



## Original Articles

# Relationships between amount and configuration indicators in real-world landscapes: Novel references for the assessment of forest cover in the Iberian Peninsula

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## ABSTRACT

Understanding the role of habitat loss and fragmentation per se is crucial to generate relevant knowledge for habitat management. In the case of forest species, this can be achieved by measuring forest amount and configuration metrics at the landscape scale, including their relationship. We aimed to characterize the relationship between forest amount and configuration metrics in real-world landscapes of an extensive area, identifying forest amount thresholds that discriminate among forest fragmentation levels. We also investigated whether ecological and political contexts could affect the strength of the relationship. We comprehensively analyzed forest cover in the Iberian Peninsula (20.56 million ha, year 2,018). We calculated Forest Area Density (FAD) and three configuration metrics by employing a moving-window procedure. From metrics' surfaces we derived bivariate probability-density scatterplots, a synoptic Fragmentation Level indicator (FL) and subsequent classification and correlation analyses. For Number of Patches and Edge Density (ED) maximum values and variability appeared at FAD 20% and 50%, respectively. The extreme FAD thresholds relative to FL were 89% and 55%, potentially representing fragmentation and extinction thresholds for a generic forest species. Major differences between Portugal and Spain were found in ED in the Mediterranean Ecoregions, being wildfire regimes and ownership patterns plausible explanations. We provide insights into the patterns of forest cover and metrics' references valuable to identify areas of concern for management and conservation in the region, as well as a foundation for further research on the ecological responses to forest fragmentation.

## 1. Introduction

Habitat loss and fragmentation are central components of habitat alteration, a landscape change process that refers to both components unified into a single interdependent process (Hadley and Betts, 2016). Within this framework, habitat loss, as the removal of habitat, results in changes in landscape composition, and habitat fragmentation, as the breaking apart of habitat, results in changes in landscape configuration (Hadley and Betts, 2016), which when considered independently of habitat loss give rise to the concept of fragmentation per se (sensu

Fahrig, 2003). These two components affect biological processes differently (Fahrig, 2003; Cushman et al., 2012; Lehtilä et al., 2020; Harsh et al., 2022; Moore et al., 2022), so the distinction between them is relevant.

Enumerating the mechanisms mediating the ecological effects of habitat fragmentation, Wilson et al. (2016) claimed that fragmentation derives from habitat loss and added a third separate mechanism to those directly attributable to each component of habitat alteration, the indirect or interaction effects arising from the interplay of habitat loss and changes in configuration, as it was previously shown by Didham et al.

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(2012). Moreover, it has been suggested that, when studying the ecological effects of habitat alteration, conflicting results may arise from the lack of consideration of this interdependence, even considering habitat loss as the primary driver in real-world landscapes (Püttker et al., 2020 and references therein). Contrasting perspectives do exist on the interdependence (or independence) of these different mechanisms and on the weight and role that they may play on the ecological effects of habitat alteration (see an attempt to reconcile them in Valente et al. (2023)). In any case, it can generally be assumed that habitat loss implies changes in habitat configuration and that both are intrinsically linked.

A practical way of measuring habitat loss intensity is by means of habitat amount. Villard and Metzger (2014) hypothesized that “a specific portion of the gradient in habitat amount will be characterized by the interaction of habitat amount and configuration effects on species persistence”. This portion is delimited at its lower and upper ends, respectively, by the “extinction threshold” (ET) and the “fragmentation threshold” (FT). Above the FT only habitat loss will matter for species persistence, and below the ET the species will hardly survive. Then, assuming a homogeneous matrix, habitat configuration will have a higher influence on species at intermediate values of habitat amount, where configuration has potentially the greatest variability (Villard and Metzger, 2014; Andrén, 1994; Fahrig, 2003). Furthermore, Hadley and Betts (2016) claimed that the ET for a given species will vary as a function of habitat configuration.

In general, the relationships among landscape metrics, and specifically those involving habitat amount, are of particular interest in habitat alteration analysis. Currently, it is acknowledged that landscape metrics must be interpreted considering the proportional abundance (relative habitat amount in the landscape) at which they are calculated (Gustafson, 2019). Moreover, the covariance of configuration metrics with habitat amount is a major challenge in fragmentation research (Villard and Metzger, 2014). A deep understanding of the behavior of landscape metrics, usually assessed under controlled conditions, is a prerequisite for proper ecological interpretation of landscape structure (Neel et al., 2004). In the case of the relationship between habitat amount and configuration, such controlled conditions have been deployed mostly through computer simulations and binary landscapes to derive empirical distributions of metrics (e.g., Gustafson and Parker, 1992; Villard et al., 1999; Rempel and Csillag, 2003; Neel et al., 2004; Long et al., 2010a; Wang et al., 2014; Villard and Metzger, 2014).

In her highly cited review, Fahrig (2003) generalized the relationships of habitat amount with five configuration metrics based on previous works from different authors. Importantly, that authors found non-linear relationships between habitat amount and configuration metrics. Püttker et al. (2020) stated that different biodiversity responses to habitat loss and fragmentation per se along the gradient of habitat amount could simply result from the non-linear relationships between metrics. Then, these relationships are of importance in the context of conservation planning. However, research based on data from real-world landscapes and large areas is scarce, although some exceptions from North America do exist (e.g., Neel et al., 2004; Long et al., 2010a; Pickell et al., 2016). To the best of our knowledge, no study has addressed comprehensively habitat amount and fragmentation relationships in the Iberian Peninsula (IP), southwestern Europe. Moreover, in this region it is still unknown whether typical habitat amount and configuration relationships (e.g., Fahrig, 2003) hold, and whether fragmentation patterns established upon computer simulations are equally frequent in these real-world landscapes.

The long history of landscape changes and ancient forest loss in the IP (Valbuena-Carabaña et al., 2010; Reboledo and Pais, 2014; Nunes et al., 2019b), together with its high biophysical and cultural heterogeneity, make this region especially interesting for studying forest cover pattern. Although recently forests have undergone considerable expansion (González-Ávila and Elena-Rosselló 2009; Gómez-Sanz et al., 2014; Oliveira et al., 2017; Bento-Gonçalves et al., 2018; Nunes et al., 2019c),

forest fragmentation patterns still exist in many areas (Forest Europe, 2020; Table 34A). These patterns might affect, for example, the use of forest fragments by medium-sized carnivores (Virgós et al., 2002), connectivity in networks of protected areas (De la Fuente et al., 2018), or conservation planning to address climate and landscape change in the future (Cánibe et al., 2022).

Pickell et al. (2016) highlighted the potential of currently available forest cover maps, derived from satellite imagery and consistent across extensive areas, to understand how patterns of landscape structure vary spatially. We took this opportunity and conducted a mensurative study (McGarigal and Cushman, 2002; Hadley and Betts, 2016) in a large and contiguous area, the IP, to investigate the relationship between forest amount and configuration metrics in real-world landscapes. Our objective was to provide novel statistical and spatial references for the assessment of forest cover pattern in the IP. Specifically, we aimed to i) characterize the forest amount-configuration relationship, and ii) identify forest amount thresholds that discriminate among forest fragmentation levels as measured by configuration metrics. In addition, we intended to explore potential underlying drivers of forest cover pattern (i.e., its variability) within the study area, so we also aimed to iii) investigate whether ecological and political contexts affect the strength of the forest amount-configuration relationship. Our findings offer crucial context for forest and conservation planning and are a prerequisite for further correlating patterns and processes.

