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Impact of Roads on Environmental Protected Areas: Analysis and Comparison of Metrics for Assessing Habitat Fragmentation

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Abstract: The present study focuses on evaluating the effect of fragmentation caused by road infrastructures on a territory with singular characteristics such as low population density and a high proportion of its surface area protected by the Natura 2000 network. Based on the IFI, UFI, M_{eff} and DIVI metrics, the state of fragmentation of the landscape units (LU) was studied from two different approaches, considering two different protection figures, and the degree of suitability of the metrics used for the objective pursued was analysed. The results show that the expressions proposed for the indicators which measure the fragmentation of landscape units (LU) originated by road infrastructures (IFI, M_{eff} and DIVI) assess different causes and consequences in the territory than that proposed for fragmentation originated by urban areas (UFI). The combination of all indicators allows for the identification of shortcomings and strengths of the LU analysed and, consequently, evaluation of the effectiveness of the design of the LU and need for improvement. The outcomes of fragmentation analysis of the LU in the area under study varied depending on the criterion applied and the protection figure considered. A general increasing trend for all indicators was found in terms of the number of LU units and LU surface as the level of fragmentation rises. The results of this study are useful for decision-making on territory and road infrastructures management and new approaches to the organisation of the Natura 2000 network.

Keywords: road infrastructures; Natura 2000 network; protected natural areas; environmental management; landscape fragmentation metrics; landscape unit

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1. Introduction

The road infrastructure network is one of the main causes of fragmentation of natural habitats in which wildlife thrive [1–3]. Through the European Landscape Convention (ELC), organisations such as the European Union reflect nowadays the importance of the conservation of natural environments [4–6]. At the scientific level, authors evaluate equations and situations in which landscape fragmentation may constitute a risk to the natural environment. Battisti C. et al. reviewed the number of scientific investigations on the subject in recent decades and the approaches of the works on the basis of the keywords used [7].

This study assessed the state of fragmentation caused by road infrastructure in landscape units belonging to the Natura 2000 network in the Extremadura region (Spain). This is an area with low population density and a large dispersion of municipalities, which is classified in the European administrative category NUTS-3. The effect of roads was evaluated through the specific indicators Infrastructural Fragmentation Index (IFI), effective mesh size (M_{eff}) and the degree of landscape division (DIVI) and, indirectly, through the Urban Fragmentation Index (UFI) indicator, which measures the fragmentation caused by urban areas.

The road network has historically offered a service to society adjusted to the demands of each period and conditioned to the existing technical and economic capacities. At the beginning of the road network development, this double dependence meant that these infrastructures had to be built in accordance with the topography of each territory. This implied that the construction works did not significantly transform the terrain's profile, but rather adapted to it [2,3,8]. Technological advances and the needs and demands of society lead to the construction of more disruptive roads that can involve the formation of physical barriers in the territory through which they run [9–12].

The European Directives 97/49/EC and 92/43/EEC introduce strategic guidelines for nature conservation in the framework of the European Union [13,14]. The need for preservation and recovery of the natural environment becomes widespread in the institutional and social spheres, becoming a global concern. The European Union established the Natura 2000 network (RN2000) in 1992, which aims to protect flora and fauna and to preserve and improve natural habitats through the designation of Protected Areas (PA) [14,15]. The European Environment Agency is in charge of assessing landscape fragmentation and its trend in Europe in order to know the evolution of fragmentation in the Natura 2000 network in recent years [16].

The extent to which any infrastructure impacts on the natural habitat is complex to determine [2,3,12,17–19]. This topic is approached by different authors from a social and environmental point of view in a general or particular way for specific infrastructures in order to evaluate the intrinsic effect of the infrastructures [17–23]. Different landscape fragmentation metrics have been proposed for this purpose, which are used by different researchers depending on the case study. Indicators such as the IFI and the UFI are employed for the assessment of landscape fragmentation [24–28]. While the IFI is focused on evaluating the effect of linear infrastructures on landscape units (LU), based on the geometry of the LU, the portions generated by fragmentation and the intrinsic characteristics of roads, the UFI assesses the effect of population settlements on these landscape units. This index is based on the geometry of the LU and the surface of the urban areas of municipalities. The IFI and the UFI are indirectly related indices since the existence of urban areas requires the existence of a network of linear infrastructures proportional to the number and size of the towns they connect. Other indicators of landscape fragmentation, such as the M_{eff}, the effective mesh density (S_{eff}) and the DIVI, proposed by Jaeger J. [29,30], are only based on the geometry of the LU and of the parts into which the landscape is divided. They are also used by different researchers to determine landscape fragmentation [31–37]. The authors Schmiedel. and Culmsee used the M_{eff} to estimate the fragmentation of natural areas, combining different sources of fragmentation for the calculation of the metric, in order to evaluate the vegetation richness of the studied area [31]. The M_{eff} is also applied by the European Environment Agency to analyse the effectiveness of protection versus the fragmentation of the Natura 2000 network [16].

De Montis et al. [24] addressed landscape fragmentation in natural areas of special conservation in Spain and Italy through the IFI and the UFI. A review of the different metrics used for fragmentation calculations was conducted and it was found that two possible calculation equations exist for both the IFI and the UFI. Bruschi et al. [28] studied the level of fragmentation of Italian National Parks due to transport infrastructures through the IFI. The M_{eff}, the S_{eff} and the DIVI are used by different authors to assess the fragmentation caused by infrastructure of anthropic areas, natural spaces and ecosystems [34–40]. Based on M_{eff} and S_{eff}, Lawrenceid et al. [6] studied anthropogenic landscape fragmentation in the LU of the Natura 2000 network in Europe. The results reflect, in different areas in Europe, the existence of insignificant changes in terms of fragmentation in the LU covered by some type of environmental protection, according to the criteria established in their research. In addition, differences in the evolution of fragmentation are evidenced according to the age of the protected LU, orography or development of the region. This study is based on a preliminary analysis of the European Environment Agency (EEA) that qualitatively analyses the fragmentation of these natural areas and suggests that fragmentation in protected areas is lower than in unprotected areas, [16]. Almenar, J.B. et al., analysed the evolution of habitats in Luxembourg as a support tool for territorial planning [31]. Similarly, Schmiedel and Culmsee used fragmentation metrics in local forest management policy, assessing the appropriate minimum plot size in forests and estimating the social impact and response of citizens [31]. The direct relationship between landscape fragmentation (LF) and the decrease in the quality of ecosystems, the reduction in the number of individuals of a species and disappearance of species have been highlighted in different publications [24,28,41–44].

2. Materials and Methods

2.1. Landscape Metrics

The infrastructural fragmentation index (IFI) makes it possible to study the interaction between the territory and linear infrastructures. Two expressions were suggested for its calculation in the scientific literature. Di Ludovico and Romano [45] proposed Equation (1) for the analysis of habitat fragmentation due to roads, while La Rovere et al. [46] studied the concept of infrastructure fragmentation density using Equation (2).

$$\mathrm{IFI} = \frac{\left(\sum_{i=1}^{i=n} \mathrm{L_i} * \mathrm{O_i}\right) * \mathrm{N} * \mathrm{Pt}}{\mathrm{At}} \tag{1}$$

$$\mathrm{IFI} = \frac{\left(\sum_{i=1}^{i=n} \mathrm{L_i} * \mathrm{O_i}\right)}{\mathrm{St}} \tag{2}$$

where L_i is the length of the section of linear infrastructure contained in the evaluated landscape unit; O_i is a dimensionless occlusion coefficient between 0 and 1, which represents the degree of disruption that the linear infrastructure exerts on the territory; N is the number of parts into which the evaluated landscape unit has been divided; Pt is the total perimeter of the evaluated landscape unit; At is the total area of the evaluated landscape unit and St is the reference surface. The index i corresponds to the different infrastructures present in the analysed area and n is the total number of infrastructures.

Equations (1) and (2) are similar, but there are two differences. Firstly, there is the term $N * Pt$, which has increasing values as the areas become more fragmented. Secondly, there is the denominator which, in Equation (1), is the total area of the assessed landscape unit, while in Equation (2) it is a reference area; therefore, equal for the different assessed landscape units.

