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Forest Fragmentation in Bavaria: A First-Time Quantitative Analysis Based on Earth Observation Data

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Abstract

Anthropogenic and climatic pressures can transform contiguous forests into smaller, less connected fragments. Forest biodiversity and ecosystem functioning can furthermore be compromised or enhanced. We present a descriptive analysis of forest fragmentation in Bavaria, the largest federal state in Germany. We calculated 22 metrics of fragmentation using forest polygons, aggregated within administrative units and with respect to both elevation and aspect orientation. Using a forest mask from September 2024, we found 2.384 million hectares of forest across Bavaria, distributed amongst 83,253 forest polygons 0.1 hectare and larger. The smallest patch category (XS, <25 ha) outnumbered all other size classes by nearly 13 to 1. Edge zones accounted for more than 1.68 million hectares, leaving less than 703,000 hectares as core forest. Although south-facing slopes dominated the state, the highest forest cover (~36%) was found on the least abundant east-oriented slopes. Most of the area is located at 400–600 m.a.s.l., with around 30% of this area covered by forests; however, XL forest patches (>3594 ha) dominated higher elevations, covering 30–60% of land surface area between 600 and 1400 m.a.s.l. The distribution of the largest patches follows the higher terrain and corresponds well to protected areas. K-means clustering delineated 3 clusters, which corresponded well with the predominance of patchiness, aggregation, and edginess within districts.

Keywords: remote sensing; disturbance; forest loss; Germany; landscape ecology; temperate forest; bark beetle; central Europe; forest management

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1. Introduction

The threat of temperate forest degradation due to the effects of climate change is steadily escalating [1–3]. Forests provide numerous indispensable ecosystem services, especially the reduction and storage of atmospheric carbon [4,5], the cooling of the land surface [6,7], and the regulation of the hydrosphere [8,9]. Consequently, the loss of trees, and therefore vital forest structure, compromises the climate buffering function of forests [10] Reduced forest areas together with an increase in the number of isolated forest patches can furthermore have consequences for forest species and ecosystem functioning as interactions between them may change unpredictably. Thus, analyzing spatial patterns of forests is essential for understanding their role in maintaining biodiversity, supporting ecosystem functions, and enhancing climate resilience.

1.1. Fragmentation Versus Forest Loss

Fragmentation refers to the discontinuous pattern of forest patches within a landscape. Such patterns can arise from human activities (logging, historical land use or land use conversion, construction of infrastructure, soil pollution), from natural causes (windthrow, insect infestations, drought, floods, wildfire), the underlying properties of the substrate (soil type and texture, hydrology, persistence of rock outcrops), or other biophysical constraints (temperature, elevation/terrain, precipitation, solar irradiance) which contribute to the natural patchiness of landscapes. The combination of these drivers results in a landscape mosaic, which is characterized by the spatially uneven distribution of landcover types, comprising, for example, forests, agriculture, water bodies, and infrastructure. Except for the most remote forests, anthropologically developed regions exhibit patchy forest patterns. In other words, landscape patchiness is the rule, not the exception [11,12].

Fragmentation occurs when forests are broken apart into more numerous and disconnected patches, and can be considered a distinct process from forest loss [13,14]. With fragmentation per se, patches can become disconnected, but the same amount of forest area within a given landscape can still be maintained. Forest loss, on the other hand, is a process whereby the area of forest is reduced over time. Figure 1 illustrates this concept using four scenarios of forest loss. In the first frame, the forest covers 100% of the landscape; in the next, the forest is reduced to 50%. Finally, the forest is reduced to 25% of the original size in the last frame. In the shrinkage scenario, the forest area is lost, but not fragmented. This is also true in the perforation scenario, because forest connectivity is maintained even as the forested area is reduced.

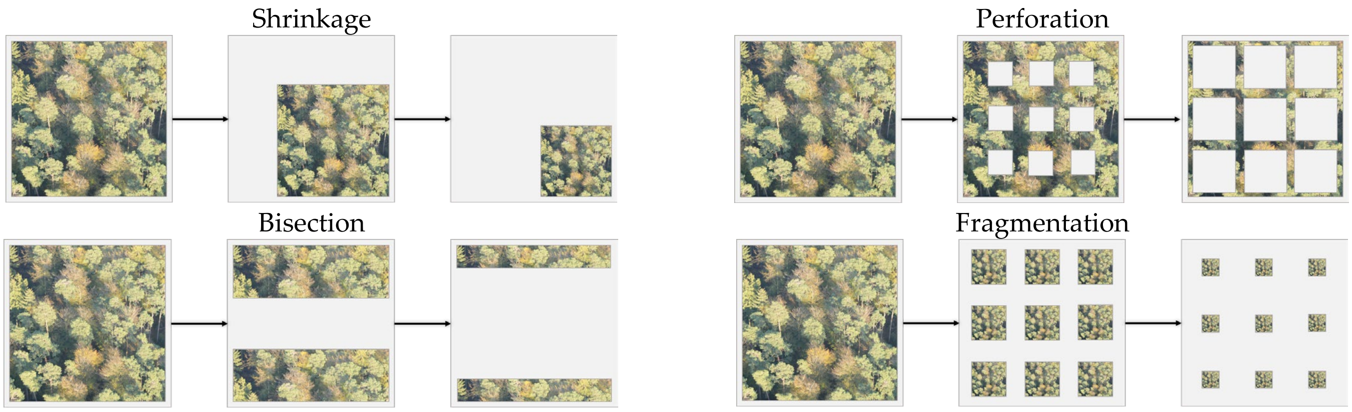

Figure 1. Scenarios of forest loss where forest area is reduced to 50% and 25%. Forest is lost in each scenario, but only in the 'bisection' and 'fragmentation' scenarios is the forest both lost and fragmented. Adapted from [11].

Bisection and fragmentation are characterized by the dis-connectivity of forest area, which we refer to as fragmentation. The figure illustrates both forest loss and fragmentation of remaining forest but it is important to distinguish this phenomenon from landscapes where the overall forest area is maintained across an increased number of individual patches. This scenario is typically referred to as 'fragmentation per se' as opposed to merely fragmentation [15]. Figure 2 exemplifies the fragmentation of forest without a reduction in overall forest area within the landscape. This distinction is significant, because the maintenance of forest area within a specified landscape despite fragmentation can still support animal habitats and ecosystem functioning [13].

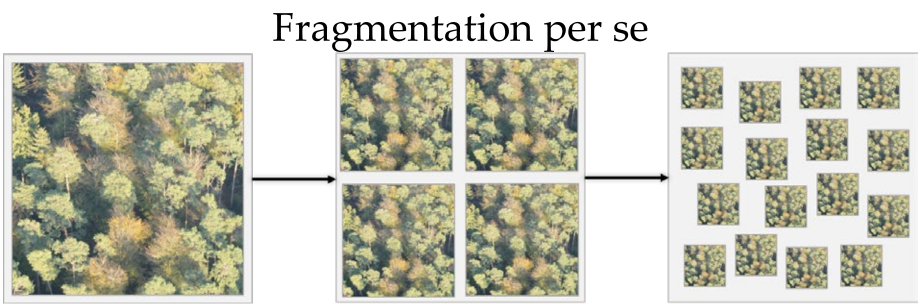

Figure 2. Fragmentation without forest loss. Forest patches are more numerous in the subsequent frames; however, the overall area of forest within the landscape is unchanged. Adapted from [16].

Because of the heterogeneity of landscapes, the degree of fragmentation of forests within them is variable. To understand the relative intensity of fragmentation, it is useful to assess landscape patterns in terms of forested area and the number of fragments, or the 'patchiness' of forests, within the landscape. Table 1 summarizes the degree or intensity of expected patchiness based on these factors, resulting in different levels of forest fragmentation.

Table 1. Fragmentation per se or 'patchiness' based on forest amount relative to number of fragments.

Forest Area	Number of Fragments	Interpretation	Patchiness
High	Low	Forests likely have larger core areas	Low
High	High	Patchiness is high; however, forest amount may be preserved	Moderate to high
Low	Low	Forest is scarce or potentially isolated	Low to moderate
Low	High	Intense patchiness, forest areas are scarce and disaggregated	High

1.2. Aggregation and Isolation

Although disconnected patches may alter functional capacity in terms of ecosystem services, biodiversity, habitats, and resilience against the effects of climate change [17–19]; counterintuitively, fragmentation can favor some species whilst disadvantaging others. This depends on the scale, distribution (isolation or aggregation of patches), cause, frequency, and degree of forest loss (if any), and also depends on the affected species. This paradox has been investigated in a wide range of habitat types and climate zones, and under various drivers of habitat loss [16]. In the majority of cases, Fahrig et al. determined a net positive effect of fragmentation independent of habitat loss.

Furthermore, while larger forests reliably support more species, disconnected habitats can genetically isolate populations thereby contributing to speciation over long time scales. However, the lack of incoming genetic diversity can also lead to population decline. Moreover, reduction in forest area predictably reduces species richness within patches. These principles were the foundation of the theory of island biogeography [20].

Although initially developed for oceanic islands, this theory came to dominate the conceptual understanding of early investigations of fragmented terrestrial habitats. However, it is important to note that islands in an ocean are not directly analogous to terrestrial habitat patches. Forests are embedded in a mosaic of other landcover types that have distinctive properties which can facilitate or hinder animal movement and plant dispersion. To simplify this concept, we focus on the number of neighboring forests to each forest and their distance to understand the isolation or aggregation of forest patches within a landscape. Table 2 summarizes these concepts below.

Table 2. The number of neighbors and the distance between patches can conceptualize how isolated or aggregated forest patches are within a landscape.

Number of Neighbors	Distance to Neighbors	Interpretation	Aggregation
High	Low	Fragmentation intensity is high but patches are less isolated	High
High	High	Fragmentation is high, and patches are more isolated or dispersed	Low to moderate
Low	Low	Fragmentation is low and patches are tightly aggregated	Moderate to high
Low	High	Patches are few and quite isolated	Low

The degree or intensity of patch isolation can thus limit or enhance the quality and quantity of species interactions. Species interactions drive underlying processes such as forest seed dispersal by birds or rodents, the movement of pathogens or infectious diseases, the facilitation of gene flow, or reproduction. These processes require the interaction of species within available habitat, which is further modulated by habitat configuration and distribution. The fragmentation of forests therefore has species-specific effects.

1.3. Edge Structure

In unmanaged forests, where human interventions are minimal or absent, forest is lost by the aforementioned natural causes, which occur at less frequent intervals than anthropogenic drivers, but can nevertheless cover large spatial areas. However, remaining forest structure (vertical layers, lying deadwood) and perimeter morphology (straight versus sinuous) are typically more heterogenous compared to human-caused forest loss [11,12,21]. The resulting structural differences between natural and anthropogenic fragmentation can favor some forest species while harming others. This is especially true for the region where interior forest is lost (perforated) where, like forest edges, microclimatic conditions differ from the interior of a forest. These abiotic conditions can furthermore be modulated by the remaining forest structure, perimeter morphology, and the adjacent landcover type [21]. This may increase biodiversity by favoring species which can easily colonize disturbed areas and prefer higher light, temperature, and windy conditions [22].

