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Forest disturbance dynamics in Bavaria: A novel approach for identifying fragmentation processes based on canopy cover loss and morphological image processing

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A B S T R A C T

Unprecedented canopy loss has become a feature of central European temperate forests in recent years and is expected to continue. Bavaria, the largest and most forested state in Germany lost 146,320 ha from September 2017 – July 2025. To investigate the dynamics of forest disturbance, we classified interior, exterior, and convergent fragmentation processes (perimeter loss, shrinkage, perforation, and bisection) over an 8-year study period by intersecting the Forest Canopy Cover Loss (FCCL) dataset with a spatial classification using morphological image processing of 10 m forest mask rasters. We delineated 762,602 individual clusters of forest canopy loss, ranging in size from 0.01 to 1228 ha. The largest clusters were identified as bisection processes and were initiated early in the study period and contained multiple sub-clusters, suggesting expansion and merging of disturbance events. Fragmentation process labeling was sensitive to the edge depth, however the most robust processes were perforation, which covered 43% of total cluster area and perimeter loss (1.8%). Although nearly 34% of forest core areas transitioned into edge zones due to perforations, perimeters were the most relatively affected zone, whereby >7% of canopy was lost. While the number of small forests ('Islets') increased by 167.9%, core forest area declined along with a 12.6% decrease in the number of patches. This pattern suggests perimeter loss and bisection of core forests. Because fragmentation processes precipitate localized canopy restructuring and landscape reconfiguration, which have distinct ecological outcomes, this approach can be further applied both for spatially-explicit modeling of forest disturbance and as an indicator for monitoring habitats and biodiversity.

1. Introduction

Disturbances are vital for forest ecosystem function (Blackburn et al., 2014). Storms, insect infestations, and disease create sporadic and abrupt small-scale loss of individual trees, forming localized canopy openings where sudden increases in sunlight and precipitation support new growth of understory vegetation (Schliemann and Bockheim, 2011). Fallen dead trees within canopy gaps can retain moisture and provide new habitats, which promotes forest recovery (Harmon et al., 2004; Thorn et al., 2017; Vichta et al., 2025). Disturbances are an essential and transitory component of a natural, functioning forest, typically contributing to localized structural and functional reorganization rather than permanent canopy loss (Muscolo et al., 2014). Therefore, depending on the scale of disturbance, this process is often beneficial (Fahrig, 2019; Swanson et al., 2011).

In recent years however, large-scale disturbances as a result of drought, pest outbreaks, and storm events have increased due to climate change (Allen et al., 2015; Senf et al., 2020). Since 2018, unprecedented drought resulted in up to 500% above average increase in forest disturbances across central Europe (Senf and Seidl, 2021). Such anomalies often have persistent effects in subsequent years (Brun et al., 2020) and are moreover predicted to increase (Grünig et al., 2026). Large-scale disturbances can lead to fragmentation of forests. Fragmentation is a process whereby a patch of forest breaks apart becoming multiple patches, which restructures forest distribution across a landscape (Haddad et al., 2015; McGarigal and Cushman, 2002). Fragmentation is often though not always coupled with a decline in overall forest area (Fahrig, 2017). When viewed from the landscape perspective, a forest undergoing fragmentation via widespread disturbances can become smaller and less connected over time. The resulting forest patches function differently than the original forest, which impacts productivity, ecosystem services, habitats, and biodiversity (Graser et al., 2025). Therefore, spatial patterns of fragmentation may be an indication of transforming forest functionality.

In central Europe, the scale and severity of disturbances in recent years has dramatically altered forest cover (Patacca et al., 2023). In Germany alone, 924,000 ha of forest canopy was lost between September 2017 and July 2025 (Thonfeld et al., 2026). Shifting climate regimes coupled with land-use history and forest management (Rüther and Walentowski, 2008) have likely intensified the severity of forest

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loss (Štraus and Bončina, 2025). For example, Norway spruce (*Picea abies*), an economically important introduced species, are not well adapted to hot, dry summers (Mauri et al., 2022; Washaya et al., 2024). Spruce are hosts for native bark beetles, which can attack drought-stressed live trees making pure monocultures susceptible to outbreaks (Das et al., 2025; Nardi et al., 2023).

In September 2017, Thonfeld et al. (Thonfeld et al., 2022, 2026) began tracking monthly forest canopy cover loss (FCCL) (Fig. 2 C). Spruce forests were the most affected; more than 449,700 ha was lost across Germany between 2018 and 2025 (Wegler et al., 2026). At the state level, forests were affected disproportionately. In Bavaria, the largest state with the most forested area, nearly 75,000 ha of spruce canopy was lost (Wegler et al., 2026). Although Bavaria was not the most affected state overall, future climate-driven losses are predicted to worsen in the region (Grünig et al., 2026), especially given that spruce forests account for nearly 38% of the forested area (942,235 ha) (Johann Heinrich von Thünen-Institut, 2022). Neighboring heavily spruce-dominated countries are also at risk: in the Czech Republic and Austria, Norway spruce accounts for roughly half of total forest area (Jandl, 2020; Šimůnek et al., 2024). Given that subsequent beetle infestations are often correlated by proximity to previous outbreaks (Kautz et al., 2011), localized losses due to bark beetles are often an indication of forthcoming infestations nearby.

A study on forest fragmentation in Bavaria found that in 2024, the state was dominated by the smallest forest patches (< 25 ha) which outnumbered all other patch sizes by 13:1. However, the largest patches