The variables in Equation (1) are objective, except for the O_i coefficient, which depends on the subjectivity with which it is valued. Romano and Tamburini proposed a method for calculating the coefficient based on road traffic flow $O_i = \frac{n}{60}$, where n is the number of vehicles per day using the road [47]. On the other hand, Biondini et al. [48] suggested values of O_i as a function of the intrinsic importance based on the typology of linear infrastructure: $O_i = 1$ for highways, $O_i = 0.5$ for roads with a high expected traffic load (national and regional roads), and $O_i = 0.3$ for local roads. All these values have been used by different researchers [24–26,28,46]. Ledda and De Montis [25] evaluated the influence of the occlusion coefficient for the calculation of the IFI, reaching the conclusion that the IFI seems to be sensitive to the variation of O_i according to a progressive and linear trend.

Another disruptive effect on the territory, not contemplated in the IFI, is the influence of urban settlements located within an environmental area. The use of natural resources and the development of economic or recreational activities affect the natural habitat within a certain radius of influence. This is indirectly related to the existence and use of infrastructures. Furthermore, the dispersion of small urban agglomerations favours the multiplication of local roads, while the concentration of large urban centres limits the number of roads but increases the importance of their impact. The Urban Fragmentation

Index (UFI) assesses the fragmentation of the territory regarding the urban settlements it contains. De Montis et al. [24] examined the relationship between the IFI and UFI indices in 6 landscape units (LU). They found some relationship between the indices but concluded that 6 LU are not enough to define a statistically significant relationship between the two fragmentation indicators. In this work, the UFI is used as another fragmentation indicator that can reinforce the IFI values obtained. From the review of indices carried out by De Monties et al. [24], Equations (3) and (4) are extracted as possible formulas for the calculation of the UFI:

$$\mathrm{UFI} = \frac{\frac{\sum_{i=1}^{i=n} S_i}{A_t} * \sum_{i=1}^{i=n} p_i}{\sqrt[2]{\pi * \sum_{i=1}^{i=n} S_i}} \tag{3}$$

$$\mathrm{UFI} = \frac{\left(\sum_{i=1}^{i=n} p_i * S_i * o_i\right)}{A_t} \tag{4}$$

where S_i is the surface area of the urban settlement; p_i is the perimeter of the urban settlement; A_t is the total area of the landscape unit; o_i is the dimensionless occlusion coefficient established according to the permeability of the urban settlement or its neighbourhood. The index i corresponds to the different urban settlements present in the area analysed and n is the total number of urban settlements.

As is the case of the IFI, o_i is a subjective variable. Romano and Tamburini [47] proposed, for the study of fragmentation of large landscape units in Italy due to the growth of urban agglomerations, values of o_i according to the nature of the urban area (industrial 100%, business district 80%, intensive residential areas 60%, and extensive residential areas 40%). This classification was subsequently used by other authors for studies of territorial fragmentation due to urban areas [24,26,48] although the classification of urban settlements in one of these classes is complex.

The M_{eff} is an indicator that allows studying the effective parcel size of a LU fragmented by both linear infrastructures from a purely geometric point of view and by surface elements [29,30]. This indicator is not affected by the existence of small area patches and, in the case that all patches have the same size, the effective mesh size would be that area. In this sense, a higher M_{eff} value represents a lower landscape fragmentation and vice versa. The measurement unit of M_{eff} will be that considered for the areas in the calculation using Equation (5):

$$M_{eff} = \frac{\sum_{i=1}^{n} \left(A_i{}^2\right)}{A_t} \left(\mathrm{km}^2\right) \tag{5}$$

where A_t is the total area of the landscape unit and A_i is the area of the fragmented surface. The index i corresponds to the different surfaces into which the area analysed has been divided due to the linear infrastructures and n is the total number of parts.

From the M_{eff}, two other metrics are derived: the effective mesh density (S_{eff}) and the degree of coherence C or DIVI [29]. The S_{eff} represents the occupancy of the M_{eff} (expressed as a percentage of one) in relation to an established surface area, which some authors set as 1 km^2 [30]. Since the S_{eff} can be interpreted as the inverse of M_{eff}, it has not been considered as a metric in the results section. The DIVI or C can be understood as the probability that two individuals can be found in a given environmental area. It is the representation of the M_{eff} in the LU area expressed as a percentage of one. Values close to 0 represent highly fragmented areas and those close to 1 indicate non-fragmented areas [26,30].

$$S_{eff} = \frac{1}{M_{eff}} \tag{6}$$

$$\mathrm{DIVI} = \mathrm{C} = \frac{M_{eff}}{A_t} = \sum_{i=1}^{n} \left(\frac{A_i}{A_t}\right)^2 \tag{7}$$

where M_{eff} is the effective mesh size; A_t is the total area of the landscape unit; A_i is the area of each of the fragmented surfaces. The index i corresponds to the different surfaces into which the area analysed has been divided due to the linear infrastructures and n is the total number of parts.

2.2. Territory, Demography and Landscape Units

The region of Extremadura is made up of the two largest provinces in Spain, Cáceres and Badajoz. It is located in the central-western strip of the Iberian Peninsula, with an extension of more than 41,600 km^2 and resembles a rectangle with east–west sides of 170 km and north–south sides of 250 km (Figure 1). It ranks as the sixth region in Spain in terms of the highest number of protected landscape units and the sixth region in Spain in terms of the highest percentage of protected area. In terms of area, Spain has 27% of its territory protected, above the European Union average of 18%. Figure 1 places the study area in the context of Europe and shows all the environmental zones with all the protection typology of the Extremadura region superimposed on roads and urban settlements.