Forest structure can vary by species, management practices, age class, and distance to the forest perimeter [23]. For example, trees along a mature perimeter, where the vegetation has developed according to the edge conditions, often exhibit branches at lower positions on stems. Along a newly exposed (disturbed) perimeter, trees develop with greater light competition within the forest interior and branches tend to dominate higher positions. Thus, stems become exposed to abrupt changes in abiotic conditions. This difference in structure modulates a profound 'edge effect', which is caused by the penetration of sunlight, thereby creating microclimatic conditions along perimeters and in edge zones [24]. Although disturbances are usually transient, the effect on growth of surrounding trees can persist, even after perforations or edges have regrown [25]. Figure 3 characterizes the variability along a mature perimeter (A) and a recently disturbed perimeter (B, C) of spruce-dominated forest near Garmish-Partenkirchen (A, B) and Wessling (C).

To conceptualize the edge effects in a forest or landscape, it is also necessary to account for the area of forests. If the overall amount of forest is large, the area where edge effects occur is relatively small. By the same token, in landscapes or patches with small, forested areas, perimeters and thus edge effects tend to dominate the forest. This is significant, because trees stressed by temperature may be less resilient to droughts, insect infestations, or other disturbances [26]. Table 3 summarizes the so-called edginess potential for different ratios of forest area to perimeter length.

Geospatial forest fragmentation analysis focuses on three essential zones of the forest: the perimeter, edge zone, and the core of individual patches. Additionally, the focus is on their aggregation/isolation and distribution within the landscape. The edge zone is a transitional region of forest up to 100 m interior to a forest perimeter, which can act as a microclimatic buffer for the core zone, which is the remaining interior region [27]. Depending on management practices, perimeters and edge zones usually exhibit different biotic and abiotic characteristics and conditions compared to forest interiors in addition to the increased occurrence of invasive species (Figure 4A–E) [28].

(**A**) (**B**) (**C**)

Figure 3. A mature forest perimeter where tree architecture has developed according to conditions along the forest perimeter (**A**). Recently disturbed perimeters expose spruce stems to increased sunlight, wind, and temperatures (**B**,**C**).

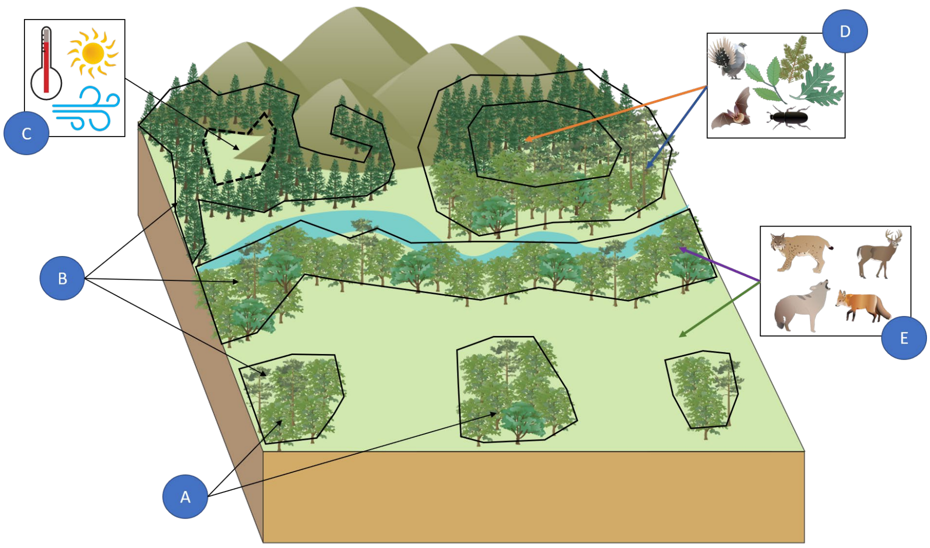

Figure 4. Simplified examples of fragmentation patterns with polygons outlined. Numerous small patches have no distinct core zone (A), variation in patch shapes (simple/geometric, linear, highly complex) (B), and perforations within forests resulting in longer perimeters and exposure to increased sunlight, temperature, and wind (C). Large continuous forests may have a distinctive buffer region (100 m, blue)—the 'edge'—and interior (orange)—the 'core'—which can support a greater number of species (D). Linear patches can act as corridors to support animal movement (purple); meanwhile, decreased connectivity between patches can have species-specific impacts on animal movement and migration (green) (E). Adapted graphics are courtesy of the University of Maryland (Center for Environmental Science, Integration and Application Network) Media Library, CC BY-SA [29].

Table 3. The 'edginess' or amount of edge is a function of the length of the perimeter of forest patches and the area of patches within the landscape.

Perimeter Length	Patch Area	Interpretation	Edginess
High	Low	Patches are likely long and narrow with very little if any core area	High
High	High	Patches are large and may have numerous perforations, edge effects are likely minimal	Low to moderate
Low	Low	Patches are likely small, geometric, perhaps without any core area	Moderate to high
Low	High	Patches may be medium sized with few or small perforations	Low

1.4. Fragmentation Analysis

Importantly, fragmentation must be analyzed within the context of a defined landscape area [30]. Characteristics of forest patches such as amount and distribution, perimeter length, core and edge area, shape, and neighboring patch configurations can then be aggregated within landscape boundaries. Landscapes can thus be utilized as units for ecological investigations, for example, investigations regarding forest species abundance based on total habitat amount within or amongst discontinuous patches. To determine the intensity of fragmentation, the number of fragments, patch distribution (aggregation or isolation), and edginess can be assessed in relation to the remaining metrics within a landscape unit.

Analysis of remotely sensed imagery is an effective approach for monitoring forest condition and disturbance [31]; it is an under-utilized tool in the study of forest fragmentation, and it is furthermore ideal for large-scale applications [32]. Given the profound differences between fragmented forests and contiguous forest ecosystems [33], an assessment of fragmentation in the largest and most forested state in Germany is needed. Furthermore, the topic has not yet been investigated on the state scale using Earth observation (EO) data [34]. Understanding landscape patterns and processes is moreover important for the formulation and assessment of forest management strategies within the context of climate change and conservation. Therefore, forest fragmentation across Bavaria can be efficiently investigated by analyzing satellite data and is the subject of this inquiry. We present

- A characterization of forests using structural and functional fragmentation metrics based on patch size categorization;
- The spatial and terrain distribution of fragmentation;
- State-, county-, and district-level results which can support data-driven forest policy and management decisions.

2. Materials and Methods

2.1. Study Area

Bavaria is located in southeastern Germany, bordering the Czech Republic to the east and Austria to the south. Its large size, the abundance of forest cover relative to other German states, and its central European position make Bavaria an important region for species migrations and a key habitat for resident species. On the eastern border, the Bavarian Forest National Park (BFNP) together with the Šumava National Park in the Czech Republic form the Bohemian Forest Ecosystem, the largest contiguous forest in Central Europe. This area supports many unique species and provides critical ecosystem services, especially for the region's hydrological system. Understanding forest dynamics in Bavaria is therefore essential.

Forests characterize more than one-third of the land surface in Bavaria and predominantly comprise Norway spruce (*Picea abies*), European beech (*Fagus sylvatica*), Scots pine (*Pinus sylvestris*), and oak (*Quercus* sp.), with larch (*Larix* sp.), fir (*Abies* sp.), maple (*Acer* sp.), birch (*Betula* sp.), and others making up smaller fractions. The species composition varies based on forest ownership and management, patch size, protection status, and elevation [35]. Broadly speaking, species distribution follows a gradient whereby broadleaf deciduous forests dominate Lower and Middle Franconia, and coniferous species, namely spruce, dominate in higher elevations of the remaining districts becoming monocultures along the eastern and southern borders of Bavaria [36]. Mixed forests are typically found at elevations less than 600 m.a.s.l. and can be the result of careful forest management practices. In recent years, there has been a push to increase the diversity of mixed forests due to their apparent resiliency of mixed over monocultured forests [37].

Bavaria exhibits a heterogenous mosaic of landcover types. Forests, urban areas, rivers, agriculture, and transportation infrastructure form a patchy landscape across the state, a consequence of historical land use practices, soil types, and topography. Large charismatic animal species, including lynx (*Lynx lynx*), roe and red deer (*Capreolus capreolus*, *Cevus elaphus*), capercaillie (*Tetrao urogallus*), hazel and black grouse (*Tetrastes bonasia*, *Lyrurus tetrix*), moose (*Alces alces*), and even wolf (*Canis lupus*), can be found, especially within the protected forests, like the BFNP [38]. Moreover, landscapes and patches across Bavaria provide key habitats, including the last colony of greater horseshoe bats (*Rhinolophus ferrumequinum*) in Germany [39], and for migrating birds such as Eurasian cranes (*Grus grus*) and white storks (*Ciconia Ciconia*) [40,41].

The state of Bavarian forests today is a result of historical development and recent management schemes. Germany was subject to post-war reparations which were partly paid in the form of timber. This left the region in need of efficient afforestation strategies, which resulted in the vast deliberate replanting of non-native Norway spruce [42]. This fast-growing conifer quickly reforested areas of Germany that were less vital for agriculture and infrastructure, particularly higher elevations, steep slopes, and in less productive soils. The spruce still forms the foundation of the forestry sector. However, the natural forest condition of Germany, which developed after the last glacial period, featured broadleaved deciduous species. Initially, oak and later beech dominated the landscape; the European beech is still the most common deciduous tree in Bavaria.

Large regions of state-owned forest in Bavaria are granted protected status. Nature reserves and parks, biosphere reserves, Natura2000 sites, and national parks together cover about one-third of the forest area [43,44]. In Figure 5, national parks are depicted separately from all other levels of protection (Figure 5A). However, most of the forested area in Bavaria is privately owned (Figure 5C). Topography in Bavaria varies from low mountain ranges in the north and middle of the state, to pre-Alps in the south, reaching nearly 3000 m.a.s.l. (Zugspitze, 2962 m). Most of the land area is less than 600 m.a.s.l. (Figure 5B). The climate follows a similar spatial gradient whereby northern counties are warmer and drier, and southernmost districts within Swabia and Upper Bavaria, and Lower Bavaria in the east, are cooler and wetter. In recent decades, climate across the state has shifted to milder winters and hotter, drier summers (Figure 5D,E).