## 2. Methods

In this study we followed the workflow outlined in Fig. 1. Based on a forest cover layer, we computed one landscape metric related to composition and three to configuration. The calculations applied a moving-window procedure which resulted in the creation of a raster surface for each metric, thus deploying a gradient-based approach (gradient attributes of categorical patterns (Cushman et al., 2010)). Ecological Regions and countries were further used as factors for analyses of the strength of the amount-configuration relationships.

### 2.1. Study area

Our analysis was conducted in the Iberian Peninsula (IP), covering two countries, Portugal and Spain (Fig. 2). The IP is located in south-western Europe and displays diverse environmental conditions. Most areas have a Mediterranean climate characterized by hot, dry summers and mild, wet winters. In the north and north-west regions, the Atlantic influence leads to higher rainfall and milder temperatures compared to the southern regions. The lithology is also varied, existing not only different acidic rocks but also calcareous substrates, particularly in the eastern half. The IP is home to eight Ecological Regions (ERs) (Fig. 2), mostly dominated by sclerophyllous vegetation, typical from Mediterranean climate regions. However, there are also other types of vegetation classes such as forests, scrublands and grasslands. Forestland in the study area covers approximately 20.56 million hectares (15.3 % in Portugal and 84.7 % in Spain), according to the data here produced. Holm oak (*Quercus ilex*) is the dominant tree species in the study area. Other prominent species are the broadleaved *Quercus suber*, *Q. pyrenaica* and *Q. faginea*, as well as various pine species, such as the more thermophilic *Pinus halepensis* and *P. pinea*, and the more montane *P. nigra* and *P. sylvestris*. The dominant tree species in managed plantations are *Pinus pinaster*, *Eucalyptus sp.*, and *P. radiata*, particularly across the northern and western regions of the IP.

### 2.2. Data sources and pre-processing

We used two primary data sources: TCD2018, a raster layer representing the Tree Cover Density in the year 2018, obtained from the Copernicus Land Monitoring Service (CLMS, <https://land.copernicus.eu>), and the Digital Map of European Ecological Regions (DMEER),

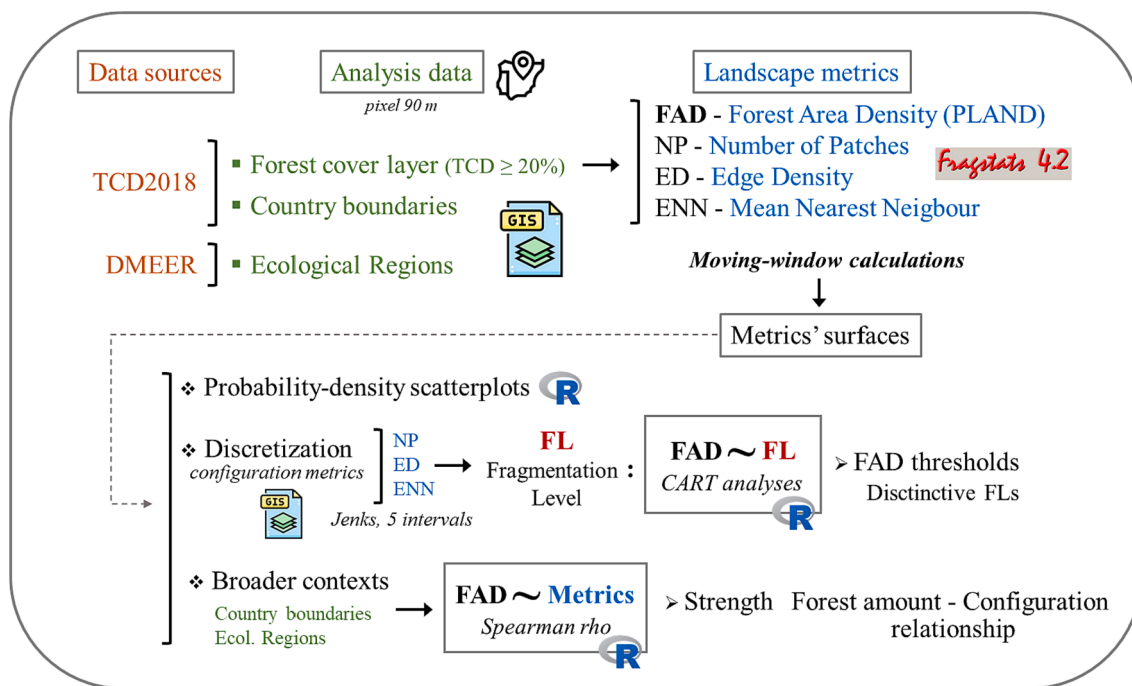


Fig. 1. Schematic flow-chart of the methodology followed in this study. TCD2018: Tree Cover Density layer in the year 2018 (source: Copernicus Land Monitoring Service, see link in the text); DMEER: Digital Map of European Ecological Regions (source: EEA, see link in the text).