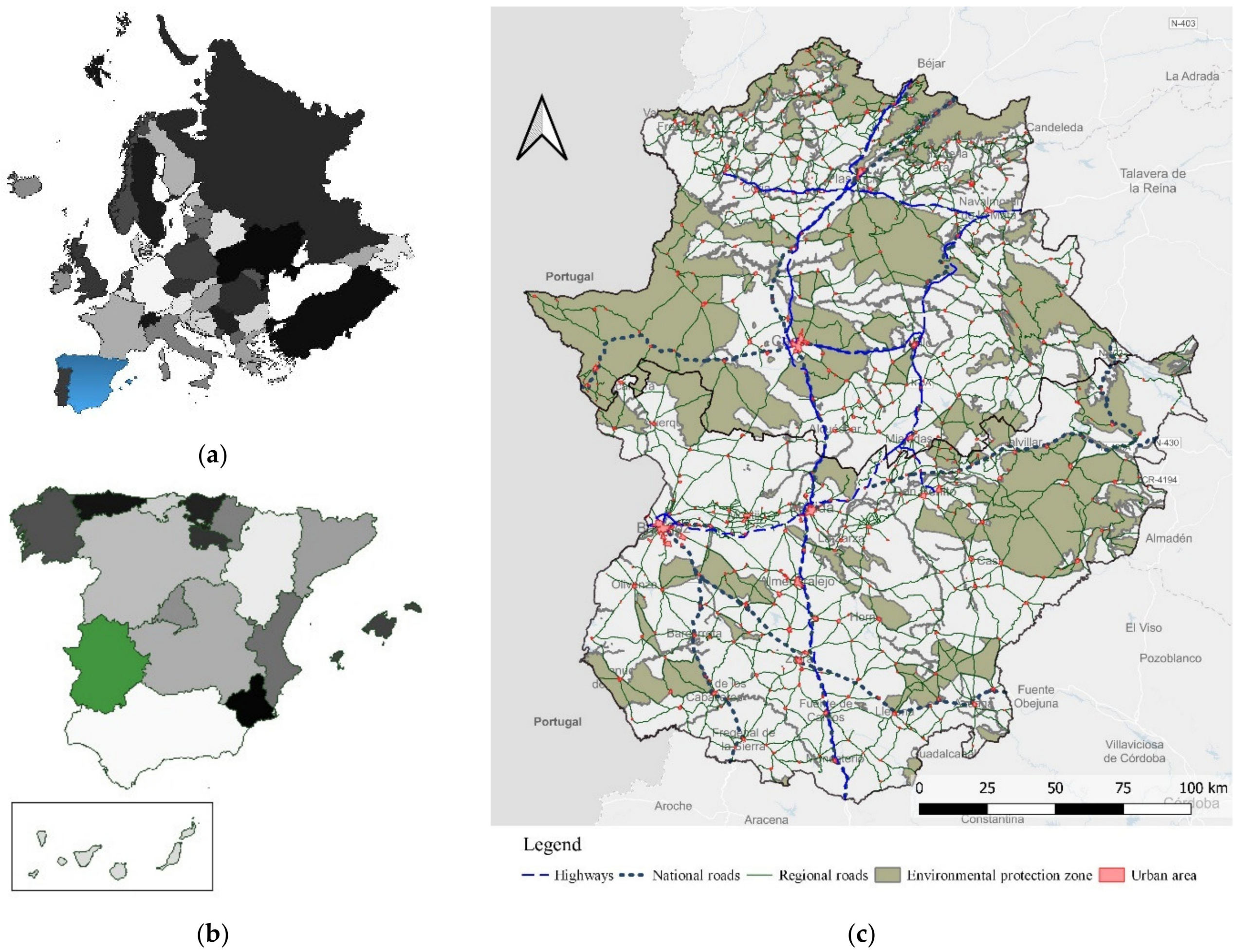


Figure 1. Spatial contextualisation of the study area. (**a**) Location of Spain (in blue) in Europe; (**b**) location of Extremadura (in green) in Spain; (**c**) map of Extremadura with communication routes and urban and environmental protected areas.

The population density of Extremadura is 26.4 inhabitants/km^2, while the averages in Spain and Europe are 91.4 and 109 inhabitants/km^2, respectively [49]. The region has 165 municipalities in the province of Badajoz and 223 in the province of Cáceres. Figure 2 shows the distribution of municipalities according to the number of inhabitants. An inverted pyramid can be observed in which 31.44% of municipalities have less than

500 inhabitants and only 9% of municipalities have more than 5000 inhabitants [50]. An extensive road network is necessary to connect all these municipalities distributed over the large surface area of the region, with a total length of 9105 km. This network is divided into distinct categories according to the traffic capacity and the size of the municipalities connected: state road network, with 21 roads and 1593 km; regional road network, with 104 roads and 3794 km; and local road network, with 402 roads and 3718 km.

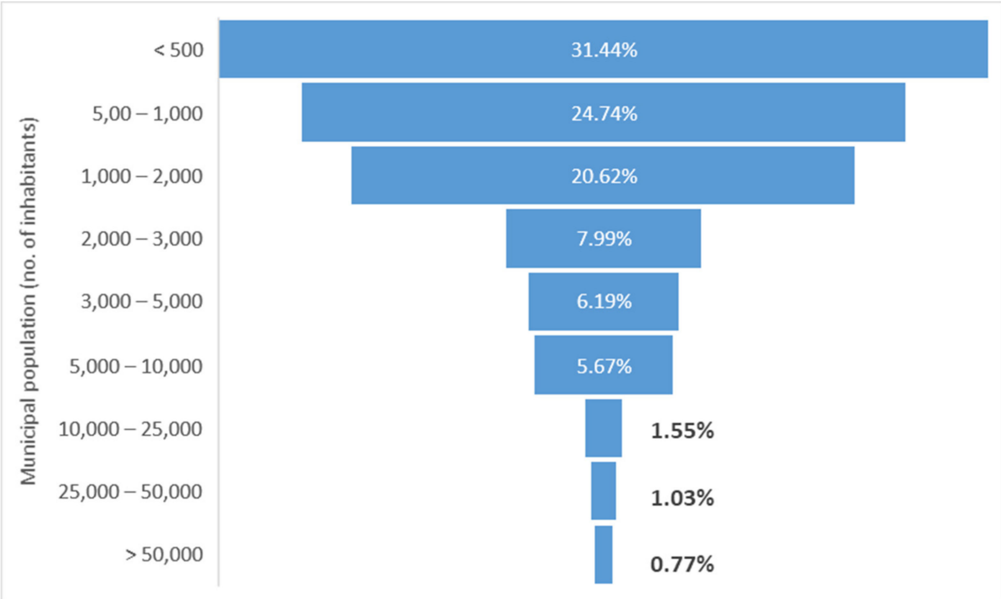


Figure 2. Distribution of municipalities by population in Extremadura (Spain) [50].

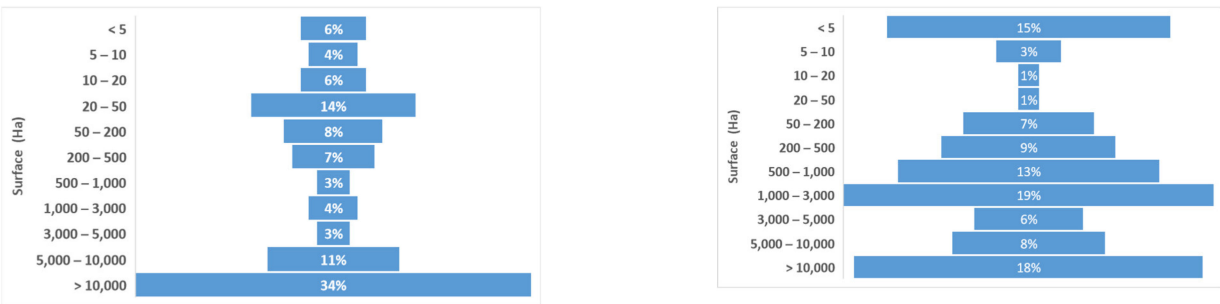
In relation to the orography of the territory studied and its relevance for the design and construction of the road infrastructures, the geography of Extremadura is predominantly made up of peneplains as a characteristic form of smooth and not very abrupt landscapes. Based on data from the European CORINE Land Cover 2018 project [51], landscape typologies are classified into five classes: artificial surfaces, agricultural areas, forest areas with natural vegetation and open spaces, wetlands and water bodies. Table 1 shows the proportions of surfaces in Extremadura according to the above classification. Data show that artificial land (urban and industrial) is under-represented in comparison with agricultural and forestry areas. Table 1 shows the representation of land uses extracted from the information of [51]. It is observed that the two largest fractions of land use in Extremadura are mostly agricultural areas (62%) and forest and seminatural areas (35%), with a minority of artificial surfaces (1%).

Table 1. Land use areas in Extremadura (Spain) [51].

Land Use	CLC 2018
Artificial surfaces	0.99%
Agricultural areas	61.92%
Forest and seminatural areas	35.37%
Wetlands	0.00%
Water bodies	1.72 %

The Natura 2000 network [14] determines two typologies of protection as Special Bird Protection Areas (SPAs) and Special Areas of Conservation (SACs) [14]. SPAs were defined in 1995 and recently updated in 2009 [13,52]. This line of protection is aimed to "preserve, maintain or re-establish a sufficient diversity and area of habitat for all bird species" [52]. There are landscape units with other figures of environmental protection that seek the preservation of habitats with similar premises to the Natura 2000 network. The following should be considered in this group: site of community importance (SCI), biosphere reserve, RAMSAR areas and natural, national or international parks [14,53,54]. The number and extent of the landscape units in Extremadura that are part of the existing Natura 2000 network is an indication of the institutional commitment to habitat conservation. At present, 34% of Extremadura territory is protected by one of the abovementioned environmental protection types. Of these, the Natura 2000 network (SPAs and SACs) represents the largest protected area with 71 landscape units of SPA protection (11,016 km^2) and 89 landscape units of SAC protection (9332 km^2). Considering each type of environmental protection figure independently, national parks constitute 0.43% of the total area, natural parks 0.87 %, Special Bird Protection Areas (SPAs) 26.15%, Special Areas of Conservation (SACs) 22.40% and biosphere reserve natural spaces 9.04%. In Extremadura, both the number of areas under these other types of protection and the area involved is much lower than that of RN2000. Moreover, part of the surface area included in these LU was already protected as an SPA or SAC. Therefore, this work focuses on the individual analysis of the Natura 2000 network. It is also important to bear in mind that often the same landscape unit is protected by both Natura 2000 network protection categories (SPA and SAC). In other cases, a LU with SAC protection is contained in a larger LU with SPA protection or vice versa. This is why the result of fragmentation of landscape units with SPA and SAC protection can be similar in certain cases.