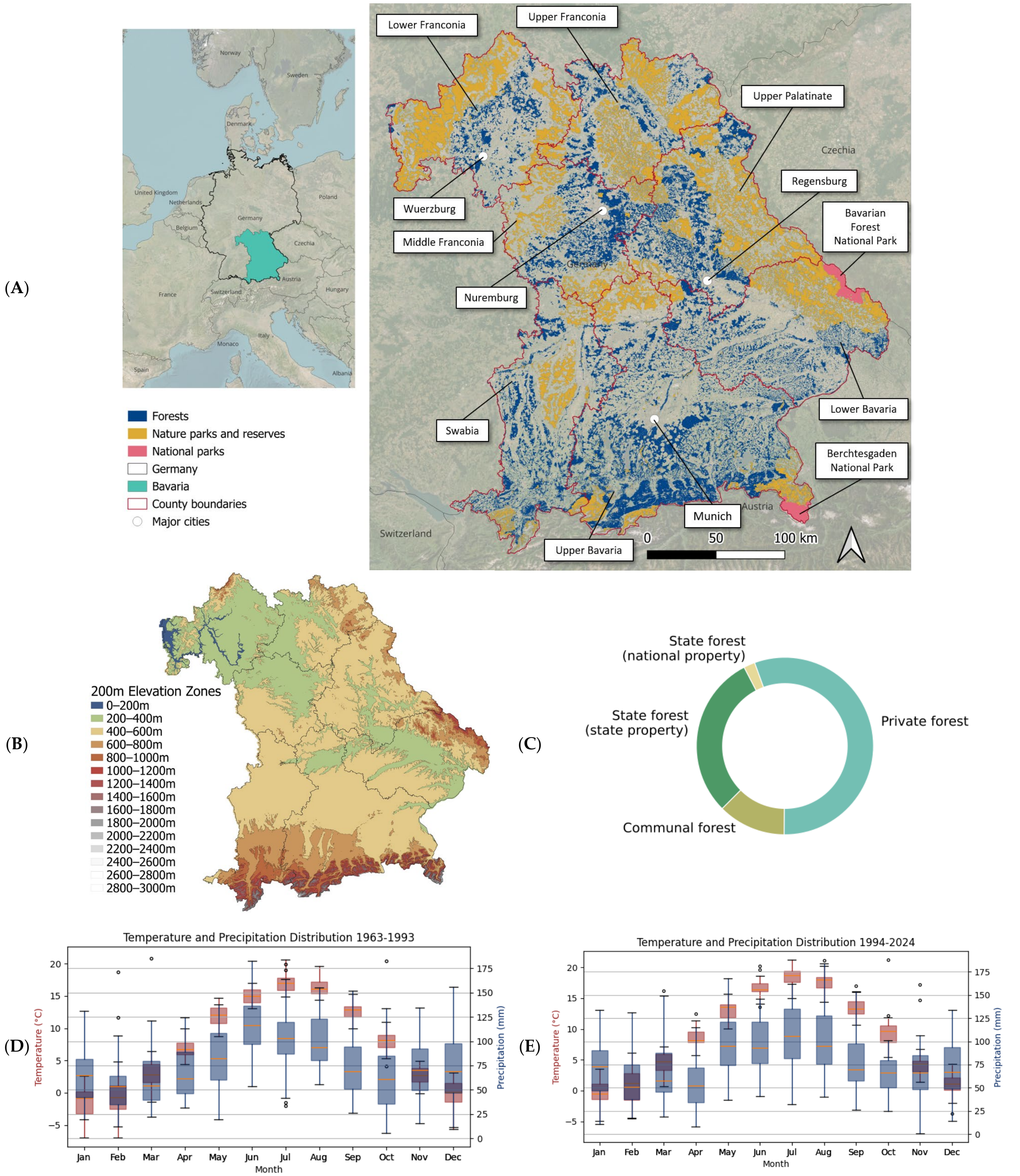

Figure 5. Overview of Bavaria: forests and protected areas (**A**), topography (**B**), forest ownership (**C**) and climate (**D**,**E**). Adapted from [34].

2.2. Data

The workflow for the methodology is presented in Figure 6. All data processing and the preparation of figures were completed in Jupyter Lab [45] (version 4.0.6) using Python [46] (version 3.10.12). Maps were produced using the matplotlib package [47] and using QGIS [48] (version 3.34.13). Principal component analysis and K-means clustering were conducted using R (version 4.4.2) [49] with the packages FactoMineR [50], factoextra [50], and cluster [51].

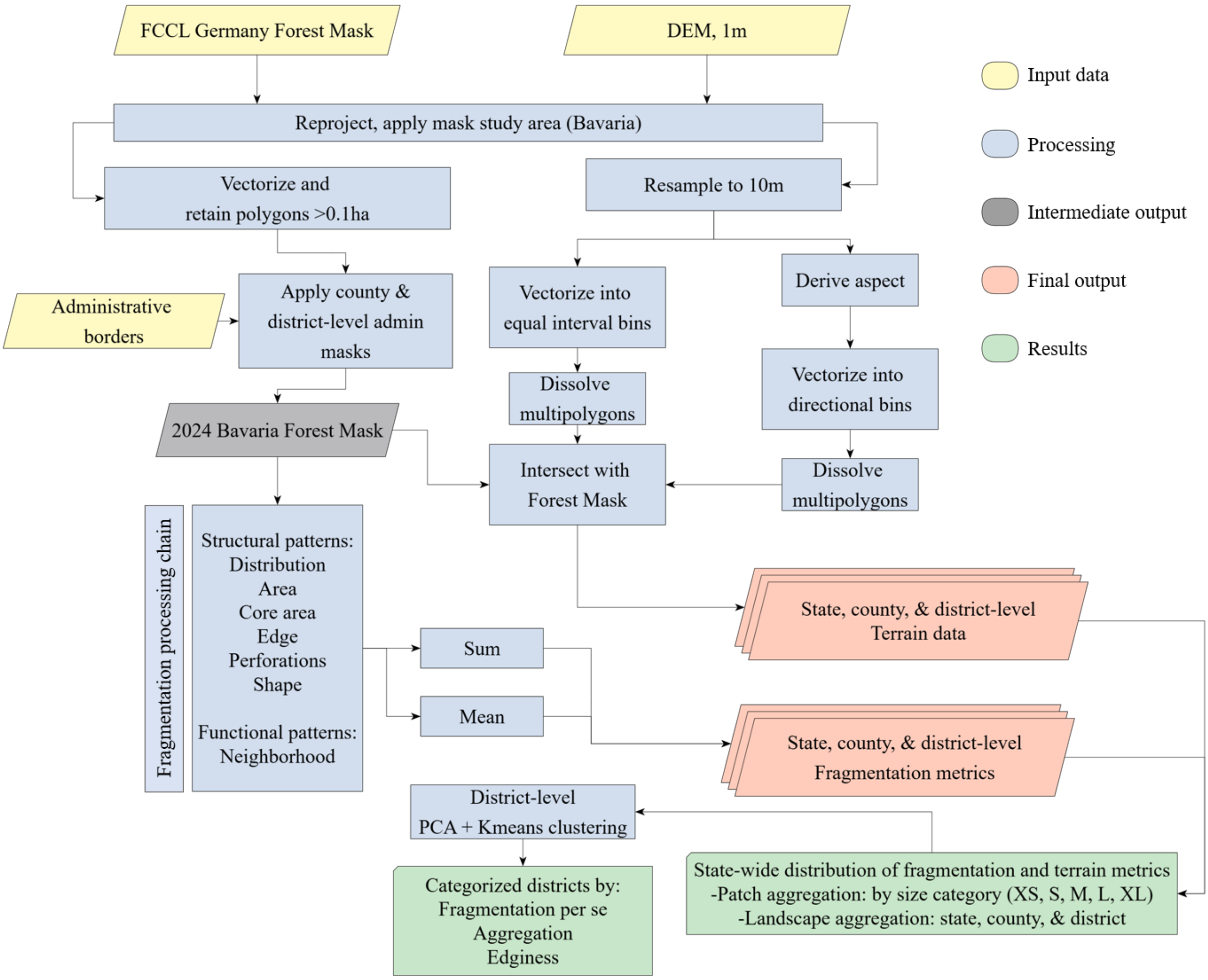

Figure 6. Summary of workflow.

The resolution and update frequency of commonly used Copernicus forest cover products varies by product [52–54]. Therefore, in this analysis, we instead applied the most recent release of the (1) the Germany-wide Forest Canopy Cover Loss (FCCL) mask, developed by Thonfeld et al. [55] (updated until September 2024), and (2) the digital elevation model (DEM) produced by the Bavarian Surveying Authority [56] (Table 4). Both datasets were re-projected using the rasterio package [57]. The EPSG: 3035 projection was selected due to area preservation in order make the most accurate geometric calculations for fragmentation analysis. Both datasets were then masked onto the study area (the federal state of Bavaria) using an administrative shapefile of the same projection.

Table 4. Datasets used.

Dataset	Description	Type	Spatial Resolution	Author	Pub. Date	Access
Forest Canopy Cover Loss (FCCL) Forest Mask	Detection based on Disturbance Index (DI)	Raster	10 m	Thonfeld et al. [55]	2025	DLR geoservice, https://doi.org/10.15489/ef9wwc5sff75, accessed on 11 November 2024
Digital elevation model (DEM)	High-resolution DEM based on ALS data	Raster	1 m	Bavarian Surveying Authority [58]		Bavarian Geoportal, www.geoportal.bayern.de, accessed on 11 November 2024

2.3. Methodology

Fragmentation analysis is a method used for understanding spatial patterns among patches of a particular habitat within a defined landscape [30]. Here, we delineated the small-scale patterns among forest patches, referred to as patch-scale analysis. Large-scale patterns are also referred to as landscape-scale patterns, where a given landscape is defined. We focused on the administrative unit as the landscape based on forest management practices, rather than on the basis of an ecological landscape scale. The purpose of this definition is to support policy and forest management decisions, which are often defined at the scale of administrative rather than ecological units.

FCCL forest mask raster data were vectorized to delineate discreet forest polygons larger than 0.1 ha. Forest polygons were then masked by county- and district-level administrative boundaries in the EPSG: 3035 projection. Metrics of forest fragmentation were selected based on FRAGSTATS definitions [59,60]. We then developed an independent calculation processing chain in Python to derive fragmentation metrics. Metrics were divided into two categories: structural (size, shape, amount) and functional (spatial distribution) characteristics (detailed in Table 2). Within these two broad categories, 14 metrics of fragmentation were compiled using the processing chain. Furthermore, these metrics were aggregated by sum, mean, or both, resulting in 22 total measurements (Table 5).