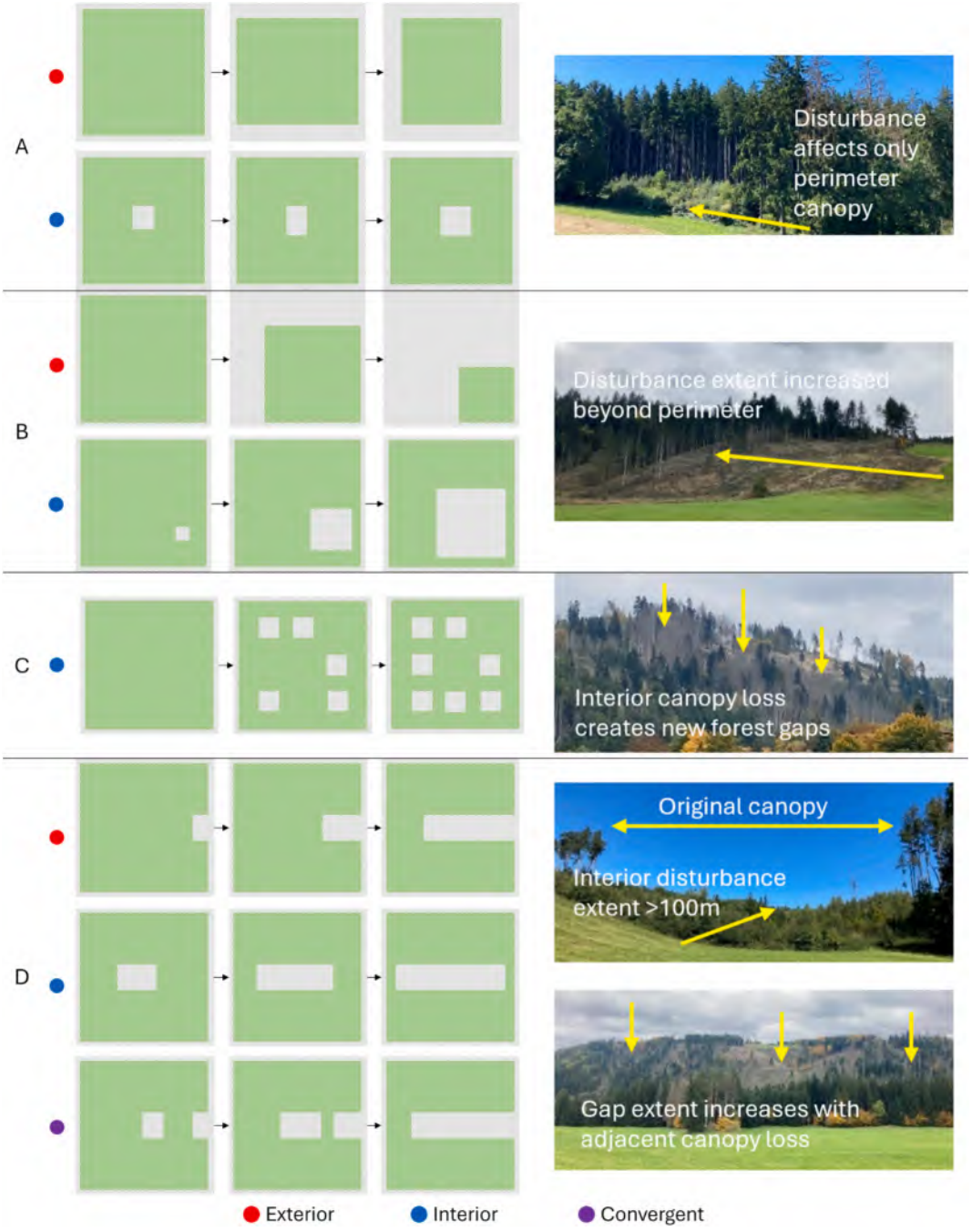


Fig. 1. Fragmentation processes and field examples from Freising (A, D) and Kronach (B, C, D). Perimeter loss (A), shrinkage (B), perforation (C), bisection (D). Adapted from (Coleman and Kuenzer, 2025). Photos: K.Coleman.

(> 3594 ha) still covered more area in total (Coleman and Kuenzer, 2025). The results of this study suggested that the process of fragmentation in Bavarian forests may be ongoing. However, the development of forest fragmentation due to canopy losses in this region remains unknown. Due to the similarities in geography, climate, species composition, and management, the dynamics of Bavarian state-scale forest fragmentation may be indicative of broader patterns on the central European scale. Considering its central location, investigating fragmentation dynamics in Bavaria is critical.

Despite extensive fragmentation research, few studies take a spatially-explicit approach for quantifying how disturbance reorganizes localized forest structure over time. Although popular, geometric approaches typically aggregate data at the landscape scale, which is less informative for determining process dynamics. Because forest fragmentation is an indicator of localized ecosystem change, a spatially-explicit investigation into the localized development of fragmentation processes in Bavaria is needed in order to examine temporal dynamic patterns with respect to the pixel-level relationships between topography, boundary orientation, and species composition. This approach would enable process-based interpretations of forest change.

Spatial processes of fragmentation were introduced by Forman (Forman, 1995) and later updated by Collinge (Collinge, 2009) for conceptualizing distinct patterns of spatially-explicit forest loss. Five processes were described: Perforation, bisection, fragmentation, shrinkage, and attrition. Unidirectional phases of spatial fragmentation processes have often been observed, whereby a disturbance initiates as a perforation (a gap in the forest interior) and progresses to bisection, shrinkage, and finally attrition (disappearance of a forest patch) (Forman, 2008; Ren et al., 2017). Clusters of disturbed trees likely grow or merge with neighboring clusters as exposed adjacent trees are susceptible to continued disturbance (Forsell et al., 2011).

In the current study, we refine Forman and Collinge and propose the following spatial processes (Fig. 1, Table 1): Perimeter loss (A), shrinkage (B), perforation (C), and bisection (D). Within a forest patch, the position of fragmentation processes can occur along the exterior (with the exception of perforation) or within the forest interior. Bisection can occur as a convergent process whereby internal and exterior processes spatially merge. Utilization of the spatial process (hereafter fragmentation process) framework can support an understanding of forest fragmentation patterns in Bavaria.

Spatial processes differ in their ecological consequences, even if the total area of forest loss is similar (Collinge, 2009; Forman, 2008). For example, if a forest patch is undergoing shrinkage, the number of patches and their connectivity typically remains unchanged. By contrast, the same area of forest lost in the process of bisection could lead to an increased number of patches and a decrease in connectivity, thereby disrupting the flow of species, genetic material, and nutrients (Li and Yang, 2015). Some processes modify patch geometry (for example by increasing perimeter length and/or complexity) while not actually fragmenting a patch into multiple distinct patches (Forman, 2008). Different processes therefore have disproportionate outcomes (Reek et al., 2025). A summary is presented in Table 1.

The spatial configuration of forest patches is important for both function (e.g., soil nutrient cycling, photosynthesis) and structure (e.g., habitats, animal movement). The core region, broadly defined as the interior >100 m from a forest boundary (Gustafson, 1998; Meeussen et al., 2020), often supports specialist species, which have narrow microclimatic, nutrient, and/or structural requirements (Almoussawi et al., 2020). In core regions, more competition for resources, especially sunlight, influences the development of canopy architecture (Nunes et al., 2023). By contrast, the perimeter (exterior boundary) and edge (between the perimeter and core) supports edge-tolerant species which favor warmer, drier, and more unpredictable conditions (Almoussawi et al., 2020; Slattery and Fenner, 2021). Trees along a perimeter thus tend to develop branches at lower stem positions and adapted root systems (Nunes et al., 2023; Xu et al., 2025). Edge regions are therefore characterized by a microclimatic gradient (from the perimeter to the core) which supports a unique composition of forest species (Harper et al., 2005; Sun et al., 2025). Due to this structural and compositional heterogeneity, perimeters and edges are often more biodiverse than forest cores (Bähner et al., 2020).

Although perimeter trees are generally more exposed, trees adjacent to newly created interior disturbances may be more susceptible because perforations produce abrupt microclimatic changes in previously stable environments (Forsell et al., 2011). Mature perimeter trees may therefore be more resilient to certain disturbances (e.g., wind) than interior trees with respect to sudden exposure (Einzmann et al., 2017). Moreover, it is not known whether exterior-edge dynamics are analogous to interior-edge dynamics, or whether boundary-adjacent processes are fundamentally different from and can be disentangled from interior processes. It is possible that fragmentation processes undergo a different development pathway when exposed trees are no longer protected by a boundary-facing perimeter of buffer trees. Consequently, the intensity, spread, and recovery of fragmentation is modulated by where in the forest (perimeter, edge, or core) the disturbance has occurred. In short, fragmentation processes affect forest regions unevenly.