Figure 3 shows the distribution of SACs and SPAs in Extremadura according to surface area. It can be noted that 34% of the LU with SPA protection have an area larger than 10,000 ha and 61% greater than 200 ha. In the case of the SACs, 18% of the LU have an area larger than 10,000 ha and 73% have an area greater than 200 ha. The surface area is a key factor in the design of landscape units, since each animal or plant species requires a minimum amount of space in its habitat. Additionally, the larger the surface area, the greater the fragmentation that is possible due to roads and the dispersion of population settlements, as these usually seek the shortest route to connect two points.



(**a**) (**b**)

Figure 3. Statistical distribution of the surface area of Natura 2000 network protection figures in Extremadura (Spain): (**a**) SPAs and (**b**) SACs.

The spatial distribution of LU with SPA and SAC protection in Extremadura is presented in Figure 4. There are LU scattered throughout the region, although a greater concentration of these can be observed in the northern zone. The northwestern fringe is the one with the highest density of protected areas. This area is located on the border with Portugal. It is a mountainous area with some rivers and is one of the least densely populated areas, ranking 3rd out of 19 administrative units in Spain and 26th out of 746 administrative units in the European Union in 2019, [49].

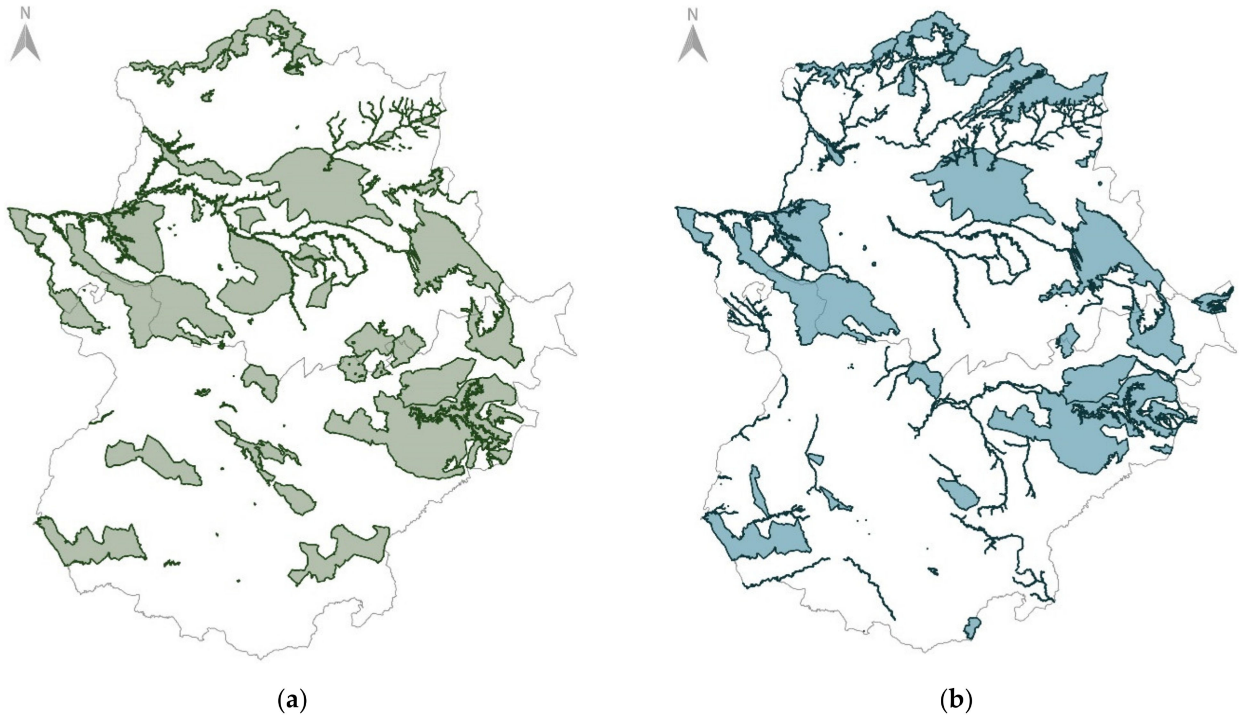


Figure 4. Spatial distribution of protected areas of the Natura 2000 network in Extremadura (Spain): (**a**) SPAs and (**b**) SACs [55].

2.3. Data Collection and Calculation Parameters Used

In the study of habitat fragmentation, cartographic data from different sources were used. The calculations were carried out in a Geographic Information System (GIS) environment with QGIS software [56]. The vectorial cartography used was in SHP format and the reference coordinate system is ETRS89, projected in UTM projection Huso 30N. The cartographic entities and origin of the two data types used are detailed in Table 2. It also specifies the type of vector data and the reference cartographic scale. The cartographic errors associated with the scale factor can influence the process of overlapping and intersection between layers at their edges. This can result in a loss of precision in the calculation of fragmentation indicators. This is because some of the boundaries of the environmental areas studied are roads or urban areas. The scale factor of data origin in the environmental figures is not defined in the metadata, but it is estimated to be at least 200,000, with an error associated with the scale of 40 m.

Table 2. Cartographic elements used in the study.

Element	Vector Data Type	Origin	Origin Scale Factor (m)	Error Associated with Scale (m)
Urban Area	Polygon	BCN200 IGN	200,000	40
Road Infrastructure	Line	Junta de Extremadura	200,000	40
Environmental Figures	Polygon	Junta de Extremadura	Not defined	-

The used equations include some parameters that need to be defined, such as the occlusion indices integrated in Equations (2) and (3). For the calculation of the IFI by means of Equation (2), a reference surface of St = 1Ha has been established in the study. The O_i values proposed by Biondi et al. [48] and previously explained in Section 2.1 were used for both Equations (2) and (3).

In the calculation of the UFI, it is complex to use the O_i values proposed by Romano and Tamburini [47] and transfer them directly to the fragmentation produced by the urban settlements included in an area protected by its environmental nature. The study area of the present work is mostly composed of municipalities with a population of less than 5000 inhabitants. Table 3 shows the occlusion coefficients used in this research, ordered according to the municipal population, understanding this parameter as representative of the human activity of the municipality and its size. For the calculation of the metrics in the SHP files of the linear infrastructures, the discontinuities produced by the bridges were taken into account.

Table 3. Occlusion index o_i used in the calculations with Equation (4).

Municipality Population (Inhabitants)	o_i
<5000	0.3
5000–7500	0.4
7500–10,000	0.7
10,000–25,000	0.8
>25,000	1

For the calculation of the IFI, given the possible cartographic errors, the following assumptions were made [27]. Road segments dividing a LU with a length of less than 5 km and patches generated with a surface area of less than 1.5 ha were not taken into account. In the calculations of the UFI, only urban areas whose surface was entirely included in the LU have been considered. Based on these parameters, the aim was to avoid possible errors produced by the design scales of the cartography used.