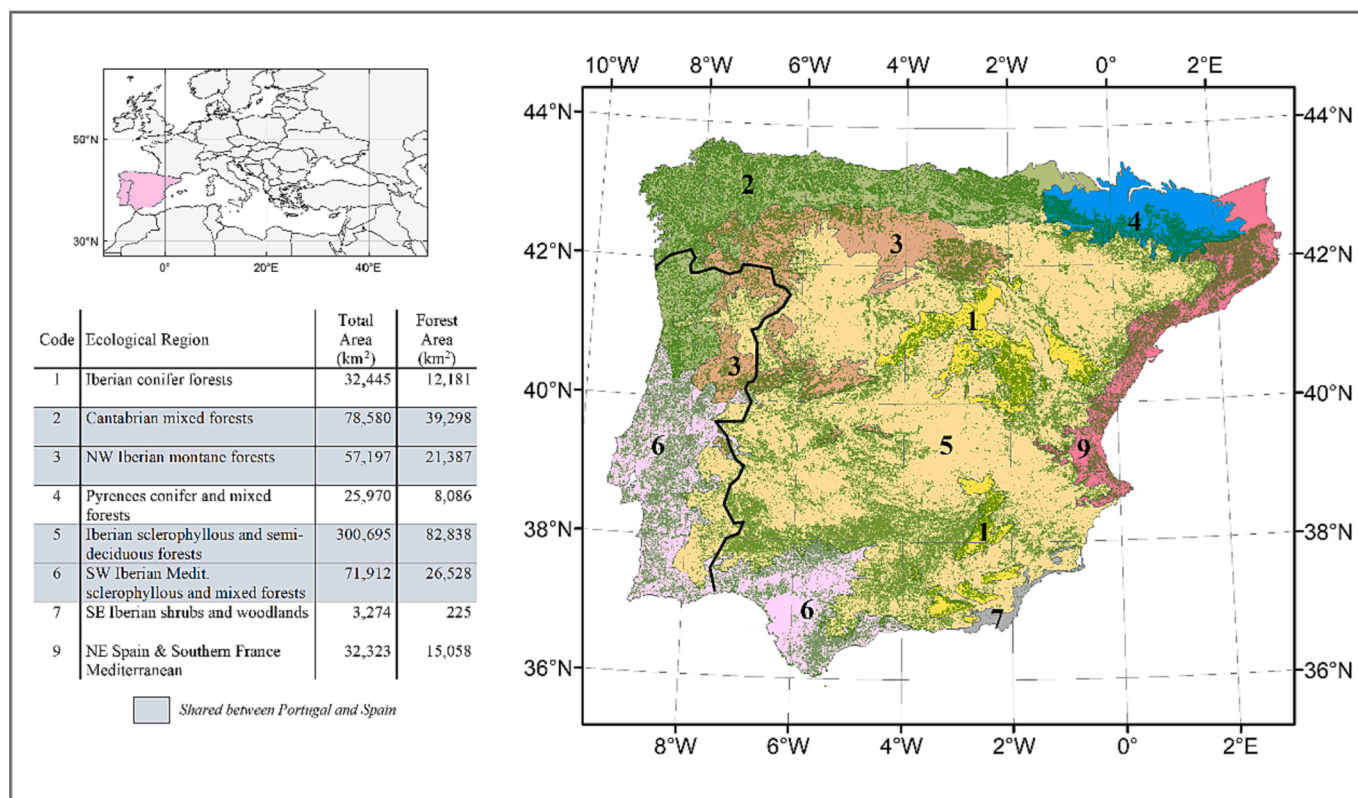


Fig. 2. Study area and Ecological Regions within the Iberian Peninsula, sourced from the Digital Map of European Ecological Regions (DMEER, see link in the text). The forestland analyzed is superimposed in green (source: TCD2018, see link in the text). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

sourced from the European Environment Agency (EEA, <https://www.eea.europa.eu/data-and-maps/data/digital-map-of-european-ecological-regions>). TCD2018 provides data on the proportional crown coverage

at 10-m spatial resolution, ranging from 0 % (no tree cover) to 100 % (complete tree cover). This layer is homogeneous throughout the EU, thus suitable for studying contemporary forests condition in areas

covering more than one country. We downloaded the National Projection Products (<https://land.copernicus.eu/looking-for-national-products>) and reprojected the Portuguese layer to the coordinate system of the Spanish one (ETRS 1989 UTM Zone 30 N). To identify forest pixels, we established a 20 % TCD threshold based on the Spanish National Forest Inventory's definition of (dense) 'forest' land use class (Alberdi et al., 2016), which is more restrictive than the Portuguese definition that uses a threshold of 10 % (Tomé et al., 2016). Moreover, this threshold is the same used to identify the 'forest' land use and land cover class in the Spanish landscape monitoring system SISPADES (González-Ávila and Elena-Rosselló 2009; Gómez-Sanz et al., 2014).

We primarily followed a pattern-oriented approach (Fischer and Lindenmayer, 2007), focusing more on the broader landscape pattern. A species-oriented approach was also partially adopted by considering forest cover as a proxy for habitat of a generic forest species, which is akin to the generic focal species shown in Watts et al. (2010). Consequently, a binary 'forest/non-forest' layer was produced by resampling the 10-m TCD2018 layer to 90-m, using the TCD mean value and retaining as forestland those 90-m pixels with mean TCD  $\geq$  20 %. The 90-m resolution was adopted to produce a tractable dataset in computational terms (we obtained circa 25 million of forest pixels). In addition, this resolution is a multiple of both the original TCD dataset (10-m) and the previous Landsat products (30-m) used in many large-scale landscape analyses (e.g., Lindquist and D'Annunzio, 2016; Xie et al., 2019; Shafizadeh-Moghadam et al., 2021) which allows for correct alignment of datasets and results for aggregation if required.

The ecological context of forest pixels was obtained by means of the DMEER (Fig. 2), which delineates and describes distinct ecological areas in Europe on the basis of climatic, topographic and geobotanical data, together with expert judgement. Then, this map displays areas with relatively homogeneous ecological conditions at a scale of 1:2,500,000, enabling comparisons and assessment of biodiversity. In the IP, the DMEER includes eight Ecological Regions (ERs), four of which are only present in Spain (Fig. 2).

### 2.3. Forest amount and configuration metrics

We selected three widely-used landscape metrics directly linked to the effects of fragmentation per se on habitat configuration: Number of Patches (NP) to measure subdivision of forest patches, Edge Density (ED) to account for extent of edge effects, and mean Euclidean Nearest Neighbor (ENN) as indicator of isolation. For forest amount, the compositional aspect of landscape structure, we considered Forest Area Density (FAD) at a fixed observation scale (Riitters et al., 2002; Vogt et al., 2019).

Instead of analyzing the global landscape pattern in the study area, we exhaustively analyzed the landscape surrounding every forest pixel, quantifying the local landscape pattern as it may be perceived by an organism of interest (Cushman et al., 2010), a generic forest species in our case. For this, we set the size of the local landscapes at 81 x 81 pixels (7,290 x 7,290 m or 5,314.41 ha). From the point of view of faunal species, this landscape size is large enough to accommodate the home range of most Iberian mammals that use resources from forests, such as medium-sized carnivorans (e.g., *Martes martes*, *Martes foina*, *Meles meles*) and felids (*Felis silvestris*, *Lynx pardinus*) (see Kelt and Van Vuren (2015) for home range references; the species mentioned above from circa 220 to 950 ha). In light of the preceding, we deemed relevant this landscape extent, although being aware that for the kind of species previously mentioned this size may include not only home territory but also nearby dispersal areas. In this respect, Estavillo et al. (2013) noted that ecological thresholds for organisms larger than small mammals may be apparent only when considering landscapes larger than the 3,600-ha landscapes they studied. In addition, the landscape size we selected was found as the most appropriate to distinguish multiscale FAD profiles by forest types in Spain (González-Ávila et al., 2023), thus suitable to consider variability in forest cover pattern.

The four landscape metrics were calculated by means of Fragstats 4.2.1 (64 bits version) (McGarigal and Marks, 1995). FAD was obtained through the PLAND metric (relative abundance, in percentage, of a given landscape class). In this case, PLAND is analogous to FAD at a fixed observation scale as we treated 'non-forest' pixels in the forest cover layer as 'non-fragmenting'. We applied the moving-window procedure at the class level, using a binary raster layer (1-forest; 0-non-forest) without missing data nor background class (i.e., the window moves from a forest pixel to another forest pixel). This procedure allows mapping forest pattern attribute surfaces (see Cushman et al., 2010) for each individual metric, which provide a comprehensive view of local forest conditions that can be combined with other variables.

Finally, the four metrics' surfaces were stacked in RStudio 2022.121.0 software. To analyze the bivariate relationships between FAD and the configuration layers (NP, ED and ENN), probability-density scatterplots were generated from random samples of two million pixels (seed 1234) utilizing the ggdensity v0.1.1 package (Otto and Kahle, 2023).