This investigation introduces a process-based classification framework to identify and analyze spatially-explicit fragmentation. Conventional fragmentation analyses typically rely on aggregated landscape metrics, which are limited to summary descriptions of structural patterns. Instead, by labeling localized disturbance events as individual fragmentation processes, this approach enables:

- Quantification of disturbance-driven changes to core, edge, and perimeter regions
- Assessment of the relative susceptibility of forest regions to disturbance
- Identification of distinct fragmentation processes, their sensitivity to the influence of edge conditions, and development pathways
- A flexible basis for spatially-explicit statistical modeling of the drivers of fragmentation processes

Table 1
Fragmentation processes and their respective outcomes on landscape configuration exhibit an increase (upward arrow), a decrease (downward arrow), or no change (right arrow). Black indicates a highly likely or certain outcome; grey indicates a possible outcome. Adapted from (Forman, 1995).

Fragmentation Process	Number of Patches	Mean patch size	Core area	Landscape connectivity	Perimeter length	Landscape forest area
Perimeter loss	↑	↓	→	↓	↑	↓
Shrinkage	→	↓	→	↓	↑	↓
Perforation	→	↓	↓	→	↑	↓
Bisection	↑	↓	↓	↓	↑	↓

2. Materials and methods

2.1. Study area

Bavaria is the largest federal state in Germany and is situated at the geographic center of the European Union (Gadheim – 49.8431° N, 9.9019° E - WGS84) (Fig. 2 A). Roughly one third of all forest cover in Germany is located in Bavaria, which is itself more than one third forest-covered (Fig. 2 B). There are four main dominant tree species in Bavarian forests: Norway spruce, European beech (*Fagus sylvatica*), Scots pine (*Pinus sylvestris*), and Oak (*Quercus petraea* and *Quercus robur*). A gradient of tree species exists across the state, corresponding to elevation, annual mean temperatures and precipitation patterns whereby broadleaf deciduous forests occur predominantly in northwestern counties (the Franconian region) and coniferous forests dominate eastern and southern counties (Blickensdörfer et al., 2022; Wegler et al., 2025). Mixed forests are typically the result of more recent deliberate forest management strategies, due to the apparent resilience of mixed over particularly spruce monocultured forests (BMLEH, 2025; Jandl et al., 2019; LWF, B. L. für W. und F, 2015; Rüther and Walentowski, 2008). Forests in Bavaria range in size. The smallest forests, as defined by the Bavarian Federal Ministry of Agriculture, Food, and Regional Identity (BMEL, 2024) are no less than 0.1 ha, while the largest contiguous forest patches are nearly 50,000 ha (Coleman and Kuenzer, 2025) (Fig. 2. D).

2.2. Data processing

The data processing workflow can be found in Fig. 3. All datasets were processed using the high-performance computing cluster 'terra-byte' administered by the Leibniz Supercomputing Center and Python (Van Rossum and Drake, 2009). Figures and maps were created using Python, R (R Core Team, 2020), and QGIS (QGIS Development Team, 2026).

2.2.1. Forest canopy cover loss (FCCL) dataset

To investigate the dynamics of forest fragmentation in Bavaria, we analyzed forest masks from the most recent update of the Forest Canopy Cover Loss (FCCL) product from Thonfeld et al. (Thonfeld et al., 2026). The FCCL product detects 10 m pixel-level forest disturbance at monthly intervals from September 2017 to July 2025 and thus contains 95 months of canopy loss data (see Fig. 2 C). The product is publicly available and updated at regular intervals (https://geoservice.dlr.de/web/datasets/fccl).

The FCCL utilizes all available Sentinel-2 Level-2 and Landsat-8/9 surface reflectance imagery to generate cloud-filtered time series for