3. Results and Discussion

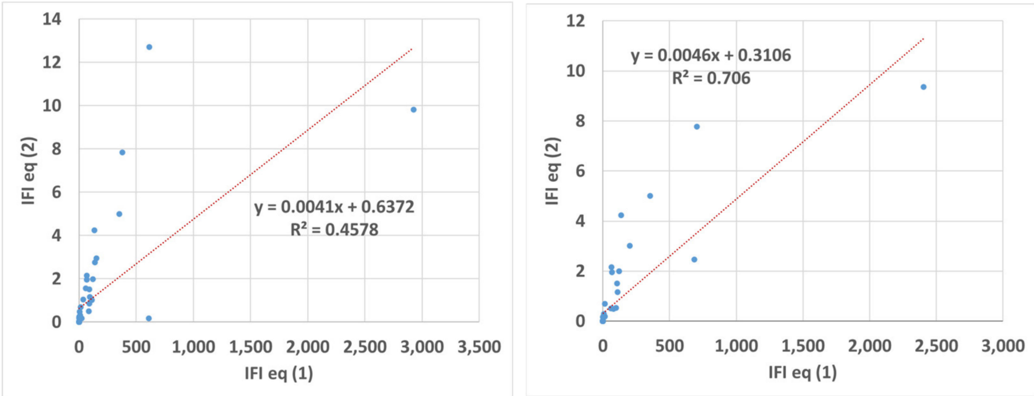
The relationship between the results found for each index IFI and UFI was first analysed by considering the different equations proposed in the literature. Secondly, a study was developed regarding relationships between the different fragmentation metrics used. Finally, a graphical analysis of fragmentation in the LU analysed in Extremadura was carried out in relation to the indices employed. This allowed for the contextualising of the LU distribution from a spatial point of view, according to their level of fragmentation.

3.1. Comparison of Metrics

3.1.1. Comparison of Equations for a Same Indicator

As pointed out in Section 2, in the case of some metrics for measuring land fragmentation, particularly the IFI and UFI, different mathematical expressions can be found in the bibliography to be evaluated. In this section, for each metric (IFI and UFI), the relationship between the values obtained with the different equations proposed was analysed. For this purpose, they were applied to two groups of natural landscape units, SPAs and SACs.

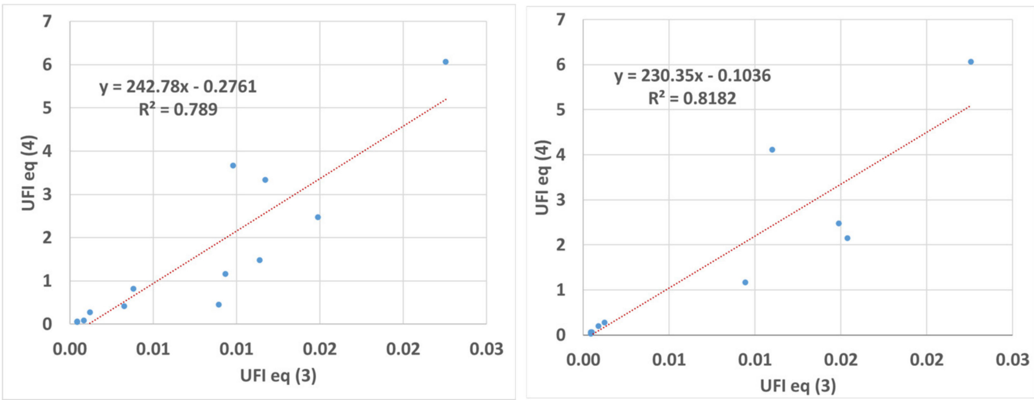
Figure 5 shows the linear relationship between the results obtained by Equations (1) and (2) proposed for the calculation of the IFI indicator when applied independently to LU with protected SPAs (Figure 5a) and SACs (Figure 5b). In both cases, a significant linear dependence was obtained at 99.9% (p value < 0.001). The explanation of the variability is 45% in the LU with SPA protection and 70% for the SACs. Given that both expressions evaluate the same cause of fragmentation of the territory, it would be expected that their results would be equivalent. However, it is observed that, in the case of SPAs, this equivalence was less than 50%, which implies the need to select one of them to obtain the fragmentation index sought. Equation (1), unlike Equation (2), takes into account in the measuring of fragmentation caused by an infrastructure not only its length and the characteristics of the road, but also aspects related to the effect of the infrastructures, through the factor $N * Pt$. Additionally, when dividing by the surface area of the area under study, the importance of the value obtained in the numerator with respect to the surface area of the landscape unit was evaluated. Consequently, the results shown in this study for the IFI were obtained using Equation (1).



(**a**) (**b**)

Figure 5. Relationship between the IFI indices calculated with Equations (1) and (2) for the protected areas of the Natura 2000 Network in Extremadura: (**a**) SPAs and (**b**) SACs.

The linear regression relationship between the obtained UFI values using Equations (3) and (4) for the LU of SPAs and SACs is shown in Figure 6. A coefficient of determination close to 0.8 and a significance of more than 99.9% was found in both cases (p value > 0.001). These results suggest that both equations evaluate the fragmentation of the territory in a similar way, so that they could be used interchangeably for the calculation of the UFI. Considering that, unlike Equation (4), Equation (3) does not take into account any aspect related to the characteristics of each urban settlement, Equation (4) was used in the analyses carried out in this paper for the UFI metric calculations.



(**a**) (**b**)

Figure 6. Relationship between the UFI indices calculated with Equations (3) and (4) for the protected areas of the Natura 2000 Network in Extremadura: (**a**) SPAs and (**b**) SACs.

3.1.2. Comparison of Different Indicators

Different studies compare or combine the indices used for the study of fragmentation of landscape units [24,27,46,47]. De Montis et al. analysed the relationship between IFI and UFI based on six landscape units. The results showed that there was no relationship; however, they determined that the number of landscape units analysed was not representative to obtain a conclusive result. The existence of a relationship between two different metrics, such as IFI and UFI, which measure the fragmentation induced in LU by different causes, would indicate that both the causes and the variables are related. Otherwise, each metric would explain different causes and effects of fragmentation.

The relationships studied in this paper between the metrics used and their significance are shown in Table 4. A significant relationship was only found between the IFI and DIVI metrics (N.S.: non-significant correlation (p > 0.05).

Table 4. Significance (*p* value) of the relationships studied.

	IFI/UFI	IFI/DIVI	DIVI/UFI	DIVI/M_{eff}	IFI/M_{eff}	UFI/M_{eff}
SPAs	n.s.	<0.05	n.s.	n.s.	n.s.	n.s.
SACs	n.s.	<0.05	n.s.	n.s.	n.s.	n.s.

[n.s.] Non-significant correlation ($p > 0.05$).

Table 5 presents the values of the linear regression parameters obtained as a result of the comparison between the IFI and DIVI for the LU of SACs and SPAs. The relationship was significant at 95% in both cases and indicates a decrease in IFI with increasing DIVI. The explanation of variability in SACs (21%) is higher than that in SPAs (15%).

Table 5. Regression parameters of the relationship between the values of IFI and DIVI.

	R^2	m	n
SPAs	0.15	−0.0001	0.36
SACs	0.21	−0.0002	0.43

To evaluate the results that were found in this analysis, it is important to pay attention to two aspects. Firstly, it should be noted that the different indicators of landscape fragmentation proposed in the literature have been independently applied in this study for two different protected areas (SPAs and SACs) and with a large number of landscape units analysed in each of them, given that the study was framed in a scenario with a low population density and a large dispersion of urban settlements. Secondly, it can be observed that the fragmentation effect of linear infrastructures has been evaluated by means of three different indicators that have a weak or null relationship between them. Given these considerations, the results found allow us to reach two conclusions with respect to the fragmentation indicators proposed in the literature. First, it can be said that the expressions proposed for the indicators that measure the fragmentation of LU originated by linear infrastructures (IFI, M_{eff}, DIVI) evaluate different causes and consequences in the territory than the indicator proposed for the measurement of fragmentation originated by population settlements (UFI). Consequently, although the origin of transport infrastructure is in the population settlements, to evaluate the effect of human beings on the territory, it is necessary to independently consider the urban areas and the infrastructures that enable communication between them. Furthermore, the fact that only one significant relationship was found between the indicators which measure the fragmentation of the territory as a consequence of linear infrastructures seems to indicate that, as a consequence of the variables involved in these expressions or the mathematical formulation of these variables, the three expressions are basically measuring the same causes but different aspects of the consequences which linear infrastructures associated with road transport have on the territory. It should be noted that the only significant relationship found between two of these indicators (IFI and DIVI), in both types of protection, have low explanations of variability, between 15% and 21%, depending on the type of protection considered. This therefore shows that there are aspects of the effect on the territory of linear infrastructures common to both indicators, but with a weak relationship between them.