Patch size categorization or binning was performed on the state-wide dataset using the Jenks–Caspall method [61] for clustering geospatial data. The Jenks–Caspall technique optimizes bins to minimize variance within and maximize differences between bins, and is therefore well-suited for skewed data. The operation was conducted using the mapclassify library in Jupyter Lab (version 4.0.6) using Python (version 3.10.12). We integrated terrain data into our characterization to obtain a comprehensive spatial overview of the status and distribution of forest fragmentation in Bavaria. The 1 m digital elevation model (DEM) produced by the Bavarian Surveying Authority was resampled to 10 m and re-projected (matching all data sources). The aspect was derived from the DEM using the rasterio [57] and numpy [62] libraries. Using the equal interval method, we binned the DEM data into 200 m elevational zones, beginning at zero and using 3000 m above sea level (m.a.s.l.) as the maximum elevation. True elevations across Bavaria range from 108 to 2962 m.a.s.l. To derive the percent forest cover for each elevation zone, we used the overlay function to intersect the forest mask data with the elevation data, using the forest patch size categorization as subsets.

Similarly, we categorized the aspect data into four orientation bins using 315–45° as North, 45–135° as East, 135–225° as South, and 225–315° as West. The resulting multipolygons for each aspect orientation were dissolved into a single layer and intersected using the overlay function with the forest mask data subset by forest patch size category.

Following FRAGSTATS definitions, we distinguished metrics by landscape pattern into two categories: structural and functional. Structural elements measure spatial or geometric attributes of forest (or other habitat) patches within a selected landscape unit. In the present study, the administrative unit is the landscape. Functional metrics consider the distribution of patches within a landscape with respect to surrounding nearby patches.

When considered in the context of other metrics, structural and functional elements can uncover patterns and intensity of forest fragmentation.

Table 5. Description of fragmentation metrics.

Landscape Pattern	Category	Metric (Aggregation)	Unit	Description or Formula	Interpretation
Structural	Distribution	Number of patches (sum)	n/a	The total number of patches within a given landscape or administrative unit	High values suggest discontinuous forest within a given landscape.
Structural	Area	Area (sum, mean)	Hectares	Area of forest patch(es)	Higher values suggest more continuous forest when the number of patches is low.
Structural	Core Area	Core area (sum, mean)	Hectares	Core forest area considering an edge depth of 100 m	Value indicates size of core forest.
		Core area % (mean)	Hectares	Percent of core area, considering an edge depth of 100 m	High values suggest a higher ratio of core to edge area.
Structural	Edge	Perimeter (sum, mean)	Meters	Patch perimeter length	High values suggest greater exposure to edge effects.
		Edge area (sum, mean)	Hectares	Edge depth (100 m) is a measure of the region of forest from the perimeter edge toward the core area	Trees inside edges experience higher sunlight, wind, temperatures and drier soil conditions.
		Edge area % (mean)	n/a	The ratio of edge area (100 m edge depth) to overall area	Higher values may equate to lower overall core area.
Structural	Perforations	Number of perforations (sum, mean)	n/a	Number of perforations in a forest patch or landscape	Highly complex patch shapes and increased exposure to edge effects.
		Perforated area (sum, mean)	Hectares	Area of perforations in a forest or landscape	High values can suggest increases in shape complexity.
Structural	Shape	Paratio (mean)	n/a	$perimeter/area$	Higher values equate to higher shape complexity (varies with size of patch).
		Shape index (mean)	n/a	$(0.25(perimeter))/(\sqrt{(area)})$	Higher values equate to higher shape complexity (employs a constant to correct for size).
Functional	Neighbor-hood	Number of neighbors (sum, mean)	n/a	Counts neighboring forests based on edge-to-edge distance within 200 m buffer of each patch.	Increases over time can indicate higher fragmentation intensity.
		Area of neighbors (sum, mean)	Hectares	Area of neighboring patches within 200 m buffer.	High values indicate large nearby forests.
		Proximity	n/a	$\Sigma\,(a_{ijs}/d_{ijs}^{2})$	High values indicate nearby patches are large and more aggregated

2.4. Description of Metrics

2.4.1. Area

Metrics are presented with increasing complexity, starting with area, which considers individual patches and their aggregated area within a landscape or administrative unit. This and subsequent area measurements are given in hectares. The area of forest within a landscape distributed amongst the number of patches can suggest the intensity of fragmentation (see Table 1).

2.4.2. Core Area

The category of core area considers a defined edge depth, where the effects of sunlight, temperature, wind, and soil moisture differ from the interior of the forest. This depth can depend on several factors including climate, topography, canopy cover, species composition, and disturbances ranging from harvesting operations to insect infestations. In this study, following the examples in the literature [63], we characterized the core area with a 100 m edge depth.

2.4.3. Edge Area

Edge area can be conceptualized as the inverse of the core area. Edges are divided using two metrics, the perimeter length (given in meters) and the area of the edge zone, which are derived using the aforementioned edge depth employed in the core area calculations and expressed as the sum, mean, and percent. The amount of perimeter or edge area relative to the total area or core area of forests within a landscape can be used to understand the dominance of edge effects in a landscape or single forest (see Table 3).

2.4.4. Perforations

Perforations are gaps that form in the core area of a forest. In this investigation, based on the forest mask derived using the Disturbance Index, perforations which occurred after September 2017 (the beginning of the FCCL study period) are a result of detected disturbances due to drought, insect infestations, windthrow/storms, or harvest [64], which can be considered distinct from pre-existing gaps such as meadows or roads. However, these perforations are not distinguishable in the current study. Perforations can be measured in terms of their overall distribution by both amount and area, and the percent of the forest in which they are located. The result of perforations is effectively an increase in the perimeter and thus the edge area of the forest.

2.4.5. Shape

Two metrics for measuring shape were selected for this analysis: the perimeter–area ratio and the shape index. Taken together, shape metrics can reveal complexities in forest patch geometry that arise from forest canopy loss. Complex shapes equate to longer perimeter lengths (including within perforations), resulting in an increased edge area where trees are exposed to abiotic elements.

2.4.6. Neighborhood

Neighborhood metrics are calculated by constructing a buffer (radius 200 m in this analysis) around each forest patch. The analysis of neighborhoods vis-à-vis the proximity of patches is typically a function of species; birds, ungulates, and insects will have different requirements in terms of distance traveled between patches. The accepted search radius can range from 100 to 500 m or more depending on the application [65,66]. We therefore followed examples from FRAGSTATS software guidelines and selected an intermediate search radius in order to make general inferences about forest patch aggregation and to make comparisons across landscapes [59]. The patch edge-to-edge distance is measured within the buffer area. Metrics calculated include the number of neighbors within the 200 m buffer, the distance between them, and, in addition, the area of these neighboring patches. Proximity was calculated using neighbor distance and patch area. The aggregation or isolation of individual patches and forested landscapes can be inferred from the number of neighbors and the average distance between patches within a landscape (see Table 2).

2.4.7. Metric Aggregation

Metrics were analyzed at the forest patch level and aggregated at the landscape level. Administrative units (state: *Land*, county: *Regierungsbezirk*, district: *Landkreis*) were used to delineate landscape borders. Where forest patches straddled an administrative border, the patch was divided (clipped) by the administrative polygon and the metrics were calculated and aggregated for only the area within the administrative unit. This scenario was not common and therefore did not result in meaningful increases in patch number.

2.5. Principal Component Analysis (PCA) and K-Means Clustering

Given the exploratory nature of this investigation and the number of fragmentation metrics presented, we conducted a principal component analysis (PCA) and K-means clustering to uncover broad landscape fragmentation patterns. PCA is a commonly employed unsupervised method for reducing data dimensionality [67]. PCA emphasizes components that account for the greatest variance, thereby reducing noise whilst highlighting dominant patterns. Dimensionality reductions using PCA are especially useful for understanding ecological patterns where large amounts of data can be highly correlated. This is essential for fragmentation data due to the apparent correlation of metrics [68]. For example, larger patches tend to have longer perimeters, a potential for larger core and edge zones, and may have more and larger perforations. Therefore, PCA was used to address multicollinearity.

K-means clustering partitions observations into a user-defined number of internally similar groupings which are distinct from one another in terms of Euclidean distance [69]. Clustering results can be interpreted based on fragmentation metrics for each grouping.

PCA was performed on scaled fragmentation metrics to reveal data structure. Following Kaiser's criterion [70], components were retained from principal components with eigenvalues (corresponding to variance) greater than 1. Metrics with absolute loadings greater than 0.25 were used to determine input data for K-means clustering. The elbow method and silhouette scores were used to guide the selection of the optimal number of clusters [71].

3. Results

We delineated 83,253 individual forest polygons (hereafter patches), which contained roughly 2.384 million hectares of forest in Bavaria. Patches ranged in size from 0.1 (based on the minimum forest size, defined by the German Federal Ministry of Agriculture, Food and Regional Identity, BMEL [72]) to ~48,703 hectares; however, the distribution of patch sizes is not normal. Figure 7 visualizes the distribution of patch sizes after applying a log-transformation of the data. Due to the skewed nature of these data, we present the fragmentation characterization in categories based on forest patch size.

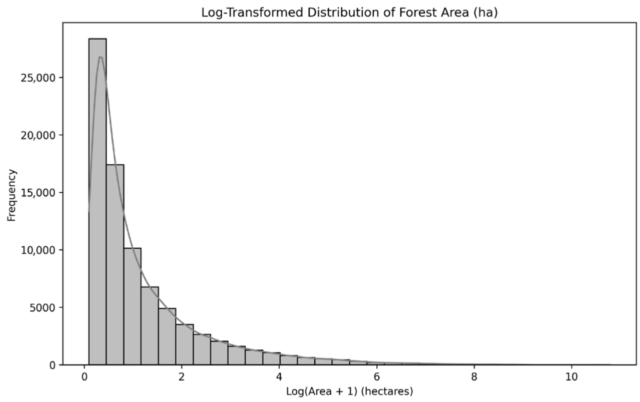

Figure 7. Log-transformed distribution of patch sizes. Small patches are overrepresented in the dataset.

Patch size categorization resulted in 5 size bins. The smallest size bin, 0.1–25 hectares, is hereafter referred to as the XS size class. In order of increasing forest size, patch categorization is as follows: 25–160 hectares (S), 160–789 hectares (M), 785–3594 hectares (L), and 3594–48,703 hectares (XL).

The spatial distribution of patch sizes across the state of Bavaria is heterogenous. The largest forest polygons are located around the periphery of the state, namely in the northwest corner of Lower Franconia, the central and eastern regions of Upper Franconia, Upper Palatinate, and Lower Bavaria, and the southern regions of both Swabia and Upper Bavaria. The distribution roughly follows both the terrain of the state, with the largest contiguous forest polygons located at higher elevations, as well as the areas with a status of varying degrees of forest protection as nature areas, reserves, or parks at both the state and federal levels. Figure 8A presents an overview of the spatial and size category distribution with inset examples of fragmentation patterns.