### 2.4. Thresholding and forestland general contexts

We adopted a synthetic forest fragmentation assessment approach, resembling Ma et al. (2023), thus assuming that the effects of habitat fragmentation on biodiversity (e.g., on the persistence of forest-dwelling species) derive from the partial effects of the different configurational aspects we measured. Consequently, we considered that a synoptic indicator of total fragmentation can be obtained by summing the effects of the different configuration aspects, so the same fragmentation level can be achieved by different combinations of configuration attributes. Accordingly, we constructed an ordinal fragmentation variable (Fragmentation Level: FL) with five levels. To calculate FL, we first categorized the three configuration metrics surfaces (NP, ED and ENN) applying in ArcGIS software a natural breaks classification (Jenks) with five intervals, and reclassified these layers assigning discrete values from one (lowest fragmentation level) to five (highest fragmentation level). Then, we combined the three reclassified layers by summing their values to obtain the final FL map with values potentially ranging from 3 to 15, which in turn we reclassified as follows: 1-Low fragmentation (sum = 3); 2-Mid-low fragmentation (sum = 4–6); 3-Medium (sum = 7–9); 4-Mid-high (sum = 10–12); and 5-High (sum = 13–15).

To identify distinctive levels of fragmentation in relation to forest amount we used classification thresholds. These correspond to values of explanatory variables that divide the response variable into two relatively homogeneous groups (Toms and Villard, 2015). We applied a Classification and Regression Tree (CART) (Breiman et al., 1984), as suggested by Toms and Villard (2015), with FL as response variable and FAD as predictor. The expected non-linear relationships between forest amount and configuration metrics, together with the combined use of categorical and continuous variables, make the CART method especially suitable for our study. To fit the CART model, we used data from all the forest pixels of the IP (circa 25 million) and the rpart v4.1.16 package in R, using as impurity measure the Gini index and a maximum depth of four levels (all other parameters set to default). We developed a 'regression' model, considering FL as a continuous variable (method = "anova") and further created a map of the forestland based on the FAD thresholds obtained.

To test whether the relationship between composition and configuration metrics was affected by the ecological context, we calculated the Spearman rank correlation coefficient ( $\rho$ ) between FAD and each configuration metric by Ecological Region (ER). The Spearman coefficient measures how well the relationship between two variables could be represented using a monotonic function, so it is used when non-linear relationships are under analysis. Significant differences in  $\rho$  between ERs indicate different fragmentation patterns likely driven by different sets of processes. We repeated this procedure at the country level and finally analyzed the interaction of both variables calculating  $\rho$  values,

by country, in the four ERs shared between Portugal and Spain. The rho calculations were made with the rcorr function from the R-package Hmisc v4.6.0 using the whole dataset.

### 3. Results

Maximum Number of Patches (NP) and highest variability were observed for FAD around 20 % (Fig. 3a). Beyond this point along the FAD gradient, the domain of NP values gradually decreased (right-skewed distribution). The HDR50 (Highest Density Region 50; region in the scatterplot computed to be the smallest region that bounds 50 % of the probability-density (Otto and Kahle (2023); yellow areas in Fig. 3) exhibited a distinctive linear-like trend within the FAD range above 46 % (NP range from 1 to 56 patches; Fig. 4).

In the case of Edge Density (ED), data projection onto the plane 'density = 0' showed a symmetric parabolic distribution (Fig. 3b). The highest value of ED (~70 m/ha) and maximum variability were observed near FAD 50 %. At this FAD value, a greater part of the data was included within the HDR80, with ED ranging from 27 to 52 m/ha. The HDR50 region (Fig. 3b, in yellow) was observed for FAD above 33 % and ED ranging from 8 to 49 m/ha (Fig. 4). Notably, ED displayed a nearly proportional decrease in the HDR50 for FAD values exceeding 60 %.

An inverted sigmoid-like curve, highly horizontal, was found for FAD and mean Euclidean Nearest Neighbor (ENN) onto the plane 'density = 0'. The range of ENN values for a given FAD maintained primarily below 800 m (Fig. 3c), although variability was higher for ENN at FAD ranges 1–6 % and 60–80 %. The HDR50 was observed within the 38–70 % FAD range, with ENN values mainly in the range 200–300 m. However, landscapes with a single forest patch, here depicted as ENN = 0, displayed a secondary peak within the HDR50, corresponding to higher

	HDR50 ●	HDR80 ●
NP	1 - 56	1 - 92
FAD	46 - 98	23 - 100
ED (m/ha)	8 - 49	6 - 52
FAD	33 - 96	5 - 98
ENN (m)	200 - 300	200 - 300
FAD	38 - 70	17 - 86
FAD (%)	0 100	0 100

Fig. 4. Minimum and maximum values of metrics (NP: Number of Patches, ED: Edge Density, ENN: Mean Euclidean Nearest Neighbor) for Highest Density Regions HDR50 and HDR80. Green striped horizontal bars depict the corresponding FAD ranges within the total forest amount gradient (0 to 100%). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

FAD values in the range of 92 % to 97 %.

The green striped bars in Fig. 4 show the FAD range where the corresponding HDR do occur, allowing to identify the overlying FAD ranges of the metrics' HDRs: 46–70 % for HDR50, and 23–86 % for HDR80. The dataset of HDR80 presents at the central FAD value of the overlying range (i.e., 55 %) the following metrics' ranges: NP: 16–60 patches; ED: 26–52 m/ha; ENN: 200–300 m, which may serve as central references around which most of the forest landscapes occur.

Regarding the synthetic Fragmentation Level (FL) index, no landscape in the Iberian Peninsula (IP) reached the potential maximum level 5 (FL 5). This implies that none of the analyzed landscapes exhibited