3.2. Analysis of the State of Fragmentation Based on Indicators

Considering the results shown in the previous section, it is possible to state that each of the metrics used represents the state of fragmentation of the LU under different approaches. Consequently, a comparative analysis of the fragmentation results obtained by each indicator is made in this section. To examine the importance and distribution of these fragmentation values, a graphical representation of the results obtained by means of the different indicators was firstly made separately for the different scenarios proposed in this study (71 LU of SPAs and 89 LU of SACs) and, subsequently, a detailed analysis of the results was carried out. In this context, it should be borne in mind that the IFI, UFI and M_{eff} indices show fragmentation on a scale without an upper limit, while the DIVI shows a result limited to between 0 and 1. To make it easier to compare the results between the different metrics and between the different protection figures studied, the establishment of a uniform scale of representation has been proposed. Thus, the equal count (quantile) formulation, implemented in QGIS software, was used for all the metrics. This formulation has been applied to each of the protection figures, SPAs and SACs; and, from the result, a single average scale of representation has been obtained for both. This is possible because the ranges of fragmentation values obtained in SPAs and SACs are similar. The fragmentation results obtained are graphically shown in Figure 7 for the SPAs and in Figure 8 for the SACs.

The IFI and UFI indicators respectively analyse the fragmentation caused by road infrastructures and urban areas. In the case of the IFI (Figures 7a and 8a), it may seem that, in a first approximation, the highest values of fragmentation were obtained for the larger LU. However, a more detailed analysis shows that there are small landscape units with high values of this indicator and that similar sized areas can have very different values among them. In particular, it can be observed that, for the SPAs (Figure 7a), there are some very small LU in the northern area with high IFI values, equal to other large LU located in more central areas. In the case of the SACs (Figure 8a), other LU can also be found in the northern zone in which the IFI has very different values despite having a similar size. In fact, both figures show that areas of intermediate size can have very different values of the indicator. This is the case, for example, of the IFI values for the four SPAs located in the southern third of the European region studied (Figure 7a). Finally, it is also interesting to note that, for both protection categories, all non-fragmented LU (zero values of the IFI) have small surface areas.

The UFI values obtained in both types of protection figures vary between 0 and 7 (Figures 7b and 8b). The representation of the results based on the UFI shows a higher proportion of non-fragmented LU, both in SACs and SPAs. Note that for the UFI, unlike the IFI, the non-fragmented LU have highly variable surfaces and no clear trend is observed relating the LU surface area to the level of fragmentation. This may be conditioned by the design of the landscape units which, in general, have been designed based on the bordering of urban perimeters. This way for designing the LU, taking into account the urban boundaries, means that the results obtained for UFI do not really reflect the influence on the LU of the neighbouring municipalities. Consequently, it is reasonable to think that the indicator is not showing the reality of fragmentation, due to the existence of municipalities close to the LU.

The M_{eff} indicator reflects the surface area (in km^2) of the effective parcel of the landscape unit. The graphic representation of the values obtained from this indicator (Figures 7c and 8c) allows us to identify the adequacy degree of the LU to the environmental protection of reference, in relation to the surface necessary to preserve the protected habitat. In principle, high values of the indicator should be related to a lower level of fragmentation of the LU. If the results shown in Figures 7c and 8c are analysed, as in the case of the IFI, it is observed that the LU with a larger surface area have a higher M_{eff} value in both protection categories. This finding may be related to the fact that the larger the landscape units are, the larger the fragmented parts of the landscape may be. Consequently, this apparent correlation between the M_{eff} value and LU size should be taken with caution. It can be noted in Figures 7c and 8c that all the non-fragmented LU are of small size. In addition, some LU can be found with M_{eff} values in the zone of maximums, even though their protected areas are not among the highest values. Examples of this result can be seen in both types of protection in the LU located in the central eastern and western areas of Extremadura. For instance, it can be found that the most western LU does not have a high surface area, but its effective parcel size is in the range of maximums. It can also be detected in the central-eastern area that two LU are very close to each other and that the one with the smallest surface is the one with the largest effective parcel size. This graphical analysis of the M_{eff} values may lead to the conclusion that the M_{eff} could be more useful to identify the degree of suitability of the LU to the surface area necessary to preserve the protected habitat than as a measure of the level of fragmentation of the LU.

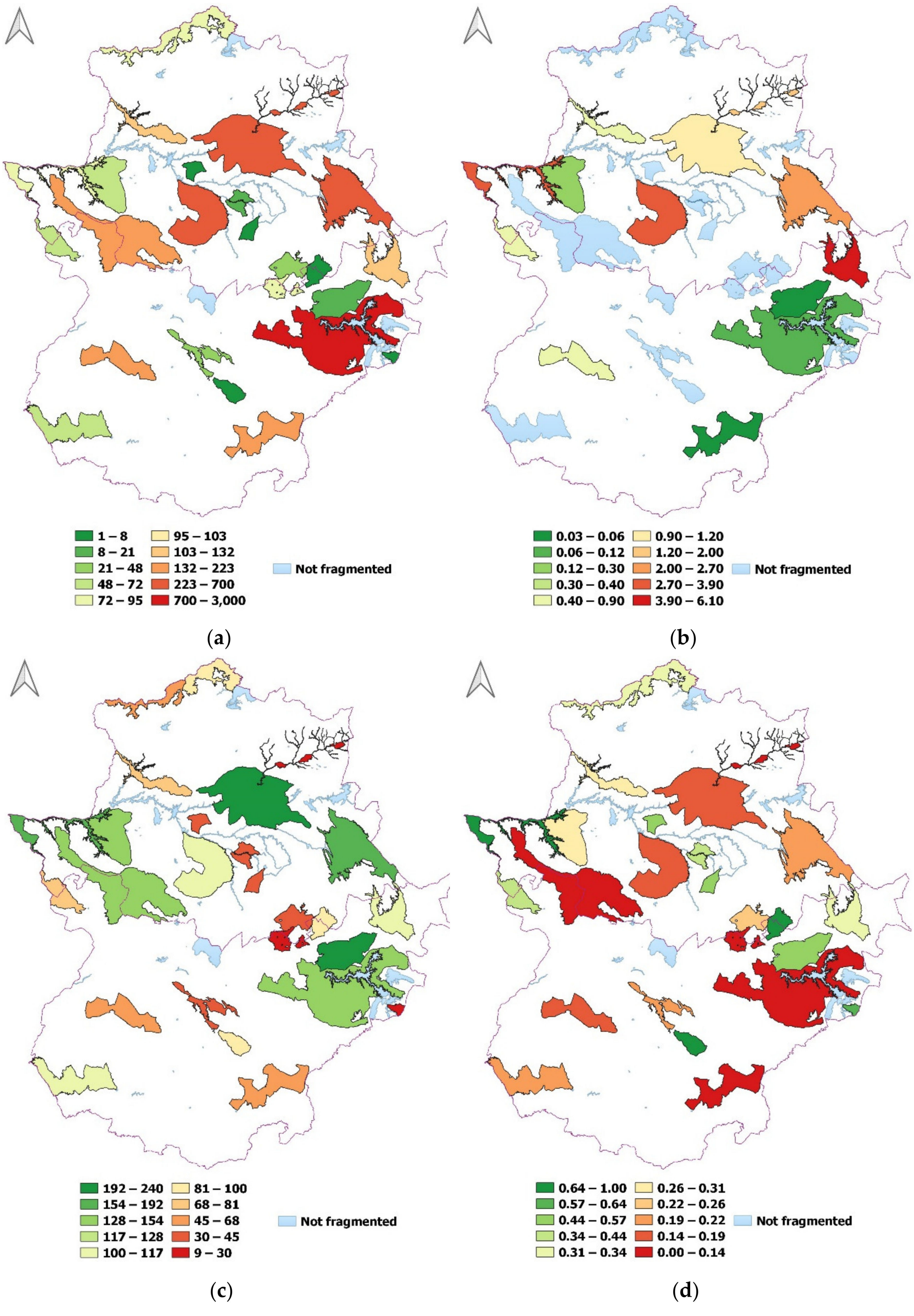


Figure 7. Landscape metrics obtained in relation to the Special Bird Protection Areas (SPAs) in Extremadura (Spain): (**a**) IFI, (**b**) UFI, (**c**) M_{eff} (km^2) and (**d**) DIVI.