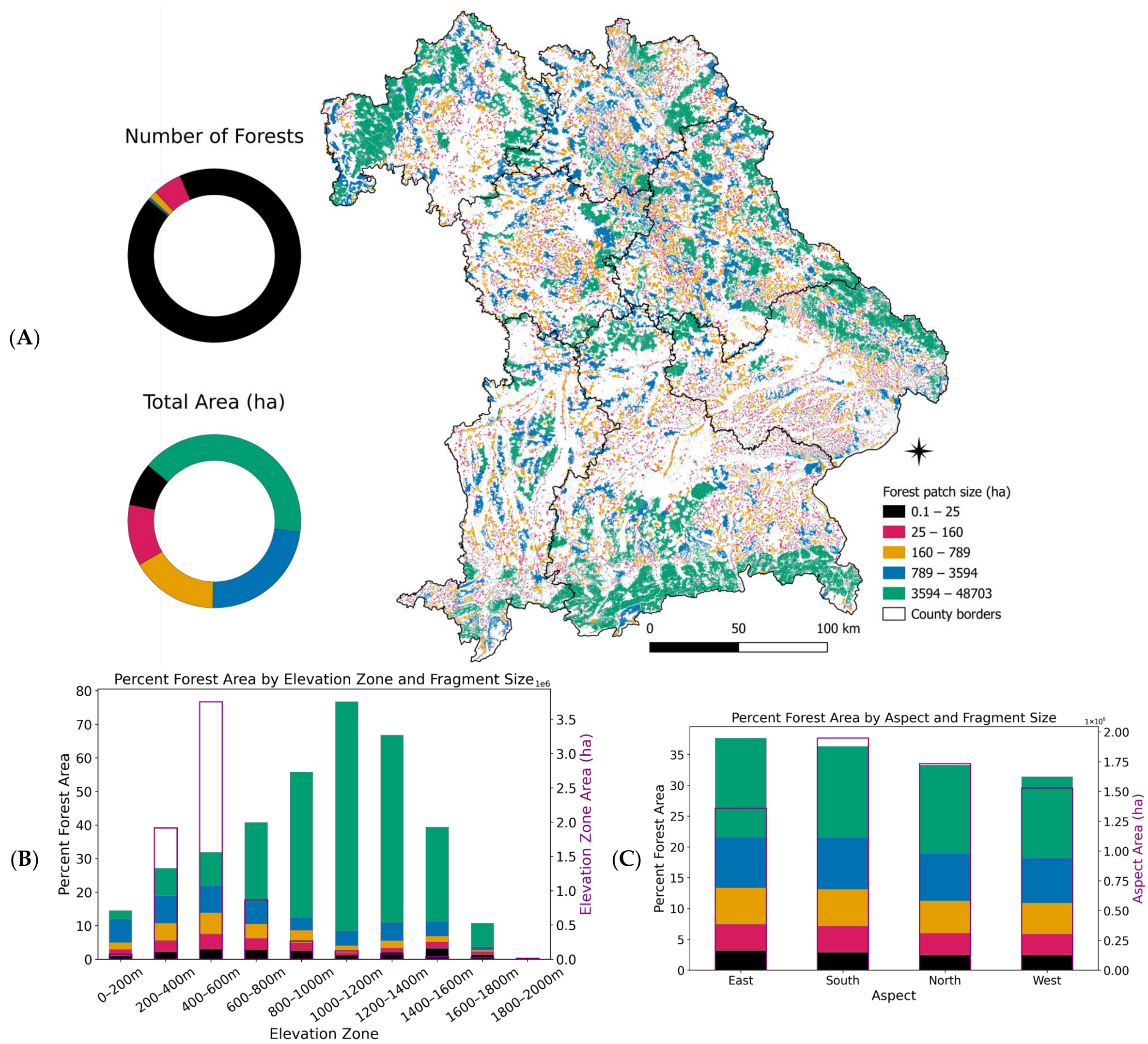

Figure 8. Overview of forest patch size and distribution (**A**). Elevations less than 600 m.a.s.l comprise the majority of area in the state; however, forest cover is highest at elevations between 800 and 1400 m.a.s.l. (**B**). Most hillsides are oriented to the south; however, east-facing slopes account for the highest forest cover (**C**).

Figure 8B,C summarize the distribution of patches with regard to terrain. In Figure 8B, above 2000 m there is no forest cover; this information is therefore omitted from this figure. The total area of each elevational zone is represented on the right y-axis, with bars outlined in black (1×10^6 ha). The 1000–1200 m elevational zone contains the highest percent of forest cover, at just over 60%; however, this zone is among the smallest, covering about 120,000 ha. The lowest elevational zone, 0–200 m, is covered by less forest than each subsequent zone until the climatic conditions limit tree growth above 1400 m. The smallest forest patches are relatively evenly distributed across the elevational zones compared to L and XL patches, which make up the largest share of forest coverage as elevation increases.

Most of the land surface area of the state falls within the 400–600 m elevation zone (about 3.75 million ha); however, only about 30% is covered by forested area.

The total area is not evenly distributed amongst the four aspect directions (Figure 8C). The majority of slopes are south-facing and have the second highest percent forest cover. The smallest slope category was east; however, these slopes had the highest percent coverage of forest. West-facing slopes had the smallest coverage overall.

Figure 9 visualizes the state-wide results of forest fragmentation pattern characterization, covering the whole of Bavaria using min–max scaling. Results are organized by the abovementioned patch size bin categorization. For detailed result tables for the state and each county of Bavaria, we refer the reader to the Supplementary Materials.

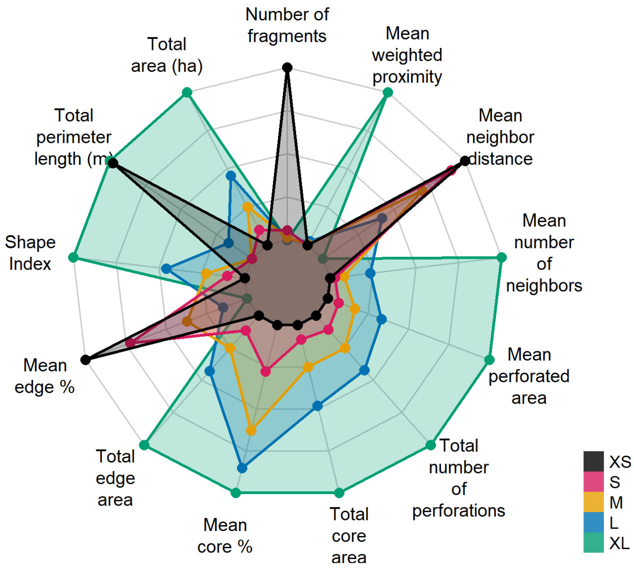

Figure 9. Comparison of fragmentation metrics across fragment size categories.

3.1. Metrics

3.1.1. Area and Number of Patches

Most forests (77,175 patches) were categorized as XS (<25 ha); however, this category covered the smallest area overall. More than 92% of forest patches cover an area less than 25 ha each, with a total area of 192,177 ha or about 8% of the total forested area in the state. The mean area of XS patches was 2.5 ha and this varied by district. Regarding the largest patches (XL), those of at least 3594 ha in size cover a total of 976,504 ha amongst 101 patches, which is 41% of forested area in Bavaria. Upper Bavaria had both the largest area of XL patches (296,475 ha) distributed amongst 21 forest polygons, as well as the highest number of XS forest patches (17,847).

3.1.2. Core and Edge Area

A 100 m edge depth was considered in this analysis. The remaining interior forest area not contained within the edge zone is considered core forest. Among the XS fragments, 99.8% lies within the 100 m edge zone. The resulting mean core areas in these patches is 0.2 ha. Edge and core area increased with increasing patch size category. However, only among patches L or larger is the average core area higher than 30%. This suggests the patch shape is highly irregular, with longer perimeter lengths and more perforations with respect to forest patch areas. For the largest fragments (XL), the average core area is 38%.

3.1.3. Perimeter

Total perimeter length did not have a strictly positive or negative correlation with patch size category. Instead, both the XS patch and XL patch categories had the longest total perimeter lengths, at about 83.9 and 84.6 million meters, respectively. The S, M, and L patch size categories had total perimeter lengths of ~51.5, ~52, and ~57 million meters, respectively. Due to the total size of the perimeter and small individual patch areas, the perimeter-area ratio, or 'paratio', was highest among fragments in the XS category.

3.1.4. Perforations

The number and total area of forest perforations or gaps increased with patch size and varied widely between counties. Less than one gap existed per XS patch on average; meanwhile, the largest fragments contained on average more than 2300 gaps across the state. Upper Bavaria had the largest area of perforations (69,164 ha), while Middle Franconia had the smallest area (12,237 ha).

3.1.5. Shape

Patch shape was measured using two metrics: the 'paratio' and the shape index. Paratio decreased with increasing patch size, reflecting the larger patch area with respect to patch perimeter length. Shape index increased with patch size. This suggests an increase in shape complexity, meaning shapes diverge from simple geometric forms (circles, squares). Shape complexity also increases with the occurrence of perforations. In Figure 10, we present examples of increasing shape complexity (A–H).

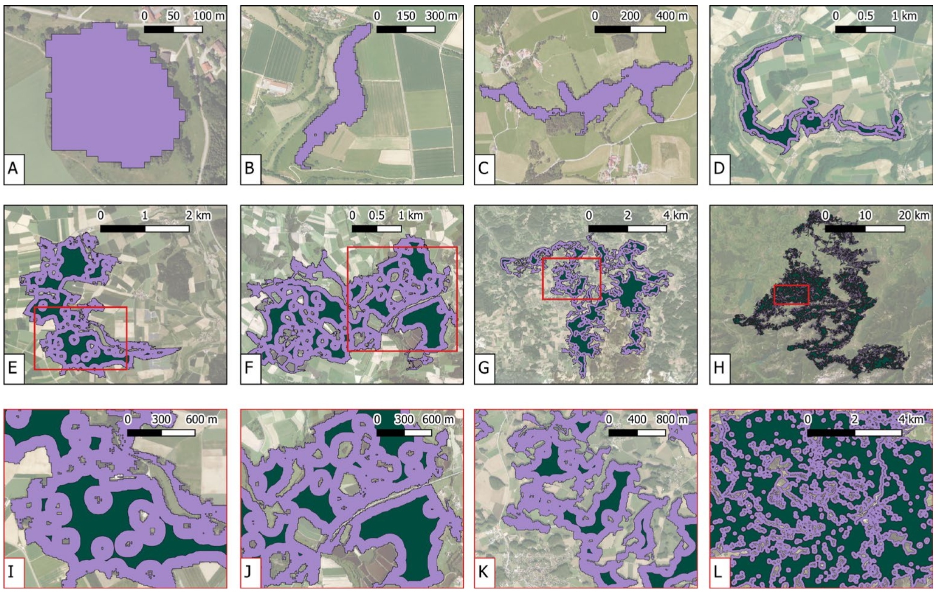

Figure 10. Examples of increasing values of the shape complexity metric. Red extent boxes are detailed in the inset maps (I-L) below E-H: 1.2 (**A**), 2.3 (**B**), 4.0 (**C**), 5.7 (**D**), 6.3 (**E**,**I**), 8.0 (**F**,**J**), 15.0 (**G**,**K**), 60.0 and (**H**,**L**). Values close to 1 indicate basic geometric shapes whereas high values indicate highly complex shapes which include perforations. Dark green represents core forest area, while lavender represents edge area at a depth of 100 m.