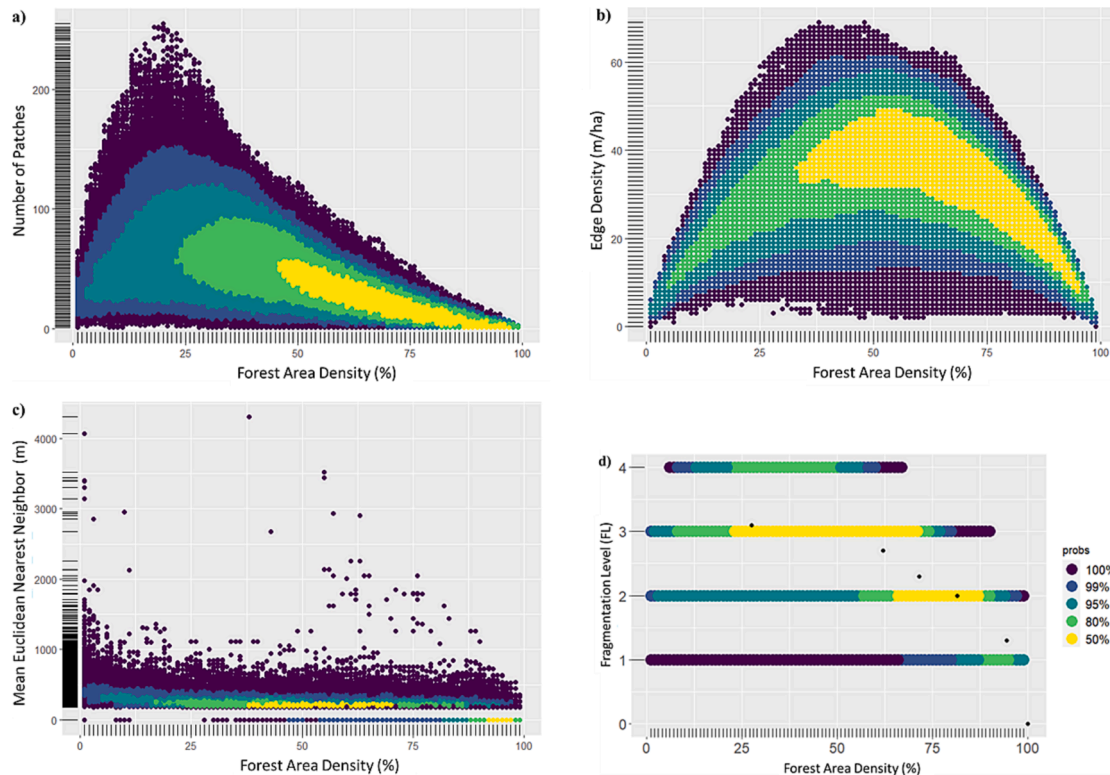


Fig. 3. Probability-density scatterplots illustrating the joint distribution of Forest Area Density (FAD) and configuration metrics. Number of Patches (a), Edge Density (b) and Mean Euclidean Nearest Neighbor (c), and Fragmentation Level - FL (d). In chart d, black dots represent the mean FAD values and their corresponding assigned FL values, obtained from the CART analysis with FL as response and continuous variable (refer to Fig. 5). Colors indicate the probability bounded by the corresponding regions, being the regions computed to be the smallest such regions that bound that level of probability, known as highest density regions or HDRs (Otto & Kahle, 2023).

simultaneously the highest values of the three configuration metrics. FL level 4 was the highest observed, covering a range of FAD from about 5 % to 70 % (Fig. 3d), while FL level 3 ranged from 1 % to 92 %, and the other two FL levels (corresponding to the least fragmented forests) were observed across the entire domain of FAD (1 % to 100 %). Despite covering FAD values ranging from 23 % to 89 %, the HDR50 was exclusively distributed between FLs 2 and 3, within two distinct and nearly non-overlapping intervals. Looking at the HDR80, density of observations showed greater concentration in FLs 3 and 4, at smaller FAD values than in FLs 1 and 2. We found maximum variability (observations in all four levels) and relatively high probability-densities in the 23–50 % FAD interval. In contrast, the less fragmented levels (1 and 2) showed maximum probability-densities skewed towards the right, with FAD values ranging from 52 % to 98 %. The FAD range 86–98 %, which corresponded to the highest probability-density in FL 1, exhibited the least variability among the different FLs. Notably, data within this range did not occur in FL 3 and 4, indicating an expected distinct pattern where forests with higher FAD values are less susceptible to fragmentation.

The most fragmented forests (FL 4) were concentrated in specific regions of the study area, mainly in the north of Portugal. In Spain, the most fragmented forests were located along the Mediterranean coast and areas surrounding the main mountain ranges (Fig. 6b). Contrarily, the least fragmented forest landscapes were found in mountain areas, in particular in the Pyrenees, Sierra Morena, Catalan Coastal, Betic and Iberian chains in Spain. In Portugal, the least fragmented forest areas (FL 2) were found only in few areas in the center of the country (Fig. 6b).

The forest amount gradient is divided into FAD ranges according to the thresholds obtained in the terminal nodes of the CART ‘regression’ model (Fig. 5). This model assigned an average FL value to each FAD range, which showed clear opposite trends. The first split of the data was found at FAD = 69 %. In the second level of the tree, splits were found at

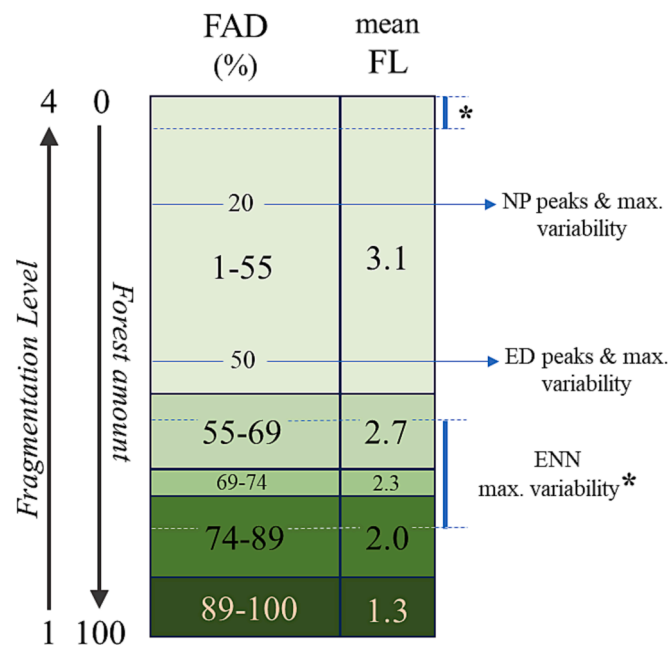


Fig. 5. Forest Area Density (FAD) ranges derived from the Classification and Regression Tree (CART) thresholds. Green color ramp follows the forest amount gradient (darker indicates higher forest amount). The CART model considered Fragmentation Level (FL) as continuous response variable, and FAD as predictor. The values in the FL column are the predicted mean FL for the corresponding FAD range. Note that FL and FAD display opposite trends. The total number of pixels analyzed was about 25.3 million. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

FAD 55 % and 89 %, and in the third only at FAD = 74 %. The longest FAD range was 1–55 %, which corresponded to the most fragmented forests (FL = 3.1). In this range the maximum values of NP and ED were attained, coinciding also with the greatest amplitudes of these metrics’ values. In the opposite side of the forest amount gradient, the FAD range 89–100 % corresponded to the smallest FL value. The general relationship between FAD and mean FL is also shown in Fig. 3d (see black dots pattern). The geographic distribution of the main FAD ranges in relation to FL is presented in Fig. 6a, being their proportional abundances in the study area 48 % for FAD range 1–55 %, 47 % for FAD range 56–88 %, and 5 % for FAD ≥ 89 %.

In terms of the strength of relationships according to ecological and political contexts, rho values consistently indicated negative correlations between forest amount and configuration metrics (Fig. 7a). NP exhibited high negative values across all ERs (-0.65 or lower), except for ER7 (semi-desertic area in the SE of the IP). In this area of low forest cover, NP values deviated from the overall pattern. ED showed negative and similarly low rho values in ERs 1, 2, 3, and 4, and considerably higher values in ER 9. In contrast, ED showed positive correlations with FAD in ER 7 (very strong) and ER 5. For ENN correlation was moderate (around -0.60 in ERs 1, 5, 6, 7, and 9) and slightly lower in the more mountainous ERs 2, 3, and 4.