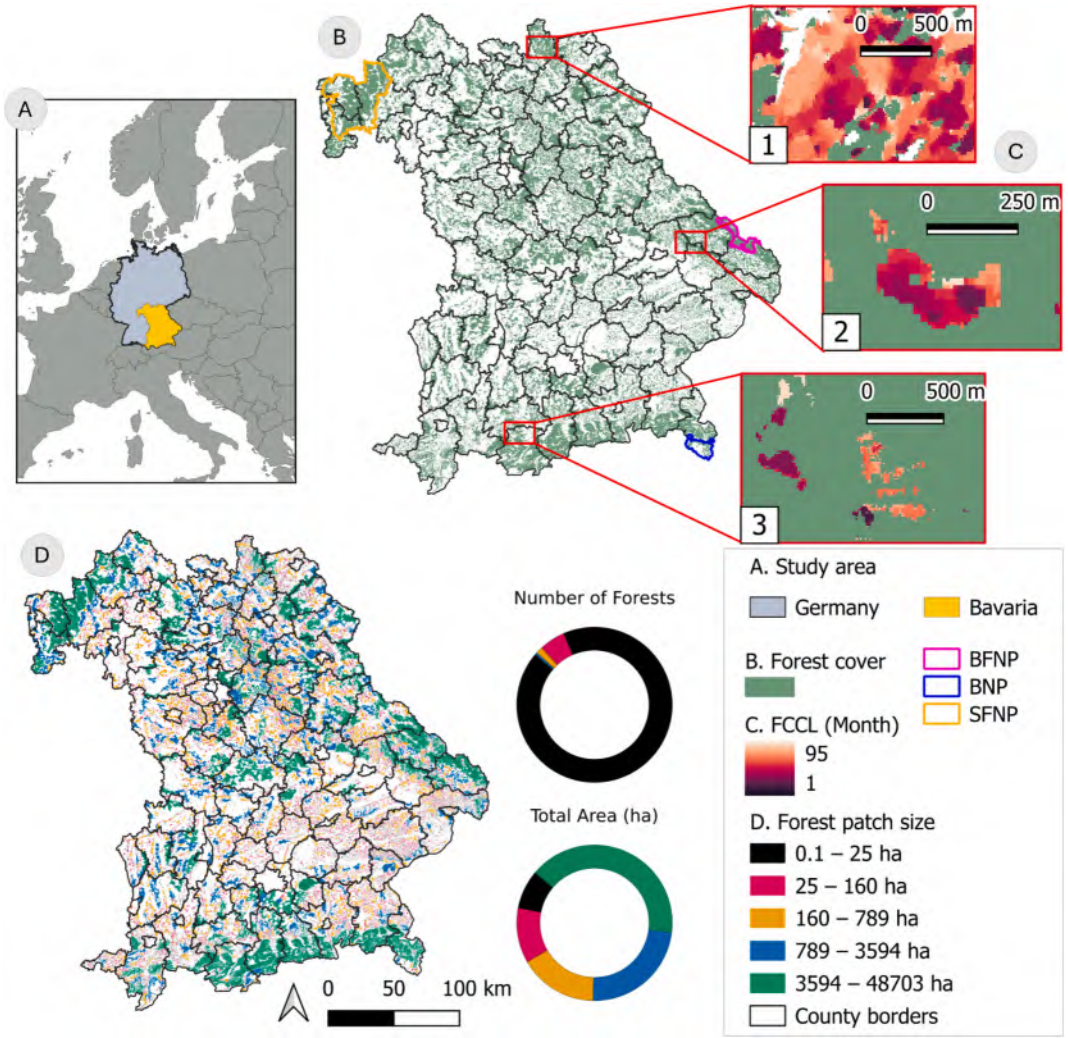


Fig. 2. Overview of Bavaria, located in southeastern Germany and situated in central Europe (A). Forest covers more than one third of the state; major forests include the Bavarian Forest National Park (BFNP), Berchtesgaden National Park (BNP) and Spessart Nature Park (SNP) (B). The Forest Canopy Cover Loss (FCCL) dataset detects forest disturbance at monthly intervals (C 1,2,3). In 2024, small forests outnumbered all other patch sizes 13:1 but covered the smallest area overall, the distribution was heterogenous (D, Adapted from (Coleman and Kuenzer, 2025).

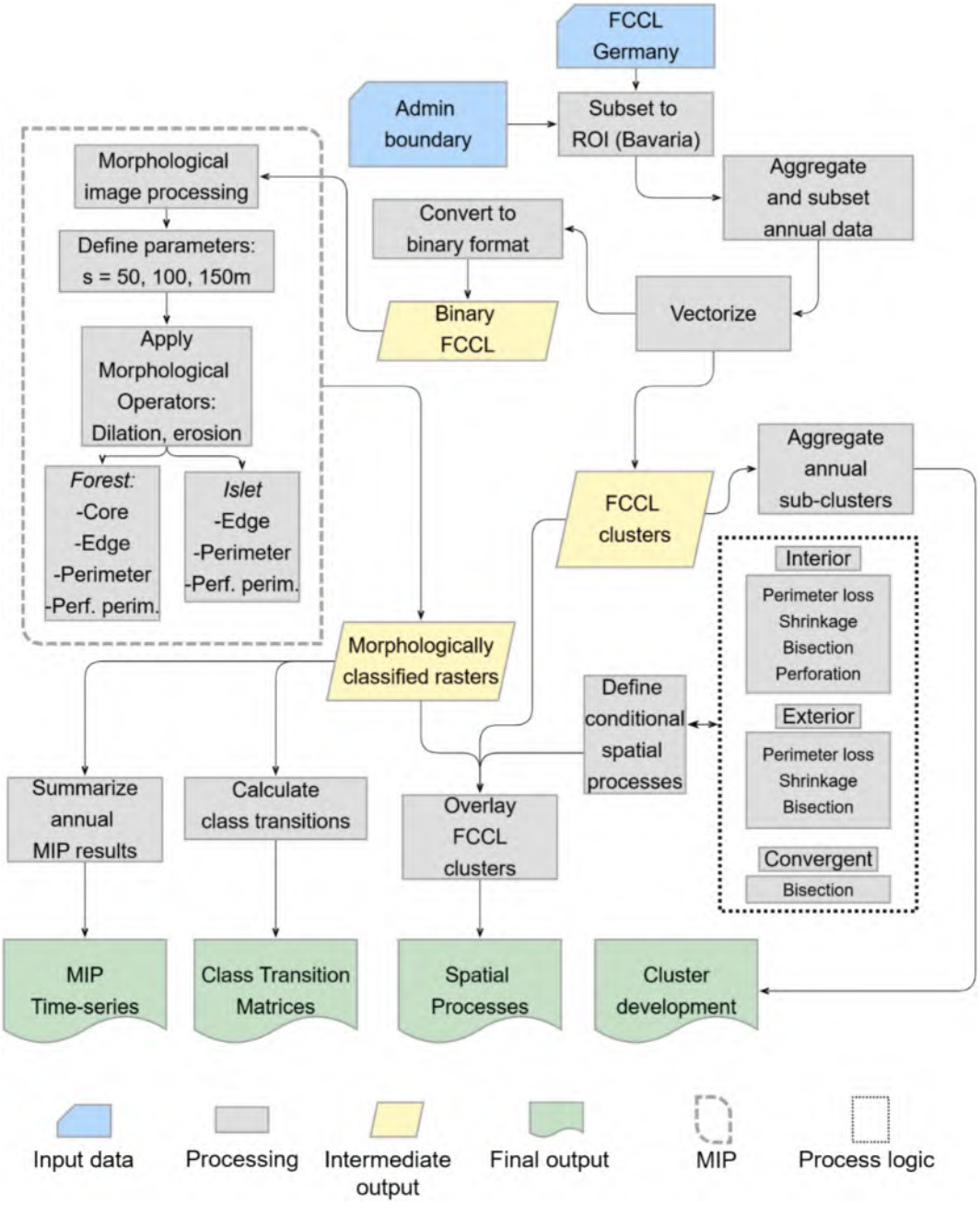


Fig. 3. Workflow for data processing.

the study period. For each image, the Normalized Difference Vegetation Index (NDVI), tasseled cap components (brightness, greenness, wetness) and the Disturbance Index (DI) were computed. Canopy loss detection was performed by applying a fixed threshold to the monthly DI anomaly layers. Pixels were classified as disturbed only if the threshold was exceeded for six consecutive months, ensuring persistent canopy loss rather than short-term fluctuations. The initial product release (2018–2020) achieved an overall accuracy of 0.93 based on validation against high-resolution Google Earth imagery. Subsequent updates through 2025, validated with an independent dataset, reported an overall accuracy of 0.92 and an F1 score of 0.90. We vectorized cumulative FCCL clusters detected in the study period following an 8-pixel connectivity rule. A conceptual illustration of the FCCL data can be found in Fig. 4.

The FCCL dataset detects only canopy cover loss; the product does not include forest gain. In a pre-print by Liu (Liu, 2025), forest loss in Germany was found to be 12:1 relative to gain. Although forest recovery is not explicitly mapped it may be implied that regrown trees in these 8 years are not considered fully recovered. Depending on local definitions, this can range from a minimum canopy height of 2–10 m and may also utilize a minimum measure of DBH (diameter at breast height) (Schliemann and Bockheim, 2011). In Bavaria, canopy regrowth of the earliest lost trees may be within this range but is not likely to have exceeded it. In other words, FCCL disturbed clusters are not fully recovered. In nearby South Tyrol, five years after a storm event caused major windfall in a spruce dominated region, only 4% of trees had regrown to a maximum of 130 cm and in 10% of plots no trees had recolonized at all (Candotti et al., 2025).

