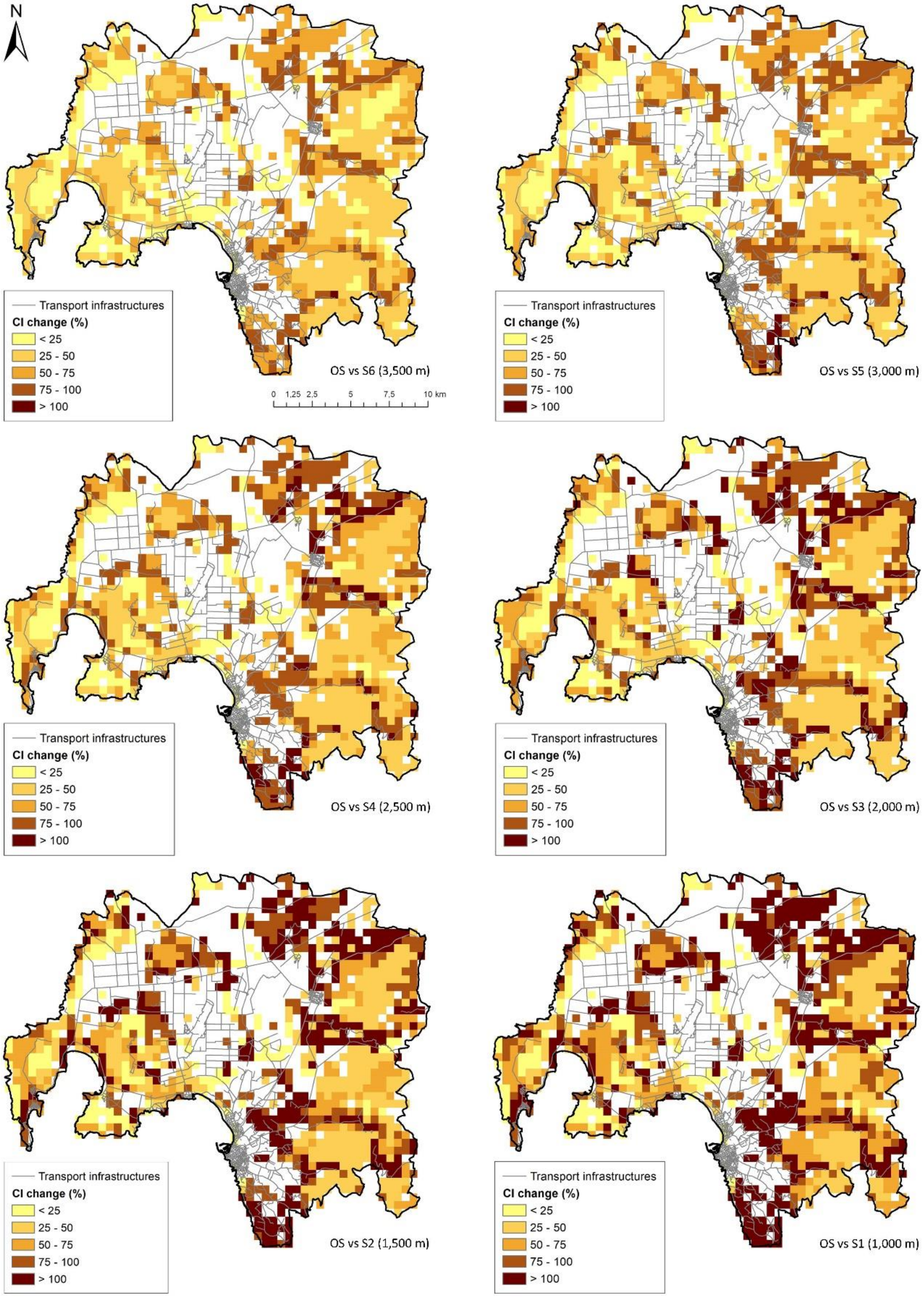
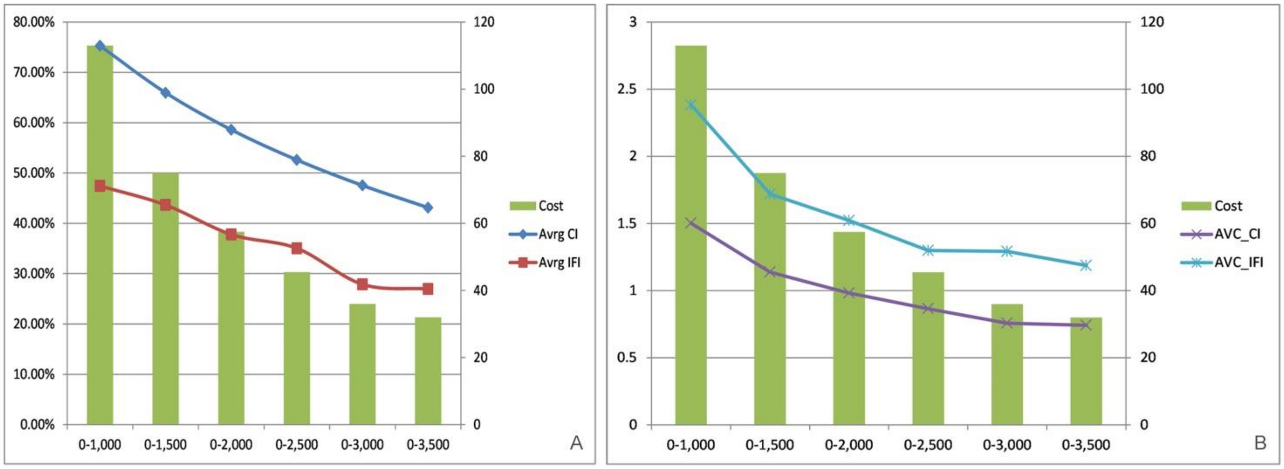

N
Transport infrastructures
CI change (%)
< 25
25 - 50
50 - 75
75 - 100
> 100
OS vs S6 (3,500 m)
0 1,25 2,5 5 7,5 10 km
OS vs S5 (3,000 m)
OS vs S4 (2,500 m)
OS vs S3 (2,000 m)
OS vs S2 (1,500 m)
OS vs S1 (1,000 m)

Figure 7


80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
120
100
80
60
40
20
0
Cost
Avrg CI
Avrg IFI
0-1,000
0-1,500
0-2,000
0-2,500
0-3,000
0-3,500
A
3
2.5
2
1.5
1
0.5
0
120
100
80
60
40
20
0
Cost
AVC_CI
AVC_IFI
0-1,000
0-1,500
0-2,000
0-2,500
0-3,000
0-3,500
B