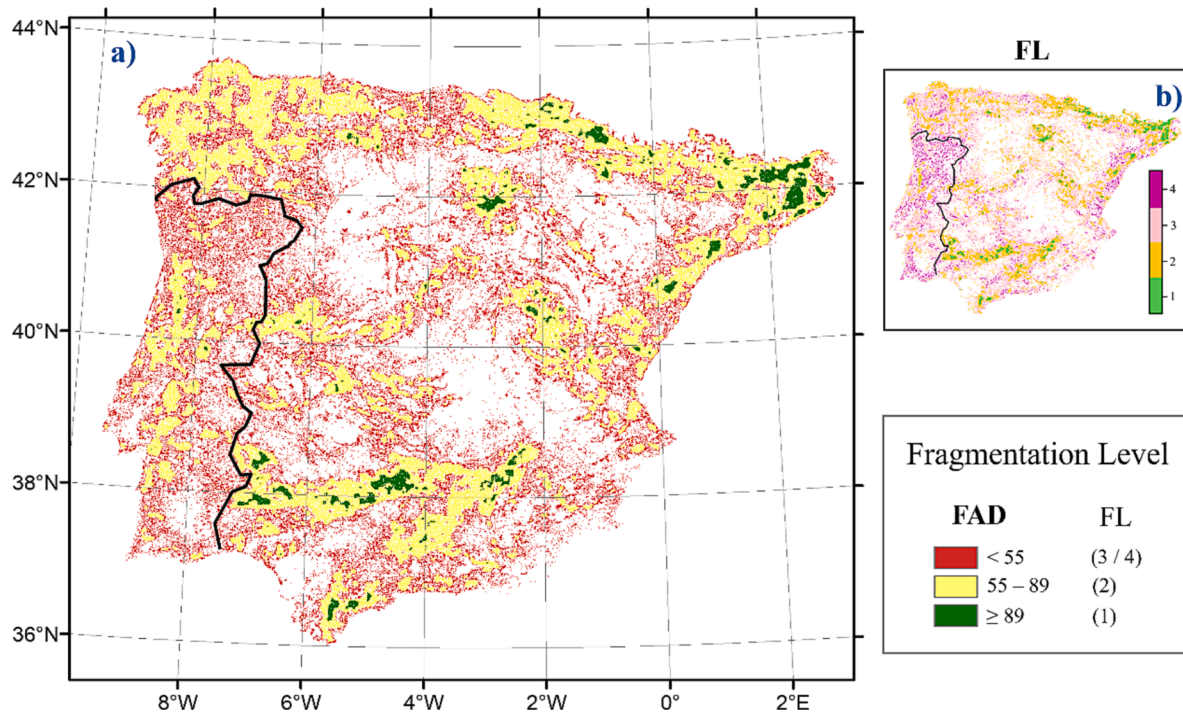
At the country level, the correlations of FAD were negative and similar with NP and ENN, but showed different sign for ED (negative in Spain and positive in Portugal; Table 1), suggesting a higher prevalence of smaller forest patches in Spain or more complex patch shapes in Portugal. The most pronounced differences between the two countries in terms of ED were observed in the ERs 3, 5 and 6 (Fig. 7), mostly located in the Mediterranean climate zone. In contrast, ER 2, primarily located in the Eurosiberian zone of the IP, exhibited comparable rho values between the two countries.

#### 4. Discussion

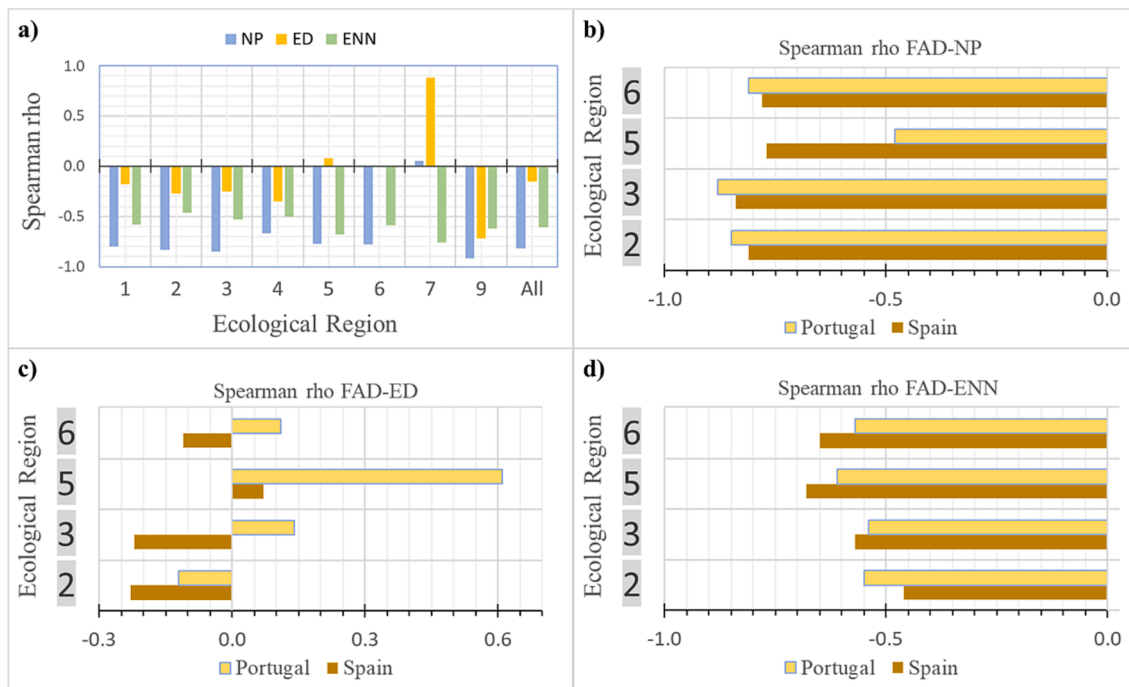
##### 4.1. Forest amount-configuration relationship in Iberian forests

The shape of the relationships between forest amount and configuration metrics, in the plane ‘density = 0’ (Fig. 3: a, b, c), is in line with the findings reported in previous work (Table 2), including the typical relationships outlined by Fahrig (2003). Most of these studies produced scatterplots and empirical distributions from simulated landscape data. Some studies included data from real-world samples (North America) for comparison and assessment of simulated empirical distributions. Here, we analyzed a Mediterranean study area, substantially different from those covered in the literature. Compared to simulated landscapes, we found in real-world Iberian forest landscapes higher variability in the distributions of the metrics (see examples in Long et al., (2010a) and Pickell et al. (2016)). We also found differences in NP (a single peak in the plane ‘density = 0’) in relation to results reported previously by Remmel and Csillag (2003) who documented a bimodal distribution of NP. Aside from this discrepancy, our results from real-world landscapes validate the methodologies employed for reproducing the behavior of metrics in the studies we revised, including forest patterns in our study area. However, given their nature, most of these studies were unable to provide metrics’ ranges for real-world landscapes. This is an important achievement of our research since it provides significant references for conservation planning of forest landscapes.

By depicting the HDRs in the scatterplots (Fig. 3), we identified combinations of forest amount and configuration metrics jointly achieving a given actual level of occurrence. For example, the HDR80 identified a majority (80 %) of actual forest landscapes upholding relatively low differences in terms of cover pattern, which may aid in narrowing management situations to analyze. Based on HDR80, we provide as general references for current Iberian forests condition FAD: 23–86 %, NP: 16–60; ED: 26–52 m/ha, and ENN: 200–300 m. These references may serve as a starting point to the deployment of a coarse-



**Fig. 6.** a) Classification of the Iberian Peninsula based on thresholds of Forest Area Density (FAD) obtained using the CART regression model, with Fragmentation Level (FL) as the response variable (the FL values assigned to each FAD interval are indicated in parentheses). Inset b) Geographic distribution of FL in the Iberian Peninsula, where lower values indicate lower fragmentation.