2.2.2. *Morphological image processing (MIP)*

To investigate core- and edge-specific forest disturbance patterns and fragmentation, morphological image processing (MIP) can be used for

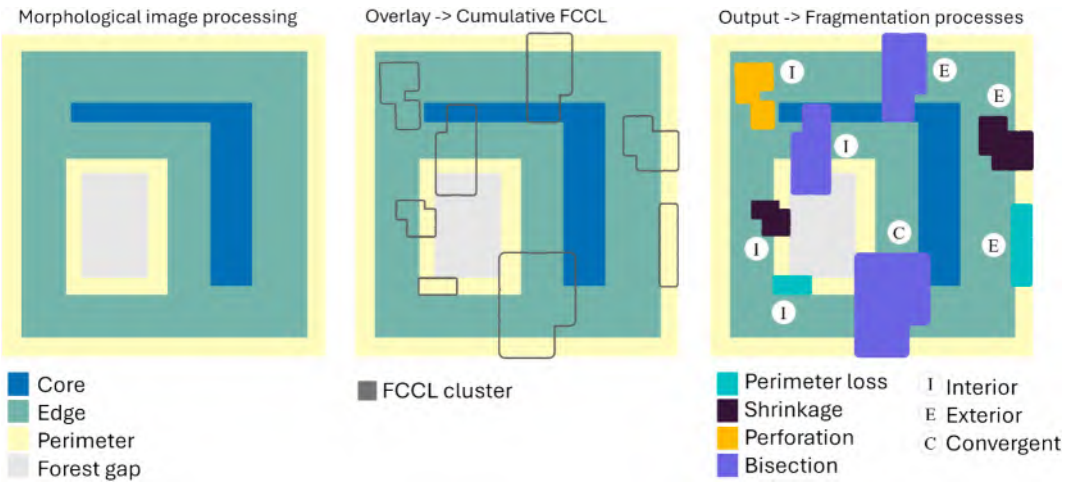


Fig. 4. Illustration of data intersection (MIP and FCCL) to produce four mutually exclusive processes of fragmentation in three positions.

classifying forest regions (Soille and Vogt, 2009). This pixel-based approach is effective for investigating spatially-explicit temporal dynamics and can be applied and interpreted at different landscape scales (Ostapowicz et al., 2008).

Analysis of MIP classes make it possible to differentiate spatial processes both internally and at forest boundaries. In general, boundary or edge regions have been studied intensively as dynamic hotspots where microclimate gradients modulate structural heterogeneity and biodiversity but may also be disproportionately susceptible to disturbance (Meeussen et al., 2020). By implementing a MIP classification, we introduce spatial specificity, which facilitates detailed investigations into localized process dynamics and development pathways.

We implemented a size-dependent morphological segmentation of binary forest maps following similar approaches (Soille and Vogt, 2009). Although mathematical morphology is commonly applied using the MSPA (morphological spatial pattern analysis) software 'GUIDOS Toolbox' (Soille and Vogt, 2022), in the current analysis we introduce a novel approach. We implemented the classification in Python using binary morphological operations (erosion and dilation) to delineate core, edge, and perimeter zones based on a distance threshold. Forest pixels (foreground) and non-forest pixels (background) were analyzed using an 8-connected foreground (4-connected background) rule. A size parameter (s), defined as a Euclidean distance threshold, was used to characterize spatial structure.

Core forest is a region whereby microclimatic conditions and biotic properties remain relatively homogenous, whereas the edge is a zone of transition which is located between the core forest and the outer forest boundary. A gradient within the edge exhibits structural and functional components different than the core forest (Schmidt et al., 2017). A generalized edge depth which considers sunlight penetration, temperature, and soil moisture has been commonly observed within approximately 100 m of the forest boundary (Forman, 2008; Harper et al., 2005; Meeussen et al., 2021). The 100 m edge width has been employed in many studies, including by the Joint Research Center (JRC) in an MSPA approach for monitoring Europe-wide forest fragmentation (Estreguil and Mouton, 2009). However, empirical studies have shown that the extent of the edge influence varies across forest types and biomes, is seasonally dependent and modulated by local topography, edge orientation, vegetation height, soil characteristics, adjacent nutrient deposition (agricultural fertilizers) and herbivore browsing. Therefore, the edge region can differ even within the same forest patch. Accordingly, we tested the sensitivity of three distance thresholds (s = 50, 100, and 150 m) for classifying fragmentation processes.

Core pixels were thus identified as forest pixels located at a distance greater than s from the nearest non-forest pixel, using the Euclidean distance transform. Forest patches that did not contain core pixels were classified as 'Islets'. Remaining forest pixels within a distance $\leq s$ from the background were classified as boundary pixels and further subdivided into perimeters (exterior boundaries), perforations (interior boundaries surrounding holes or gaps) and edges (situated between a boundary pixel and the core).

In comparison to the GUIDOS software which defines six regions: Edge, core, perforations, and three categories of connector types, our approach instead defined four regions: Perimeter, edge, core, and perforation perimeter. Therefore, this approach differs from the method proposed by Soille and Vogt in two ways. We split the edge class into three distinct zones: perimeter, perforation perimeter, and edge. This granularity allowed for differentiating edge-adjacent loss as either interior or exterior perimeter loss, shrinkage, or bisection processes. Secondly, because the present study is not concerned with connectivity per se (forest connectivity is a complex topic, deserving a separate investigation (Kindlmann and Burel, 2008)), we therefore omitted connectivity classes (bridges, loops, and branches) from our classification..

Perforations were defined using the FCCL forest mask from August 2017 (pre-FCCL detection study period) by merging the September 2017 FCCL (month 1) to the forest mask, and can therefore be considered as pre-existing forest gaps. Perimeters of pre-FCCL gaps were labeled as perforation perimeter. The distinction between exterior forest perimeters and interior perforation perimeters was needed to differentiate the loss of exterior perimeters from interior processes.

The MIP was applied to aggregated FCCL annual binary rasters for the entire state of Bavaria.

2.2.3. *Fragmentation processes*

The vectorized cumulative FCCL polygons were intersected with the result of the August 2017 MIP classification, which was used to identify four mutually exclusive fragmentation processes: Perimeter loss, shrinkage, perforation, and bisection. Fig. 4 and Table 2 present fragmentation processes and a simplified illustration of the spatial intersection of data.

Forman (Forman, 1995) introduced the following spatial processes: Perforation, dissection, fragmentation, shrinkage, and attrition. Later, dissection was updated to bisection and the process of attrition was removed altogether (Collinge, 2009; Collinge and Forman, 1998). In the present investigation, we disaggregated shrinkage into four processes: interior and exterior perimeter loss and shrinkage.

The following logic was applied to define fragmentation processes and positions, which is detailed in Table 2. 'Perimeter loss' contains pixels from the MIP class perimeter or perforation perimeter and is

Table 2
Spatial composition of fragmentation processes in Forests (green triangle) and Islets (blue square). In Islet patches, which do not contain core, bisection is a convergent process.