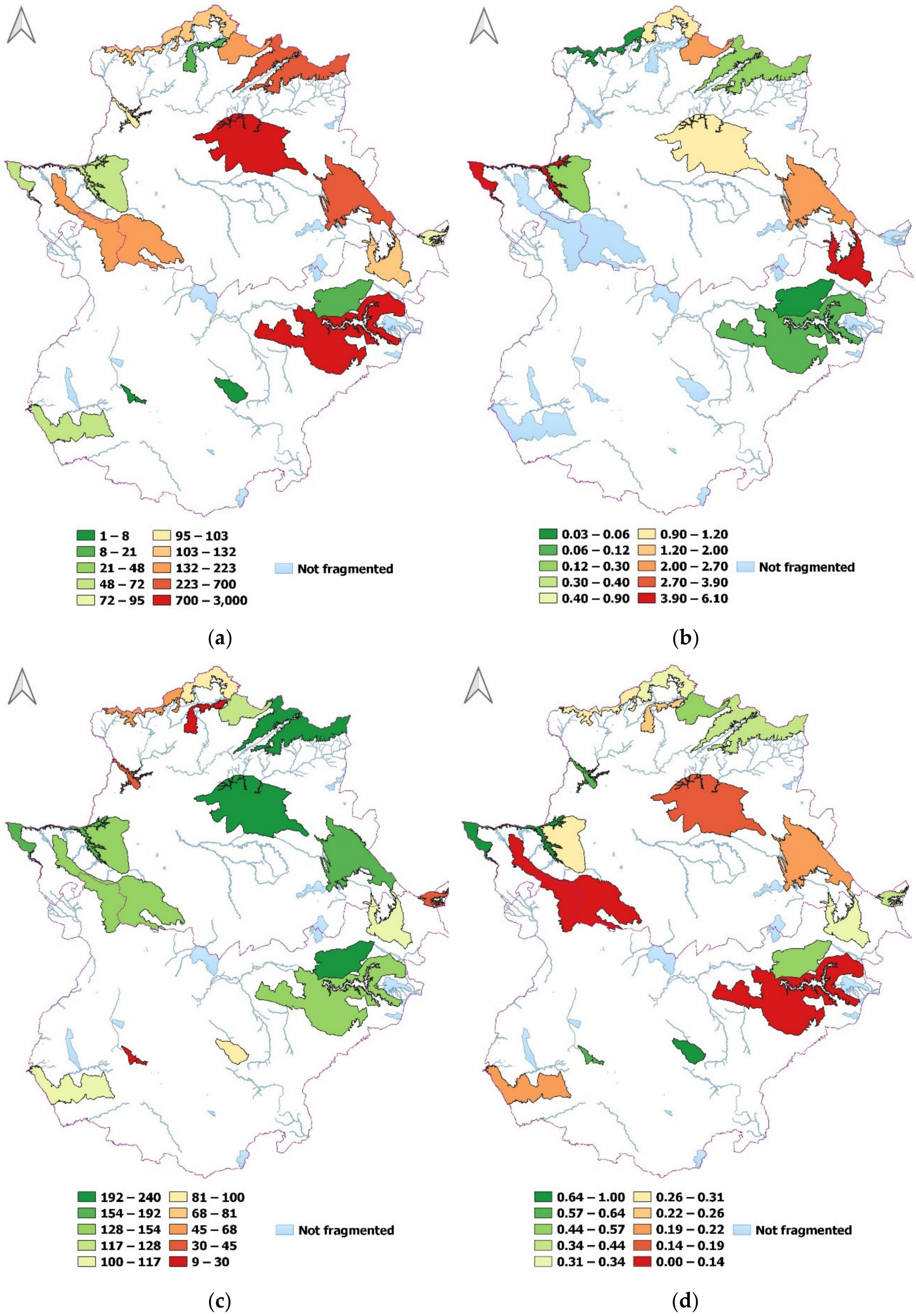
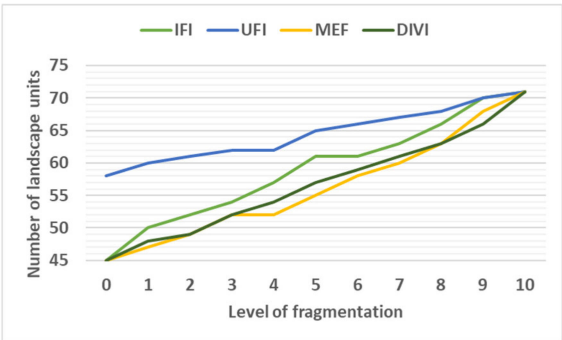


Figure 8. Landscape metrics obtained in relation to the Special Areas of Conservation (SACs) in Extremadura (Spain): (**a**) IFI, (**b**) UFI, (**c**) M_{eff} (km^2) and (**d**) DIVI.

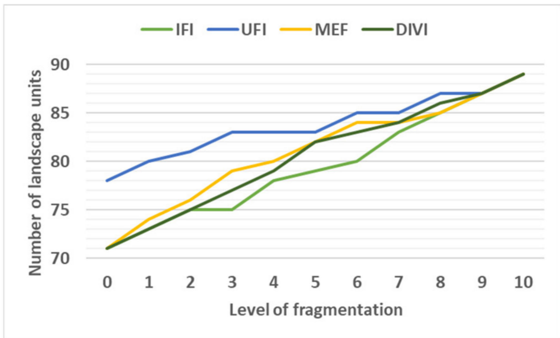
The results of DIVI show, as a percentage of one, the proportion of the M_{eff} over the total area of the LU. In smaller LU, this indicator makes it possible to determine whether they have been designed with criteria that are more or less suitable for the objectives. If the state of fragmentation of the region is analysed using the DIVI, both for the SPAs (Figure 7d) and the SACs (Figure 8d), a certain similarity can be observed with the results for the IFI. Therefore, to some extent, the comments made for this indicator would be valid for the DIVI, although it should be noted that many LU vary in the importance of their level of fragmentation depending on whether they are analysed with the IFI or the DIVI. This change does not always go in the same direction, although it seems that there is a tendency towards a greater measure of the fragmentation of an LU using the DIVI than using the IFI.

Based on the analysis of the results, it can be concluded that it is the combination of all indicators that allows for the identification of the shortcomings and strengths of the LU analysed and, consequently, assessment of the effectiveness of the design of the LU and the need for improvement.

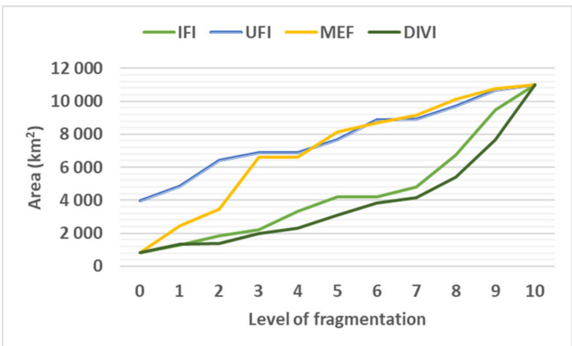
To study the relative behaviour of each of the metrics in the two protection figures analysed, Figure 9 shows the fragmentation results obtained in this study by means of a cumulative representation. The results of the four indicators for the number of SPAs (Figure 9a) and SACs (Figure 9b), and for the surface area of SPAs (Figure 9c) and SACs (Figure 9d), are plotted. For this purpose, the representation ranges used in Figures 7 and 8, from the lowest (0—not fragmented) to the highest level (10) of fragmentation, have been applied. The analysis includes 71 landscape units with SPA protection (total area of 11,016 km^2) and 89 landscape units with SAC protection (total area of 9332 km^2).