**Fig. 7.** Spearman's rho between forest amount, measured by Forest Area Density (FAD), and configuration metrics (NP: Number of Patches; ED: Edge Density; ENN: mean Euclidean Nearest Neighbor) by Ecological Region and for the entire Iberian Peninsula ("All") (a), and by Ecological Region and country ((b) (c) and (d), for NP, ED and ENN, respectively). Ecological Regions; 1: Iberian conifer forests, 2: Cantabrian mixed forests, 3: NW Iberian montane forests, 4: Pyrenees conifer and mixed forests, 5: Iberian sclerophyllous and semi-deciduous forests, 6: SW Iberian Mediterranean sclerophyllous and mixed forests, 7: SE Iberian shrubs and woodlands, 9: NE Spain & Southern France Mediterranean.

filter approach (Lemelin and Darveau, 2006) in forest planning at large scale. As far as we are aware, there is no data at the landscape scale relating species occurrence or abundance to the interplay of forest amount and configuration in the IP. For this reason, the specific

implications of these references for biodiversity merit further work, including field surveys similar to those in Estavillo et al. (2013). In the meantime, we postulate our references based on comprehensive actual forest cover pattern as a proxy.

**Table 1**

Global Spearman rho by country for the relationship of forest amount, as measured by Forest Area Density (FAD), and three configuration metrics (NP: Number of Patches; ED: Edge Density; ENN: mean Euclidean Nearest Neighbor).

Country	NP	ED	ENN
Spain	-0.82	-0.16	-0.63
Portugal	-0.79	0.18	-0.61
Iberian Peninsula	-0.82	-0.15	-0.61

**Table 2**

Comparison of our study with published studies conducted on the relationships between landscape class amount and configuration. “Yes” or “No” indicates whether a study found similar relationships to ours for the corresponding metric. NP, Number of Patches; ED, Edge Density; ENN, mean Euclidean Nearest Neighbor; nr: the metric was not reported. TE refers to Total Edge and PD to Patch Density.

Reference	Type of landscapes /Location	NP	ED	ENN
Gustafson and Parker, 1992	Simulated	Yes (partially)	nr	Yes
Andrén, 1994	Simulated	nr	nr	Yes
Saura and Martínez-Millán, 2000	Simulated	Yes	Yes (TE)	nr
Rommel and Csillag, 2003	Simulated	No	Yes	nr
Neel et al., 2004	Simulated, real / USA (3 different states)	Yes (PD)	Yes	nr
Long et al., 2010a	Simulated, real / BC, Canada	Yes	Yes	nr
Wang et al., 2014	Simulated, real / Alberta, Canada	Yes (PD)	Yes	nr
Villard and Metzger, 2014	Simulated	Yes	Yes	nr
Pickell et al., 2016	Real / Boreal zone, Canada	nr	Yes	nr

Villard and Metzger (2014) hypothesized that species persistence is affected by the interaction of habitat amount and configuration only between the ‘extinction threshold’ (Fahrig, 2003 and references therein) and the ‘fragmentation threshold’, defined in terms of habitat amount. Our CART model, based just on forest cover pattern, not on species presence, identified FAD = 89 % as the upper and FAD = 55 % as the lower thresholds. Assuming that distinctive ecological responses (e.g., different abundances of a certain guild of species, or different species richness) will occur at different levels of fragmentation (Püttker et al., 2020), the FAD ranges bounded by these thresholds represent distinct forest patterns which in turn may be linked to distinct biodiversity responses. It could be hypothesized that these lower and upper thresholds correspond to the extinction and fragmentation thresholds for a generic forest species. In that case, these threshold values fit a ‘type ii’ profile from Fig. 6 in Villard and Metzger (2014), which corresponds to species with high sensitivity to both forest amount and forest configuration. However, evidence from mammal species (Estavillo et al., 2013) and ecological theory (Andrén, 1994) suggest that the 55 % threshold is higher than expected for ET. Swift and Hannon (2010) stated that when thresholds (ET) were apparent, in the studies they reviewed, most were found within the 10–30 % range of habitat amount proposed by Andrén (1994). Therefore, the FAD threshold 55 % likely identifies a portion of the gradient amount (1–55 %) with a distinctive forest amount and configuration interaction, within which ETs for different species or guilds of species are expected to be found.

The FAD ranges where the maximum variability of configuration metrics was observed fell within the abovementioned FAD range 1–55 % (specifically around FAD = 20 % for NP, 50 % for ED, and 5 % for ENN). This finding matches the results of studies from Table 2. For example, Neel et al. (2004) found that NP peaked when the focal class comprised

15–30 % of the landscape, and Andrén (1994) that distance among patches increased exponentially around 10–20 % of remaining habitat. The high variability of configuration indices within this FAD range (1–55 %) may explain why the CART analysis did not identify additional thresholds, resulting in lower predictability of FL based on FAD compared to its complementary range (FAD 56–100 %) where three thresholds were identified. Also, it confirms that no single metric alone, from the long-standing Fragstats metrics, is capable of capturing all configuration aspects of fragmentation comprehensively. This supports the need to construct a composite fragmentation indicator that integrates different aspects of configuration, an approach proven successful in Ma et al. (2023). By summing up different configuration aspects, the FL index, here presented, provided a synoptic measure of fragmentation that consistently responded to variations in forest amount (Fig. 5).

Riitters (2019) stated that abundance of cover types and their aggregation are probably the two most important things to know about a landscape, and Gustafson (2019) emphasized habitat amount as a fundamental aspect of landscape pattern, which according to Fahrig (2013) matters more than configuration. Püttker et al. (2020) highlighted the hierarchical link between habitat amount and configuration. Our CART analysis showed the general, opposite, relationship between forest amount and fragmentation, finding more thresholds when FAD > 55 % (Fig. 5). Thus, being FL a synoptic configuration measure that revealed to be predictable, FAD has the potential to serve as a general measure of both forest amount and fragmentation, within that FAD range. This may aid in planning and management of Iberian forests under certain conditions, facilitating their assessment at broad landscape scales.

Interestingly, the FAD threshold 89 % aligns with the value used in the USA to define interior forests when assessing fragmentation at the national scale (Riitters et al., 2002; Riitters and Robertson, 2021). In the conterminous USA, interior forests accounted for 10.6 % of total forestland in 2006 (Riitters and Wickham, 2012), considering in the calculations a landscape size equivalent to ours, while in the IP they comprise approximately 4 % of the total forestland. Above the fragmentation threshold (here FAD = 89 %), species richness and abundance at the landscape scale are expected to be primarily driven by habitat amount. This can be the case of forest specialists in Iberian interior forests. Moreover, under the Habitat Amount Hypothesis (HAH) (Fahrig, 2013), considering forest pixels as habitat sample sites, it is also expected that the highest species richness at the site level is found in interior forest pixels, which exhibited the highest FAD values (see Saura, 2020), for a scale of effect around 3.6 km radius (half of the side of the square we used as landscape extent for FAD calculations).