		Perimeter	*Edge*	*Core*	*Perf. perimeter*
Interior	Perimeter loss				▲■
	Shrinkage		▲■		▲■
	Perforation		▲■	▲	
	Bisection		▲	▲	▲
Exterior	Perimeter loss	▲■			
	Shrinkage	▲■	▲■		
	Bisection	▲	▲	▲	
Convergent	Bisection	▲■	▲■	▲	▲■

therefore either an exterior or interior process. 'Shrinkage' can also refer to an exterior or interior process which consists of both MIP classes perimeter (or perforation perimeter) and edge within an individual FCCL polygon. The 'perforation' process contains edge and/or core MIP classified pixels and therefore occurs only within forest interiors. Finally, the 'bisection' process is defined as containing core, edge, and perimeter (and/or perforation perimeter) pixels. If an FCCL cluster contained all four MIP classes (perimeter, edge, core, and perforation perimeter) it was identified as convergent process. Among Islets, which contain no core area, 'bisection' occurs as a convergent process.

2.2.4. Edge depth sensitivity analysis

Fragmentation processes are defined by MIP pixel composition and therefore, the identification of both forest type (Forest, Islet) and spatial process may be sensitive to the selected edge-width (also referred to as edge-depth). Although empirical studies commonly point to an average zone of influence of 100 m from the exterior of the forest, this distance is highly variable even within a single forest patch. Localized edge effects are modulated by attributes like topography, tree species, age class, edge orientation (facilitates solar irradiance), and soil grain size (facilitates moisture penetration and retention). Thus, a one-size-fits-all approach may be insufficient. Therefore, a sensitivity analysis of edge-depth effect on MIP classes and fragmentation process identification was conducted to better quantify expected changes in output. However, because 100 m broadly encompasses the mean zone of edge influence in temperate European forests (Meeussen et al., 2020, 2021), it was selected as the baseline for this study and the sensitivity analysis.

To measure edge-depth sensitivity, three scenarios were analyzed. Using different distances for the *s* parameter ($s = 50$, 100, 150 m), three rounds of MIP raster classification were conducted and intersected with the aggregated FCCL dataset. Fragmentation processes were then identified using the within-cluster MIP pixel composition for each edge depth. The analysis was stratified by forest type and processes were additionally stratified by position (interior, exterior, convergent).

2.2.5. MIP time-series and class transitions

To produce a baseline ($s = 100$ m) time-series of changes to core, edge, perimeter, and perforation perimeter regions, MIP classified rasters were aggregated annually. Annual rasters were vectorized using an 8-pixel connectivity rule to calculate the number of patches (for all patch sizes and for patches larger than 0.1 ha) for both Forests and Islets. A transition matrix was used to identify pixel-level transitions across both Forests and Islets. The difference of the 2017 and 2025 MIP classified rasters was calculated and presented below.

2.2.6. FCCL cluster development

Fragmentation develops dynamically over time, producing edges which are often more susceptible to continued disturbance. It is assumed that because bisection processes are relatively large, that a directionality exists whereby many smaller disturbances can enlarge and merge, forming a more substantial region of canopy loss, resulting in forest fragmentation at the landscape scale.

Fig. 5 visualizes potential cluster growth dynamics. At time 1, three sub-clusters (a, b, c) already occupy the region within a future bisection FCCL (orange outline). At time 2, sub-clusters (b) and (c) have enlarged and merged, meanwhile cluster (a) has expanded and clusters (e) and (f) have initiated. At time 3, all of the sub-clusters have merged (g) and two new sub-clusters have initiated (h, i). Finally, by the end of the study period (time 4), all clusters have merged to form the bisection FCCL (j).

To investigate this assumption, per-cluster baseline ($s = 100$ m) bisection development was examined. First, the lowest value per-cluster pixel was isolated and identified by MIP region. This approach was used to indicate the development pathway of fragmentation processes relative to the region in which FCCL was initiated. Next, final cluster area was investigated with respect to the month of initial loss. Finally, annual aggregations of sub-cluster disturbances were summarized. Using the vectorized cumulative FCCL loss, we examined the annual aggregation of disturbed sub-cluster dynamics. Taken together, these investigations can support the assumption of FCCL cluster development via enlargement and merging of events over time.

Conventional fragmentation analyses describe landscape structure but do not provide a means to attribute observed localized forest loss processes to specific fragmentation landscape configuration. In order to analyze individual disturbance events and assess their contribution to patch fragmentation, the framework presented here would enable investigation of both the drivers and development pathways of fragmentation processes. This includes, for example: (i) examining the structural context of disturbance clusters (e.g., the role of edges and edge orientation in forest disturbance), (ii) identifying the spatially-explicit drivers of different fragmentation processes (e.g., the influence of species composition, elevation, soil type, or management intensity), and (iii) linking local disturbance events to patch-scale fragmentation outcomes (e.g., how the development of individual clusters contributes to patch fragmentation).

3. Results

3.1. MIP classification and time-series

Fig. 6 (A, B, and C) exemplifies the transition of MIP classes for each of the investigated edge depths ($s = 50$, 100, and 150 m) over the study period (September 2017– July 2025). Where perforations occurred, new perforation perimeters were created, in addition to a new edge area within the adjacent distance threshold *s*. Thus, perforations can generate large amounts of edge area in Forests. Meanwhile, in Islets, edge area is lost entirely when perforations emerge. Among Forest patches, as the value of *s* increased within each year, the area of core decreased while the exterior and interior (perforation) perimeter areas were relatively less affected (Fig. 6 D). The number of patches decreased with increasing *s* and across the study period.

According to the baseline ($s = 100$ m scenario), the area of Forest decreased each year together with a reduction in the number of Forest patches (Fig. 6 D). Total Forest area declined from 2,405,397 ha to 2,229,130 ha, representing a decrease of 176,267 ha (7.3%). However, a portion of forest transitioned into smaller, fragmented patches (Islets; 1.8%, see Table 3). Core forest experienced substantial decline, decreasing by approximately 513,430 ha, while its relative share of total forest area declined from 51% to 32%, corresponding to a 42% relative reduction in core forest proportion. The number of Forest patches declined by 12.62% from 10,788 to 9427 (black bars) and from 10,768 to 9394 for patches larger than 0.1 ha. Perimeter area increased over the study period. In particular, perforation perimeter area doubled in relative proportion from 1.6% to 3.8% of total forest area, increasing from approximately 48,000 ha to 89,000 ha—an 85% increase in absolute area. The spatial distribution of core, edge, perimeter (exterior and perforation perimeters combined) and number of patches for the Forest class are illustrated in Fig. 7.