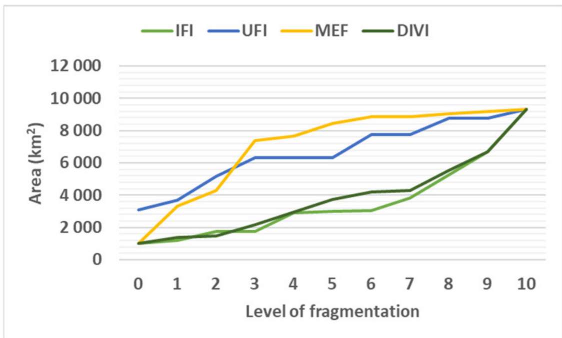
(**a**)



(**b**)



(**c**)



(**d**)

Figure 9. Cumulative representation of total number of LU and total LU surface area ordered from 0 (not fragmented) and 1 to 10 from lowest to highest level of fragmentation: SPAs (**a**,**c**) and SACs (**b**,**d**).

As shown below, each protection figure and each of these two approaches (by LU units or by LU surface) allow for a different analysis of the state of fragmentation of the LU.

Given their importance, attention is focused firstly on the LU that the indicators employed report as non-fragmented. To make this analysis easier, Table 6 shows the number, surface area involved and proportions with respect to the total values of the non-fragmented LU. If the number of LU is first considered, the most remarkable feature is the high number of non-fragmented units which, at the lowest result, represent more than 63% of the LU in the region analysed. Differences can be observed between the results in SPAs and SACs, SACs being the ones with the highest number and proportion of non-fragmented surfaces. If the indicators are examined, it is the UFI indicator, which measures the effect of fragmentation caused by urban areas, that shows the highest proportion of non-fragmented LU, reaching more than 87% in the case of SACs. In some ways, these results can be interpreted as a measure of the quality of the design of the LU analysed individually; more in the case of SACs than SPAs. If this analysis is carried out in relation to the protected surface area, the results are not of equal quality and some changes occur when comparing SPAs and SACs. The non-fragmented surface area is slightly higher than 36% in the best case and only close to 8% in the worst case. Furthermore, although the values obtained using the UFI indicator are still higher, also in terms of surface area, the non-fragmented surface area measured in the SPAs using the UFI indicator is higher than that measured in the SACs. In summary, if their function of management and protection of the territory is studied, the analysis of the non-fragmented LU indicates that the design of a significant part of them has been adequate, although when considering the general design of the total protected area, the results are not so good. Regarding the design of natural areas according to the type of protection, a better design is observed for the SACs.

Table 6. Results for the number and surface area of non-fragmented landscape units.

	LU Not Fragmented	% Relative to Total LU	Area Covered LU Not Fragmented (km^2)	% Relative to Total Area
		SPAs		
IFI, M_{eff}, DIVI	45	63.38%	845	7.67%
UFI	58	81.69%	3995	36.26%
		SACs		
IFI, M_{eff}, DIVI	71	79.78%	1027	11.00%
UFI	78	87.64%	3084	33.05%

The results are discussed below as the level of fragmentation increases. Firstly, an analysis is made of what happens in relation to the number of LU involved. It can be observed that, in both protection categories (Figure 9a,b), all the metrics used show a monotonically increasing trend as the level of fragmentation increases, or close to a linear behaviour. The slope of growth of the UFI is lower than that of the other three indicators, given that the number of non-fragmented units according to this indicator is higher. In addition, the growth is relatively similar among them, although with some difference in what happens in SPAs and SACs. It is observed that, in the case of SACs, the M_{eff} and DIVI indicators are close to the result of the UFI indicator in medium ranges of fragmentation, around value 5.

If the analysis of growth trends based on the surface area of the LU is now considered, basically three different behaviours can be observed, which are similar in the SPA and SAC areas. On the one hand, the UFI shows a linear trend in the relationship between fragmentation level and fragmented area. This indicator starts at higher values of non-fragmented area than the other indicators and shows an increasing monotonic variation as increasing fragmentation ranges are considered. Of the other three indicators, the M_{eff} shows a quick rise in accumulated area at low degrees of fragmentation and, subsequently, presents a monotonic growth. It is observed that, from rank 3 onwards, the UFI and M_{eff} curves accumulate similar surface areas in the case of SPAs, while in the case of SACs, the M_{eff} shows a linear trend similar to the UFI but accumulating higher surface area values. Consequently, the M_{eff} reflects the same or lower level of fragmentation than the UFI from rank 3 onwards when the surface area involved is considered. If the growth of the surface area is analysed for the IFI and DIVI indicators, a similar behaviour is observed, with a slow and monotonous growth of the accumulated surface area that is maintained until high fragmentation ranges are reached (rank 7). From this range onwards, there is a fast increase in surface area.

4. Conclusions

The present study assessed the fragmentation degree of the landscape units of the Natura 2000 network in the European region of Extremadura. A separate analysis has been carried out for two typologies of protection of the Natura 2000 network, Special Bird Protection Areas (SPAs), and Special Areas of Conservation (SACs). For this purpose, the IFI, UFI, M_{eff} and DIVI fragmentation indices were used.

As different expressions are proposed in the scientific literature to calculate IFI and UFI fragmentation indices, a comparative analysis was carried out for the expressions of each index. For IFI, non-uniform results were found and, in the case of SPAs, the equivalence between expressions was only 45%. For this reason, the equation that considers a greater variety of factors associated with habitat fragmentation due to linear infrastructure was selected for IFI calculation in this research. For the UFI, the two proposed equations in the literature for assessing the fragmentation of the territory are related, but the equation that takes into account a specific detail of urban configuration was considered the most suitable for calculating the UFI in this study.

As a consequence of the comparison made between the results obtained for the indicators IFI, UFI, M_{eff} and DIVI, it can be concluded that those indicators which measure the fragmentation of the territory as a consequence of linear infrastructures (IFI, M_{eff} and DIVI), although they consider the same causes, are evaluating different consequences that road transport has on the territory. It can also be concluded that the expressions proposed for the indicators which measure the fragmentation of LU originated by road infrastructures (IFI, M_{eff} and DIVI) evaluate different causes and consequences in the territory than the indicator proposed for the measurement of fragmentation originated by urban settlements (UFI). As a general conclusion for the analysis of all indicators used, it can be stated that each of the indicators identifies shortcomings and strengths of LU of a different nature, so that a combination of these is necessary to assess the effectiveness of the design of the landscape units and needs for improvement.

Considering each of the two protection categories of the Natura 2000 network (SPAs and SACs) and each of the two approaches proposed to study the landscape units (by number of LU or by LU surface), different analyses of the state of fragmentation can be carried out. If the number of LU is first taken into account, a high number of non-fragmented LU was found (>63%) and the UFI was the indicator with the highest proportion of non-fragmented LU (>87% for SACs). However, when the analysis is performed under the LU surface criterion, the non-fragmented surface of the studied area ranges between approximately 8% and 36%, depending on the case. In summary, the design of a significant number of LU seems to be adequate, although when considering the general design of the total protected area, the results were not so good. Regarding the design of natural areas according to the type of protection, a better design is observed for the SACs. When analysing what happens in terms of the number of LU units and LU surface as the level of fragmentation increases, the results obtained for the Natura 2000 protected areas in Extremadura show a general increasing trend for the indicators IFI, UFI, M_{eff} and DIVI, although with some differences in the slope depending on the type of protected areas (SPAs and SACs) and the criterion applied (by LU units or by LU surface).

The differences found based on the criteria for studying the state of fragmentation, the metrics used and the environmental protection figure for LU make the definition of the state of fragmentation of an environmental area a complex process, which must be approached from multiple points of view in order to obtain a rigorous result. Consequently, the combination of metrics and approaches carried out in this study can be a comprehensive method for the analysis of territorial fragmentation due to road infrastructures. This analysis could provide the administration and other potential stakeholders with a tool to guide decision-making on territory and road infrastructure management and new approaches to the organisation of the Natura 2000 network.

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