#### 4.2. Possible drivers of the forest amount-configuration relationship

Portugal and Spain share general environmental conditions and species (see Nunes et al., 2020 and references therein), which are part of the underlying drivers of landscape change (natural factors sensu Bürgi et al. (2004)). However, these countries differ in terms of social underlying drivers (Bürgi et al., 2004), and also in terms of history, geographical extent and population. Plieninger et al. (2016) found that the key drivers of landscape change in Europe were distinct combinations of mainly political, cultural and natural underlying processes, which we encapsulated within the ERs and the country boundaries. Then, these contexts likely have influenced in different ways the forest patterns observed in 2018. The interaction, rather than single effects, of political and ecological context showed higher variability in the relationship between forest amount and configuration, as measured by Spearman’s rho. This reinforces that complex multifaceted mechanisms may be influencing this relationship in this particular European region. ED exhibited the most significant differences among regions and countries. In ERs 3 and 6, ED displayed positive sign in rho in Portugal and negative in Spain. In ER 5 it showed the same sign but markedly

different values. The most comparable rho values between the two countries were observed in ER 2, located in the Eurosiberian zone, as opposed to the Mediterranean ERs before mentioned, suggesting a marked role of climate in the interplay between forest pattern aspects.

Wildfires pose a significant concern for the management and long-term persistence of forests in the IP (Nunes et al., 2019a). For example, the extent of burned areas in 2017 in both Portugal (442,000 ha) and Spain (178,000 ha), accounting for approximately 14 % and 1 % of the respective forest areas in a single year, indicates a substantial impact of fires in forest landscapes (Nunes et al., 2020 and references therein). Therefore, we propose wildfires as a major proximate driver (i. e., a human activity at the local level, underpinned by the underlying drivers (Plieninger et al., 2016)) of forest fragmentation in the region. We speculate that differences in fire regime may potentially explain some of the observed variations in forest patterns in relation to edge density, a metric influenced by the frequency and type of forest fires. The geographic distribution of the most fragmented forests (FL 4, Fig. 6b) exhibited a remarkable concurrence with the forest types characteristic of the northern half of Portugal ("Open forests of pines, eucalypts, or other species", and others dominated by *Pinus pinaster* and *Eucalyptus sp.* (Nunes et al., (2020)), which are closely linked to the occurrence of forest fires (Nunes et al., 2019a). Notably, these forest types are also characteristic to Spain in ER 2, which showed the most comparable rho values between the two countries.

Differences in forest ownership structure could also be a factor contributing to the observed variations. In Spain privately owned forests account for 73.04 % of the total forestland, whereas in Portugal this percentage significantly increases to 97.07 % (Forest Europe, 2020, Table 41, data for year 2015). Although official data on the size of forest properties and holdings is absent in the cited source, it appears that two distinct ownership patterns emerge in Portugal (Feliciano et al., 2015): one in the northern and central regions with small-scale holdings (below 10 ha), and another in the southern region characterized by large-scale holdings (above 100 ha), which closely resembles that of main tree species and wildfire regimes. Again, a similar small-scale ownership pattern is also characteristic of the northwest region of Spain, thus this pattern spans across both countries within ER 2.

#### 4.3. Limitations and future work

As a prerequisite to linking forest pattern and processes, our findings were solely based on forest cover pattern data. Following this, it is essential to test and validate the FAD thresholds here identified with specific ecological responses (e.g., species richness, abundance of certain species of concern) and in the context of the ET and FT hypotheses (Villard and Metzger, 2014; Hadley and Betts, 2016). This would provide valuable insights for conservation planning, ensuring that the thresholds are applicable and meaningful in specific contexts. In particular, further investigation of the FAD range 1–55 % is warranted for effective landscape-scale forest planning, as it exhibited significant variability in terms of NP, ED, and ENN.

We employed a coarse-scale ecoregional map with a limited number of categories (ERs) to explore the differences in forest patterns at large-scale. While this approach provided compelling findings, we acknowledge that a more detailed regionalization, incorporating fine-scale ecological and/or socio-economic data, would enable to identify more detailed differences in the patterns of Iberian forests. As discussed, it would be important to further investigate not only climate but also wildfire regimes, forest types, and land ownership as potential contributing factors. Also, based on this regionalization approach (e.g., Long et al., 2010b), it would be valuable a more thorough examination of the conditions under which forest amount (e.g., FAD) is appropriate as a single fragmentation indicator.

We used a fixed landscape size of 5,314.41 ha (7,290 x 7,290 m), but the investigation of additional landscape sizes would offer insights into the scale dependence of forest patterns. Specially, smaller sizes for

metrics' calculations would be relevant for guilds of species with medium to low dispersal capabilities. Additionally, incorporating temporal variables into the analysis, such as time since loss or fragmentation, would improve our comprehension of the dynamics and long-term effects of forest change over time. Further analyses using TCD thresholds different from the 20 % we applied in our study would also offer complementary results (see thresholding approach in Frazier and Kedron (2017)).

Fragmentation is a landscape-level process that can only be fully understood by studying landscapes (McGarigal and Cushman, 2002). However, conducting manipulative experiments on landscapes to separate the effects of fragmentation per se from habitat loss is often impractical. To address this hot topic (see Fletcher et al., 2018; Fahrig et al., 2019), an observational study with replicate landscapes of equal habitat amount but different configurations can be designed (Fahrig, 2003; Valente et al., 2023). The analysis and data presented in this study can be utilized to locate such replicate forest landscapes.

## 5. Conclusions

We comprehensively analyzed the forest cover pattern in the Iberian Peninsula, revealing the relationships between forest amount and configuration components. These relationships were roughly similar to those previously reported using simulated landscapes, but here we identified combinations of forest amount and configuration metrics' values in real-world landscapes from a Mediterranean study area. Based on probability-density scatterplots, we provided FAD (Forest Area Density) and NP (Number of Patches), ED (Edge Density) and ENN (mean Euclidean Nearest Neighbor) ranges as general references of the current state of Iberian forests, which could be applied to conservation planning. In addition, we defined a synoptic fragmentation indicator aggregating configuration metrics' values, and identified the FAD values 55, 69, 74 and 89 % as thresholds bounding distinct fragmentation levels, which theory predicts may be linked to distinct ecological responses. The strength of the relationships was evaluated, and differences appeared when considering underlying drivers of landscape change (Bürge et al., 2004), such as the political and ecological contexts we considered. The major difference was found for ED when jointly regarding country and Ecological Region (ER) as factor. In Portugal, higher FAD values were associated with more forest edge, unlike in Spain, but the most Eurosiberian ER 2 had comparable rho values in both countries. We speculate that wildfire regime, a major concern for forest management in the study area, is a plausible explanation for these finding. Also, forest types and land ownership may be contributing factors. Overall, our study contributes to a better understanding of the spatial patterns of forest cover in the Iberian Peninsula. By examining forest amount and its relationship with configuration metrics, it provides crucial knowledge for assessing the current state of forest fragmentation and a foundation for further research and management efforts in the region, highlighting the non-linearity of the relationships and the influence of broader contexts.

#### CRediT authorship contribution statement

**Sergio González-Ávila:** Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing, Funding acquisition. **Belén Martín:** Supervision, Writing – review & editing, Funding acquisition. **Emilio Ortega:** Supervision, Writing – review & editing. **João C. Azevedo:** Conceptualization, Methodology, Writing – review & editing, Resources. All authors read and approved the final manuscript.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

the work reported in this paper.

## Data availability

Data will be made available on request.

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