3.1.6. Neighborhood

With respect to functional fragmentation, the patterns were not necessarily linearly correlated to patch size. Instead, XS forests had the highest total number of neighboring patches within a 200 m buffer area, followed by S, M, XL, and L fragments. However, the average number of neighbors increases based on patch size category. XS patches on average had 2.1 neighbors, a number which increased with each successive larger patch. XL patches had an average of 99 neighbors each. Although the mean area of neighboring forest polygons varied by patch size, forest patches neighboring XL fragments were on average the largest compared to other patch sizes.

The distance between neighboring patches also varied between patches sizes and counties. In general, the distance between patches increased depending on the size of the patch. The nearest or most aggregated patches were found among the XL patches and surrounding neighboring patches in Lower Franconia. These were on average 58.3 m apart (considering patches within the 200 m buffer). The longest distance between neighbors on average was 86.3 m; this was seen amongst the XS patches in Upper Franconia.

3.2. Spatial Distribution

Figures 11 and 12 visualize the spatial distribution of fragmentation density patterns, aggregated at the district level in Bavaria. The metrics were normalized by district area in order to make meaningful comparisons, and the sparse data within municipalities was masked (gray polygons). Municipal districts are dominated by built-up areas, and therefore forest cover is limited or distinct from other districts.

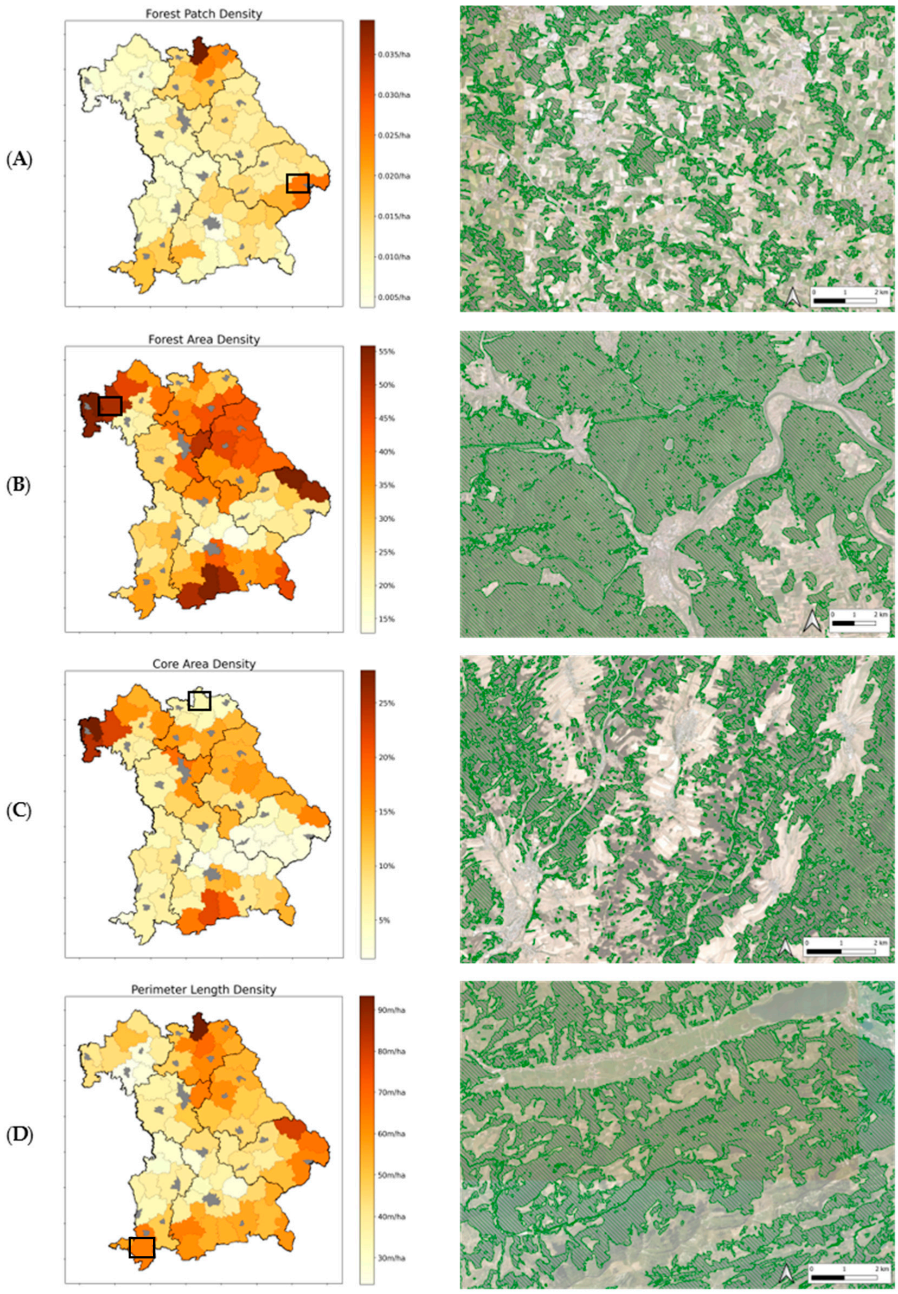

Figure 11. Distribution of forest patch (**A**), area (**B**), core (**C**), and perimeter length (**D**) densities. Inset maps indicated by black extent boxes. Forest polygons shown in green.

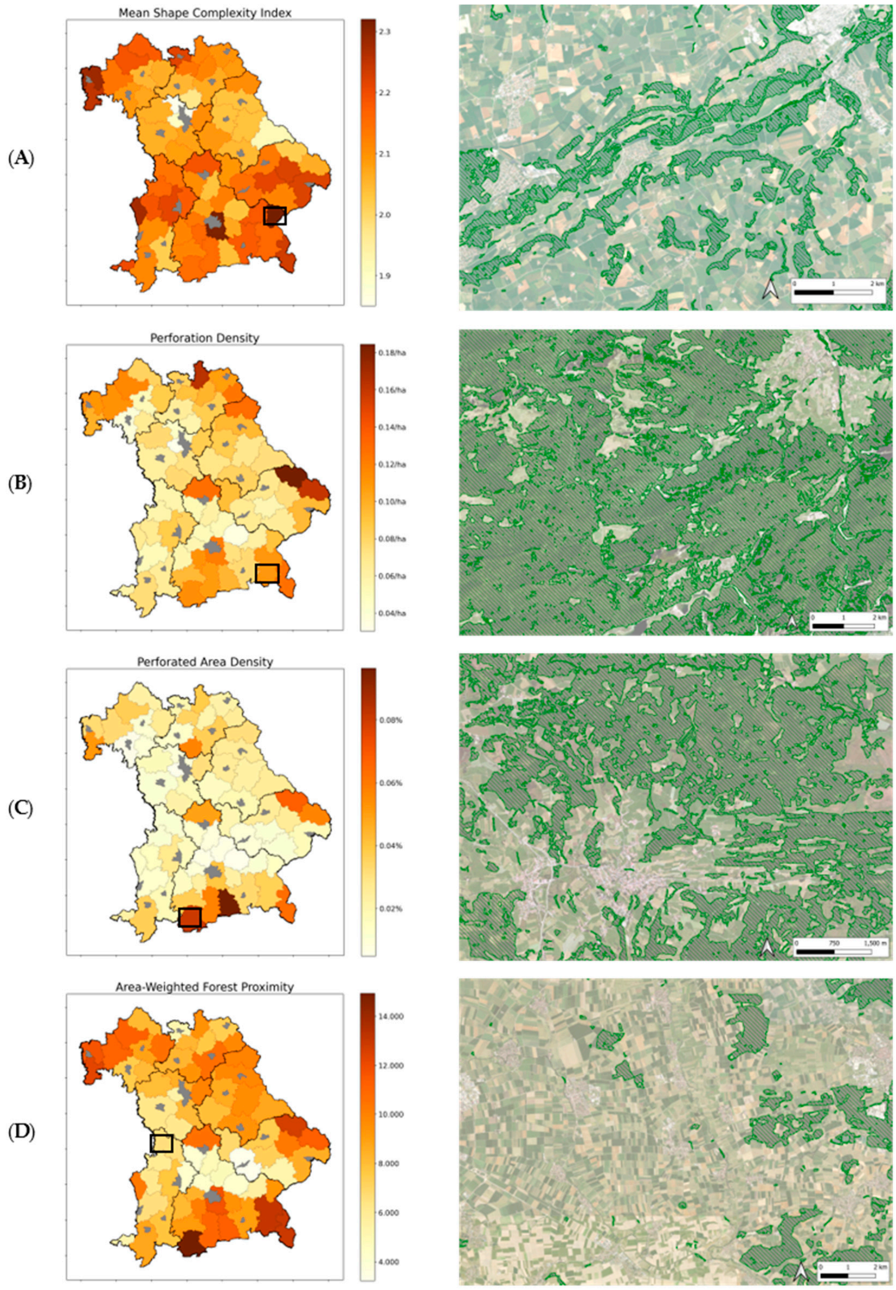

Figure 12. Distribution of mean shape (**A**), perforation (**B**) and perforated area (**C**) densities, and patch proximity (**D**). Inset maps indicated by black extent boxes. Forest polygons shown in green.

3.2.1. Patch Count Density

Kronach district, in the northeastern region of Bavaria, has the highest density of forest fragments (total number of fragments normalized by district area), followed by the neighboring Kulmbach and Hof districts, and the Passau district in the east. Figure 11A highlights the high number of fragments in the Passau district. Districts with lower patch densities were more evenly distributed across the state, with the county surrounding the city of Munich in the southern district of Upper Bavaria having the lowest density of patches per district area.

3.2.2. Area Density

Districts with the largest total forest area with respect to district area include Main-Spessart (inset, Figure 11B), Aschaffenburg. and Miltenberg in Lower Franconia; Regen and Freyung-Grafenau (corresponding to the Bavarian Forest National Park—BFNP) in the east; and Miesbach, Bad Tolz-Wolfratshausen, and Garmisch-Partenkirchen districts in southern Upper Bavaria.