Among Islets, the proportion of MIP classes changed within and

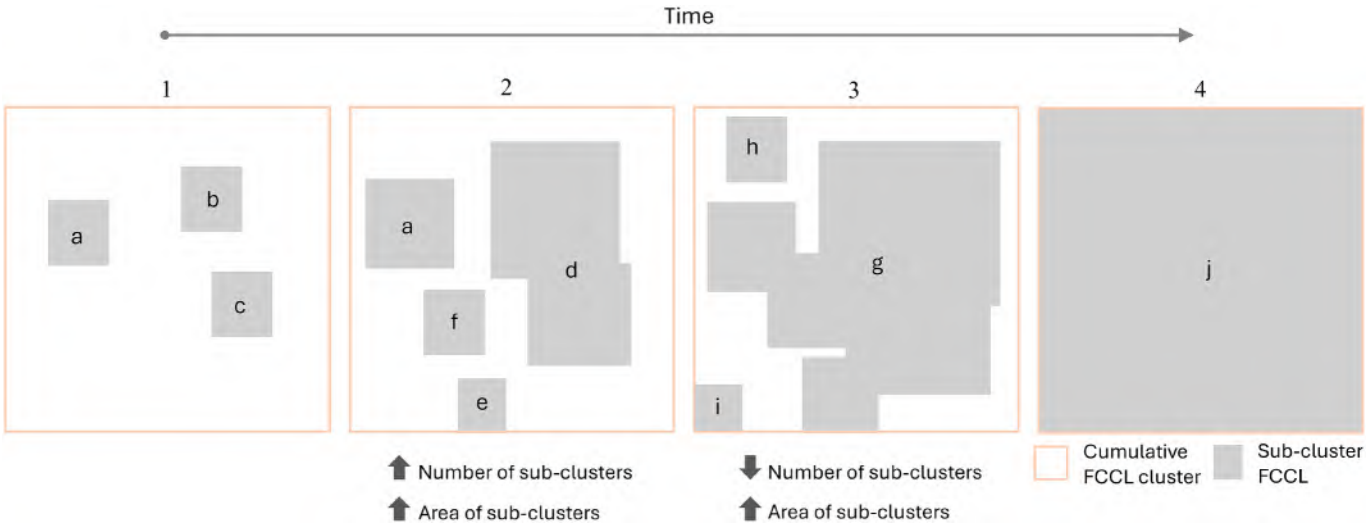


Fig. 5. Proposed growth dynamics in bisection clusters.

across years depending on *s* whereas the increase in the number of patches within a single year was less than the increase in the number of patches over the study period. Baseline (s = 100 m) total Islet area increased from 118,378 ha to 151,895 ha for all patch sizes and from 118,281 ha to 150,105 ha for patches larger than 0.1 ha. The number of Islet patches increased by 167.9% over the study period, from 62,968 to 168,703 for all patch sizes and from 58,597 to 74,508 for patches larger than 0.1 ha. While the proportion of perimeter area within Islets remained relatively constant (approximately 31%), the relative contribution of edge (Islet interior) area declined from 67.6% to 65.2%, and perforation perimeter increased from 1.6% to 3.3%.

3.2. MIP spatial distribution

The spatial distribution of the absolute changes in Forest core, edge, perimeter and the number of patches for the 100 m scenario is presented by district (*Landkreis*) in Fig. 7. Core area loss occurred throughout the state however most intensely in the districts Main-Spessart, Kronach, and Regen (Fig. 7 A). Main-Spessart lost more than 18,000 ha of core forest, a reduction of nearly 37% of core area. In Kronach district, 17,232 ha of core, or about 82% was lost, and in Regen district, nearly 18,000 or about 56% core was lost (or transitioned into other Forest or Islet classes). In total, 20 districts (Kronach, Passau, Hof, Landshut, Aichach-Friedberg, Dachau, Lichtenfels, Rottal-Inn, Kulmbach, Dingolfing-Landau, Mühldorf, Coburg, Regen, Straubing-Bogen, Altötting, Eichstätt, Deggendorf, Neustadt-Bad Windsheim, Augsburg, Starnberg) had more than 50% of core forest area lost or transitioned into other classes.

The increase in edge area followed similar spatial trends as the loss in core area, whereby the largest absolute increase in edge area, 13,276 ha, was found in the Main-Spessart district (Fig. 7 B). Eichstätt district also had a sharp increase of 10,937 ha. Aschaffenburg had the highest relative increase in edge area (88%), while 7 districts gained more than 50% in edge area (Miltenberg, Main-Spessart, Eichstätt, Haßberge, Kelheim, München, and Tirschenreuth). Only eight districts experienced edge area increases of less than 1000 ha (Kulmbach, Fürstenfeldbruck, Erding, Mühldorf, Rottal-Inn, Dachau, Fürth, and Freising). Notably, three districts had a decrease in edge area: Lindau (−37 ha), Kronach (−812 ha), and Passau (−2722 ha).

Area of perimeters (outer and perforation perimeters combined) (Fig. 7 C) increased for all districts across the state, with Regen adding more than 2000 ha of perimeter (an increase of 71%). Only three other districts had perimeter area increases of more than 70%: Eichstätt (78%), Miltenberg (77%), and Neustadt-Bad Windsheim (73%). The smallest relative increase in perimeter area was found in Lindau, which gained 48.3 ha or 5.4%.

The number of patches increased sharply in the Donau-Ries district (Fig. 7 D). In 2017, the district had 470 patches, a little more than half of the mean number of patches (805) for all districts at the start of the study period. By 2025, the number of patches in Donau-Ries had increased to 10,091, a 2041% increase. Only one other district, Berchtesgadener Land, also exceeded 10,000 patches; over the eight-year study period, 8347 patches emerged, an increase of 384%. In total, the number of patches more than doubled in about half of all districts.

3.3. MIP class transitions

The following class transition tables present the baseline edge depth (s = 100 m) proportion of each class in August 2017 which transitioned either into another class or into 'non-forest' (outright loss) by July 2025. Table 3 A is an overview of all classes combined within each overall Forest and Islet patch types. 92.5% of Forests remained throughout the study period, with 1.8% transitioning into the Islet type and 5.7% being lost altogether. Moreover, 6.7% of total Islet area transitioned into the class 'non-forest' indicating a higher relative forest loss among the smallest patches (which do not contain core forest).

Among Forests (Table 3 B), the perimeter class transitioned into non-forest at higher rates than other forest classes (7.3%), followed by edge (6.3%), core (5.2%), and perforation perimeter (4.9%). More than half (58%) of forest core area remained, while 33.7% of the core class transitioned into the edge class. A high proportion of edge pixels remained in 2025; (87.5%) 2% transitioned into perforation perimeter, 1.2% transitioned to exterior perimeter, and 3% transitioned into one of the Islet classes. Notably, about 5.5% of perforation perimeter became exterior perimeter. More than 87% remained perforation perimeter while 2.1% transitioned into one of the Islet classes. Perimeter pixels were the most susceptible to fragmentation, whereby 6.6% transitioned into an Islet class. About 86% of perimeter pixels remained unaffected throughout the study period.