3.2.3. Core Area Density

The ratio of core forest with respect to the total area per district follows similar trends as those of the total forested area. Districts surrounding the city of Munich have the smallest amounts of core forest, including Dachau, Freising, Erding, Landshut, and Mühldorf. Kronach district is shown in the inset map (Figure 11C), displaying low core forest area density.

3.2.4. Perimeter Density

The density of forest perimeter lengths tended to be higher in the north, east, and south of Bavaria. This was especially the case in Kronach and surrounding districts in Upper Franconia and the area surrounding the BFNP in the east. Oberallgau district is shown in the inset map (Figure 11D).

3.2.5. Shape Complexity Density

Figure 12A presents the distribution of the mean shape complexity index. As the index increases, forest patch shape deviates from simple geometry, becoming increasingly complex, especially for patches with long perimeter lengths and perforations. Patch shape complexity is distributed relatively evenly across the state with some exceptions featuring low mean complexity, including Cham and the districts surrounding Nuremburg (Forchheim, Erlangen-Höchstadt, and Fürth). The inset map (Figure 12A) presents the index in Altötting district where long narrow forest patches with perforations are common.

3.2.6. Perforation Density

Forest perforations (Figure 12B) are particularly abundant in the districts Kronach, Regen, Freyung-Grafenau, Traunstein (inset map, Figure 12B), and Berchtesgadener Land, which are also heavily forested districts, whereas districts with the smallest patch sizes also have the fewest forest gaps (those situated outside of Munich and Nuremberg). The highest density of perforations was found in the southern districts of Miesbach and Garmisch-Partenkirchen (inset map, Figure 12C), as well as in Berchtesgadener Land, Regen, and Freyung-Grafenau in the east. Eichstatt, in the center of Bavaria north of Ingolstadt, has a notable density of perforations, unlike the surrounding districts.

3.2.7. Perforated Area Density

The highest density of perforated area was found in Miesbach district followed by the Garmish-Partenkirchen (Figure 12C and inset map) and Regen districts. Berchtesgadener Land, Freyung-Grafenau, Bad Tölz-Wolfratshausen, Eichstätt, Forcheim, and Miltenberg districts also had high densities of perforated area. Districts with the lowest perforated area density were also districts with the smallest overall density of forest area, namely, those east of Munich in Upper and Lower Bavaria.

3.2.8. Neighborhood

The number of neighboring patches found within a 200 m buffer of every forest fragment was highest in Kronach district, a region with high total forest area and a high density of patches relative to the area of the district. Using the area-weighted proximity metric (Figure 12D), patches with more and larger neighbors indicate the denser aggregation of patches. This pattern follows the largest patches in the northern districts of Franconia, but especially in the south in Garmish-Partenkirchen, Traunstein, Berchestgadener Land,

and Regen districts. In the Donau-Ries district, forest patches have few neighboring patches, meaning forest patches are more isolated (Figure 12D inset map).

3.3. PCA and K-Means Clustering

The first two components of the PCA explained 75.5% of the variation among 16 metrics of fragmentation, aggregated within 71 districts (municipal districts omitted). According to the PCA biplot (see Supplementary Materials for all tables and plots related to PCA and K-means analysis), Component 1 (48%) accounted for most of the mean aggregations of metrics, but also included sums of perforated areas and core zones. Component 2 (27.5%) included most of the sum aggregations, but especially the sum of patches, and perimeter lengths. The sum of forest area and the mean shape complexity contributed roughly equally to both components. The first three components had eigenvalues >1 (7.6, 4.3, 1.5, respectively). The absolute loadings of the three dimensions revealed all 16 metrics to be greater than 0.25 and thus all were retained for further analysis using the K-means approach.

K-means was performed on scaled metric aggregations. Three clusters were selected for the K-means analysis based on the elbow method. The silhouette plot indicated the weak clustering of groupings, with scores 0.22, 0.17, and 0.44. Although more robust clustering may be achieved with 2 clusters (the average silhouette width was slightly higher for the 2-cluster solution (0.321)) than for the 3-cluster solution (0.309), we found the spatial distribution and metric comparison to be aligned with fragmentation patterns using three clusters. The K-means cluster plot shows three distinct clusters, using convex hulls to outline cluster shapes.

Figure 13A uses mean Z-scores to illustrate cluster patterns among fragmentation metrics. Z-scores are interpreted as higher or lower than the mean values for all clusters. Cluster 1 is distinguished by a longer sum perimeter length and a greater number of patches relative to other clusters. These districts also exhibit high total forest area, a high number of perforations, and large total amount of edge zone. This cluster is also defined by smaller-than-average mean values, including the perimeter length, number of perforations, perforated area, edge and core, and shape complexity. Cluster 2 exhibits higher-than-average Z-scores for all metrics, excluding the sum of patches, which is below both Cluster 1 and 3, indicating the fewest number of patches. Cluster 3 Z-scores are below the mean value for all fragmentation metrics.

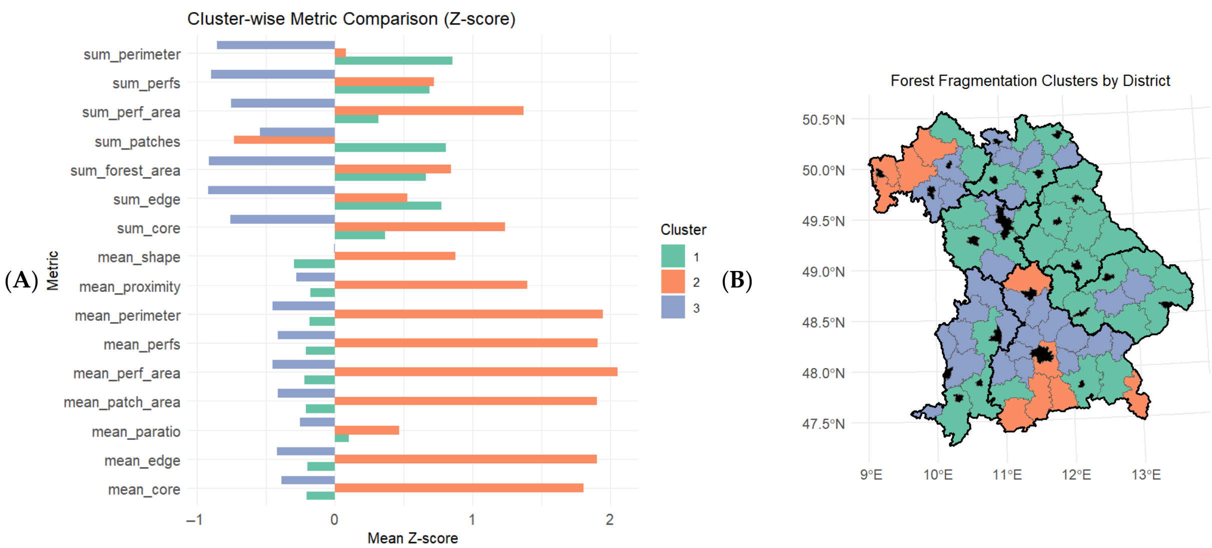

Figure 13. K-Means clustering by mean Z-scores of fragmentation metrics per cluster (**A**) and by spatial distribution of districts (**B**).

The spatial distribution of clustering patterns is similar to the pattern of forest size category. Cluster 2 contains most, but not all, of the XL forest patches in the state; Cluster 1 is correlated with a high number of L patches, while Cluster 3 is dominated by XS, S, and M forest patches, which is also indicated by the negative Z-scores observed for all metrics. Cluster 1 has the highest sum of patches while having the second highest total forest area. Cluster 2 has fewer than the mean number of patches and a large area of forest; however, the mean and sum perimeter lengths are higher than the mean, with a greater relative number of perforations and perforated area.

4. Discussion

4.1. Patchiness—Number of Patches, Forest Area, and General Distribution

Large forests represent roughly one-third of the total forested area of the state. The largest forests are located primarily in remote mountainous regions of the state, above 600 m.a.s.l., are typically state-owned, dominated by spruce, and classified as parks or reserves. The K-means clustering result suggested that Cluster 2 is the least patchy landscape. These districts are characterized by several, large continuous forests which are more aggregated than patches within other clusters. However, Cluster 2 was also dominated by perforations and perforated area which contributes to edge effects. With the greatest relative number of patches, Cluster 1 could be considered the patchiest landscape; however, patches may be more aggregated than Cluster 3, which had the lowest proximity to nearby patches and the least forested area overall.

The value of ecosystem services provided by large forests, including the regulation of the hydrosphere, cannot be replaced by any other means [8]. Therefore, the protection and management of large forests is vital [73]. Large, continuous core areas are especially important for carbon reduction and storage, and also land surface temperature regulation [10]. In Bavaria, XL forest patches together contain over 180 times the core forest area of the XS patches combined. However, due to increasing drought stress and widespread bark beetle infestations affecting spruce stands, recent large-scale forest dieback has significantly altered the carbon balance of German forests. While forest growth historically exceeded loss—leading to net carbon sequestration—this trend has been reversed. According to the most recent *Bundeswaldinventur* (BWI, Federal Forest Inventory), since 2017, Germany's forests have become a net source of carbon rather than a sink [72]. These findings are supported by eddy covariance measurements from forest flux towers, which provide high-resolution, continuous carbon exchange data. For example, recent flux observations from a Scots pine forest in southwestern Germany show a shift from carbon uptake before 2018 to net carbon release in subsequent years due to drought-induced mortality [10]. How long this trend persists will depend on forest management decisions—particularly those related to species composition and nature conservation.

Among the smallest patches, the ratio of edge to core is such that only a small percent of forest can provide core-specific habitats and ecosystem services. Meanwhile, edge effects dominate small forests and stress edge zone buffer trees, which can lead to further forest loss. Regardless, small forest patches can still deliver ecosystem services, provide habitats, and habitat connectivity across a landscape, and should therefore not be discounted as valueless [13,74]. In a study related to the effects of small woody features (comprising trees and/or shrubs and smaller-than-XS forest patches) on land surface temperatures, the authors identified a cooling effect on adjacent agricultural fields, which was modulated by patch orientation and shape [75].

4.2. Aggregation—Patch Neighborhood

A 200 m buffer was used to approximate the neighborhood aggregation of patches using distance and the proximity metric. The number of neighboring patches within a 200 m buffer increased with the forest size category. Furthermore, Cluster 2 had larger and more aggregated patches compared to other clusters. Larger patches constitute longer perimeters, and thus greater proximity to more neighboring patches. However, amongst the smallest patches, the mean number of neighbors was 2.1. Smaller patches tended to dominate Cluster 3, which also had the lowest relative proximity amongst the clusters. With few neighboring patches, together with the small size of nearby forests (2468 ha for XS and 12,708 ha for XL patches), this pattern suggests forest patch isolation and reduced habitat area, among the districts of Cluster 3 especially, which can influence habitats and animal movement in addition to plant dispersal and reduced biodiversity.

Habitat isolation and patch size are key considerations underpinning the theory of island biogeography, which has often been applied to forested landscapes and may be useful for managing forested landscapes where maintaining biodiversity is a desired outcome [20]. However, an alternative theory (the habitat amount hypothesis) proposes the conservation of a minimum habitat amount within a landscape, regardless of patch size or isolation, in order to achieve the same biodiversity goals [13]. In practice, these management considerations depend on region and purpose (and thus species composition) and foresters must weigh the cost of each theoretic approach against the benefit whether—economic or environmental [76].

The isolation of small patches may be modulated by the presence and proximity of hedgerows, which typically border agricultural fields; however, this approach was not investigated in this study. Hedgerows, analogous to the aforementioned small woody features (smaller than forests by definition), have a heterogenous distribution in Bavaria, and may act as corridors, supporting the connectivity of forest patches and thus promoting the integrity of ecosystem functioning [77].

4.3. Edginess—Perimeter, Edge Zones, Perforations, and Shape Complexity

Although Cluster 3 had the smallest edge and perimeter overall, the forest area was the smallest of the three clusters. This suggests that edge effects would dominate in individual patches, thus contributing to an overall edgy landscape compared to clusters with large, complex forest patches containing numerous perforations. Total forest perimeter length for the smallest patches (~83.9 mil m) was relatively similar to that of the largest forests (~84.7 mil m) in comparison to other forest sizes across Bavaria. Due to the apparent stochasticity of climate-driven tree mortality, forest patch shapes can become increasingly complex; therefore, complex forest shapes contribute to the length of the forest perimeter. This exposes trees to so-called edge effects, which vary considerably from conditions within the forest interior [78]. The consequences of this can include degraded ecosystems, biodiversity loss, and disruptions to animal movement and plant dispersion as forest species run out of contiguous habitat [74]. However, disturbance outcomes are not always unidirectional. The increased penetration of sunlight into gaps drives the succession of forest species and moreover provides vital habitat, moisture retention, and nutrients via fallen deadwood.

Forest edges and interiors have distinctive microclimates. Vegetation structure, species composition, microclimate, nutrient cycling, and biodiversity within edges can function as a buffer for forest interiors. This functionality is furthermore influenced by both latitude and management practices [63]. Therefore, a gradient can exist between the perimeter of the forest, penetrating the depth of the edge zone towards the core.

Forest edges play an important role, both as buffer zones for continuous forest interior core zones, but moreover as regions where generalist species proliferate, especially following disturbances. Biodiversity (of particularly forest specialists) can be negatively impacted as the forest area and connectivity of patches decrease; however, increased light penetration tends to initially benefit both early successional generalist and alien species [79,80]. In a study investigating forest edges (ecotones) in central Europe, Czaja et al. found vertical structural but also species differences between the edge and the interior. Their work also suggests the migration of wind-pollinated species towards the perimeter of the forests, which indicates a preference or adaptation for the abiotic microclimates present along forest edges [22].

Cluster 2 had the largest perforated area relative to other clusters. As new perforations within the core area result in fresh edges, depending on the size of the gap, clusters exhibit similar microclimatic conditions to the forest perimeter. Conditions within perforations can stress newly exposed trees, which leave spruce more vulnerable to bark beetle infestations, which persist in subsequent years [81]. Moreover, perforations within a forest can increase in size over time; in the protected and largely unmanaged Berchtesgaden National Park, Kruger et al. found that expansion rates of gaps in spruce forests were higher than those of other forest types [82]. The sudden increase in light availability can also be favorable even for established interior trees. In a study of mixed mountain forests on the southern border of Bavaria, both coniferous and deciduous species experienced increased growth rates along the fresh edges of forest perforations larger than 80 m^2 [25].

4.4. Terrain Distribution—Elevation and Orientation of Forest Patches

In this investigation, we included a brief description of topographical patterns of forested areas. Elevation varies across the state with most of the land surface located below 600 m.a.s.l.; however, the largest forests are primarily located at elevations above this and are predominantly east-oriented, although eastern slopes cover less total area than other aspects. Management and forest ownership often determine the location of forests; however, topography affects microclimatic conditions, which can play a role in the resilience or severity of disturbance effects.

Temperature and precipitation vary with elevation and are thus limiting growth factors, especially in mountainous terrain; meanwhile, sunlight is influenced by aspect orientation. Topographically modulated microclimates can have an effect on tree height, aboveground biomass, basal area, and species distribution [83]. Elevation, aspect, and slope (not investigated in this study) interactively effect tree growth, whereby the optimal orientation is determined by elevation [84]. With respect to disturbances, the magnitude of the forest loss can depend on elevation and slope orientation [85,86]. East-facing forest patches in Bavaria may experience microclimatic advantages over other orientations, especially south- and west-facing patches. Broadly speaking, eastern slopes could experience less frost due to morning sunlight whilst avoiding direct afternoon sun exposure, which could reduce evaporative demand. These conditions would also have an effect on soil moisture, which furthermore supports forest growth. It may also be possible that forest loss during recent years has had a disproportionate effect based on aspect orientation, resulting in the higher proportion of forest cover on east-facing slopes. A follow-on investigation will address this gap using time-series forest loss data.

Edge orientation can also influence abiotic conditions which support temperature-dependent insects like the European spruce bark beetle (*Ips typographus*). Therefore, understanding the distribution of forests with respect to fragmentation metrics and terrain can supplement spruce forest management given that bark beetles prefer warmer, drier conditions which can be useful in predicting and managing future outbreaks [87]. In the BFNP, south-facing edges were twice as likely as north-facing edges to be infested in subsequent years following a nearby infestation [81]. Future analysis could consider aspect-elevation interactions to further inform targeted management strategies.

4.5. Methodology, Further Considerations, and Limitations of the Study

The metrics for this analysis were selected from FRAGSTATS definitions of forest zones, shapes, and distributions. We found the FRAGSTATS methodology to be well-established, comprehensive, and widely applied to various ecological habitats (Google Scholar returns over 7000 related publications since 2021). We therefore built our calculation processing chain based on these definitions. Other methods based on definitions of forest connector types, for example, bridges, islets, loops and branches, following [88,89] (732 citations at the time of writing this manuscript) are equally valid, would produce similar outcomes, and may be considered in future analysis. A broader analysis of the process of forest fragmentation development will be the subject of a follow-on investigation.

Despite being monotemporal, the current analysis provides valuable insights into structural fragmentation across the landscape. Edge effects may dominate districts where the number of patches is high, the average forest size is small, and patch shapes are highly complex. It is also possible to identify large continuous core areas that provide numerous ecosystem services and represent a larger share of forest area within a landscape. This information can be used to further investigate these particular zones, for example, with respect to vegetation vitality or soil moisture within edge zones or at perimeters, which could be conducted using ground-based measurements or with remotely sensed indices. Importantly, a characterization of the spatial distribution and composition of forest patch elements (perimeter, edge zones, core area, and patch aggregation) was not available until now for the entire state of Bavaria or at aggregated administrative levels.

However, fragmentation is a dynamic process, driven by natural and anthropogenic disturbances that alter the structure of a forest over time. The resulting fragmented forest patches may therefore function differently than the original continuous forest. As such, understanding how and where the process of fragmentation is progressing requires multi-temporal analyses. Using time-series data, it would be possible to monitor trends in forest structure (e.g., area, shape, perforation dynamics, connectivity) and assess how fragmentation evolves across zones (core, edge, perimeter) and terrain gradients (elevation, slope, aspect). Multi-temporal analysis is useful for assessing whether forest loss occurs together with patterns of fragmentation like shrinkage, bisection, and the perforation of forest patches. Such analyses are crucial for guiding long-term forest conservation and adaptive management strategies.

Management plays a significant role in determining the future of forests, since the determination of species propagation after losses is vital for the outcomes of services provided by Bavarian forests. Natural disturbances along edges are key factors influencing local biodiversity; meanwhile, highly managed core areas are often species-poor monocultures. In future studies of forest fragmentation in Bavaria, analyses based on forest ownership (state or private) may be useful for reaching a target audience of managers, owners, and/or policy-makers. Furthermore, analysis based on protected status could determine the effectiveness of management schemes in the context of fragmentation patterns. Moreover, the addition of connectivity-focused analyses is also necessary for understanding the distribution of forests in the context of habitats and conservation.

5. Conclusions

We classified forest patches based on size and calculated both structural and functional fragmentation metrics. Thus, we characterized the distribution of fragments, both spatially and with respect to terrain, and presented our findings within the context of state-, county-, and district-level administrative units to support forest policy and management decisions. We focused on the amount and distribution of patches, forest core and edge zones, and the densities of each metric within districts.

Although more than a third of the land surface of the state is covered by forests, the results suggest that the forest landscape of Bavaria is dominated by fragmentation per se, given that the smallest patches (<25 ha) outnumber all other patch sizes. The number of small patches together with the amount of edge zone and perimeter length relative to the core area also suggests that edge effects dominate the smallest patches, which contain no core area. The largest forests are distributed at the highest elevations and are predominantly east-facing, a phenomenon that warrants further investigation.

Taken together, the relative patchiness, the aggregation of patches, and the edginess provide context for understanding the level of fragmentation intensity within a landscape. The metrics approximating these concepts were the number of patches, perimeter and edge (including perforations), shape complexity, and neighborhood (proximity). A hotspot of these indices of fragmentation was found in Kronach and Regen districts, which exhibited high densities of forest patches and perforations, respectively. Therefore, it suggests that these districts may have a relatively higher intensity of fragmentation compared to other landscape units (districts), irrespective of forest loss.

PCA retained all standardized metrics for clustering using the K-means method. Groupings revealed a forest patch size correlation, which resulted in three clusters approximating patchiness, aggregation, and edginess. In addition to the fragmentation metrics of individual forests and landscape aggregations, cluster patterns may furthermore be a factor of species, forest ownership or protected status, management practices, terrain, or disturbances due to drought, storms, or infestations.

These results contribute to a growing body of forest research in Bavaria based on EO data. In order to better understand fragmentation patterns in the context of forest loss, studies using multi-temporal data are needed. Understanding fragmentation is imperative, considering the climate-driven degradation of essential services and benefits provided by temperate forest ecosystems. Future work should therefore concentrate on uncovering drivers and hotspots of fragmentation and the subsequent effects on the forest ecosystem.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/rs17152558/s1, Supplementary File, Table S1: Fragmentation results for the state of Bavaria, Table S2: Fragmentation results for Lower Bavaria, Table S3: Fragmentation results for Lower Franconia, Table S4: Fragmentation results for Middle Franconia, Table S5: Fragmentation results for Swabia, Table S6: Fragmentation results for Upper Bavaria, Table S7: Fragmentation results for Upper Franconia, Table S8: Fragmentation results for Upper Palatinate.

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