Within the Islet patch type (Table 3 C), transitions were also variable. Similar to the pattern seen in Forests, the perimeter class also transitioned into non-forest at higher rates than other classes (7.5%). However, a higher proportion of perimeter remained unchanged compared to Forests (92.1%). Meanwhile, more than 12% of perforation perimeter became outer perimeter, which is notably higher than in Forests. Overall, exterior perimeter and perforation perimeter pixels exhibited the highest transition rates to non-forest, indicating disproportionate susceptibility relative to their spatial extent, despite their lower

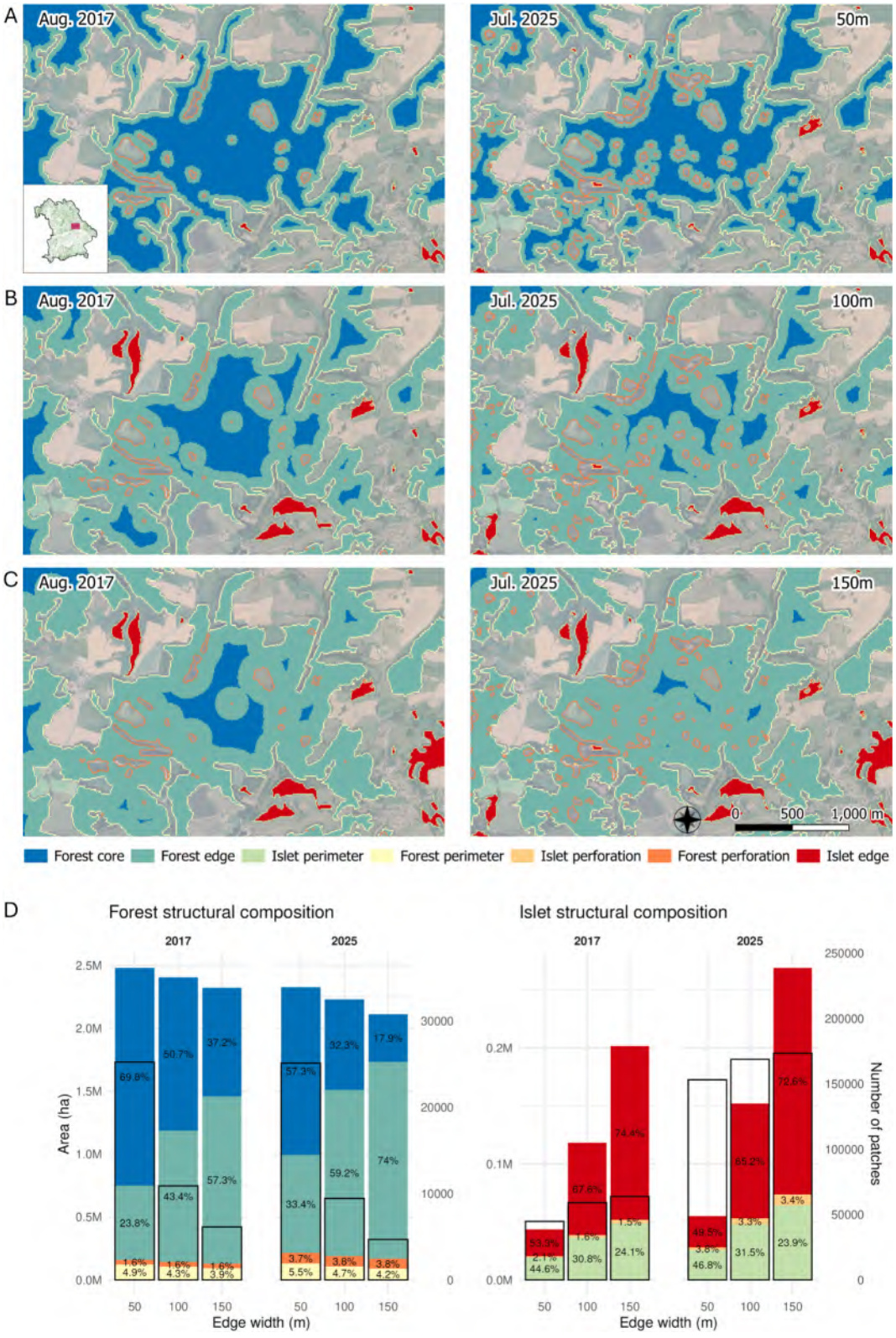


Fig. 6. The influence of edge depth on MIP class dynamics. An example map shows the MIP labels ($s = 50$ m) (A), the baseline condition ($s = 100$ m) (B), and the widest edge depth ($s = 150$ m) (C) in 2017 and in 2025. Note the substantial edge area created by perforations. Time series of MIP changes in Forests and Islets (D) for each of the edge depths and the number of patches. Scale for number of patches (black bars) on right y-axis.

representation in initial FCCL events which is described in the following section.

3.4. Fragmentation processes

3.4.1. Edge-depth sensitivity

An analysis of process sensitivity to s was carried out to investigate

Table 3
Baseline (s = 100 m) MIP transition matrices (2017–2025). Aggregated class transitions (A), Forest transitions (B), and Islet transitions (C). Values represent the percentage of area in each 2017 class transitioned to each 2025 class. Rows sum to 100% (± rounding).

			2025		
		Aggregated	*Forest*	*Islet*	*Non-forest*
		Forest	92.5	1.8	5.7
A	2017	*Islet*	0	93.3	6.7

			2025					
		Forest	*Core*	*Edge*	*Perf. Perim.*	*Perimeter*	*Islet*	*Non-Forest*
		Core	58	33.7	2.5	0.2	0.3	5.2
		Edge	0	87.5	2	1.2	3	6.3
		Perf. Perim.	0	0	87.6	5.4	2.1	4.9
B	2017	*Perimeter*	0	0	0.5	85.6	6.6	7.3

			2025			
		Islet	*Edge*	*Perf. Perim.*	*Perimeter*	*Non-Forest*
		Edge	88.8	1.3	3.5	6.4
		Perf. Perim.	0	82.8	12.4	4.8
C	2017	*Perimeter*	0	0.4	92.1	7.5

whether the approach produces robust classifications irrespective of edge width. Fragmentation process identity, the number of clusters per process, and the area was affected by s. Importantly, the number of patches classified as either Forest or Islet also depended on this parameter. Islet patches are distinguished by the absence of core pixels and thus an increase in s also precipitated an increase the amount of Islet patches whilst the number of Forest patches decreased.

At the end of the study period (July 2025), 762,602 FCCL clusters were delineated. According to the 50 m scenario, 711,336 FCCL clusters (93.3%) were classified within Forests while 51,266 clusters (6.7%) were classified within Islets. In the baseline scenario (s = 100 m), 661,755 clusters (86.8%) were classified within Forests and 100,847 (13.2%) were within Islets. Finally, in the 150 m edge depth scenario, we classified 621,086 FCCL Forest clusters (81.4%) and 141,516 (18.6%) Islet clusters.

The sensitivity of process identification was partly, though not entirely a consequence of patch size classification. However, some processes which do not contain edge pixels (interior and exterior perimeter loss, perforation) retained the baseline classification and were thus not sensitive to a change in s and were instead sensitive only to patch size. Fig. 8 details the sensitivity of fragmentation processes by patch size and position (interior, exterior, convergent). The sensitivity of s is centered on the baseline condition (s = 100 m).

Islet processes consistently increased in both number and area as the edge depth increased and thus the number of Islet patches also increased. Likewise, as the edge depth decreased, so did the number of Islet patches and thus precipitated a decline in the number and area of fragmentation processes irrespective of position. However, among Forest patches, the sensitivity to s was more dynamic. Because of the dependency on the composition of core pixels, the process most sensitive to edge width was bisection. Process identification tended to shift from bisection to shrinkage with increasing s. Perimeter loss and perforation processes were the least sensitive i.e. the most robust classification

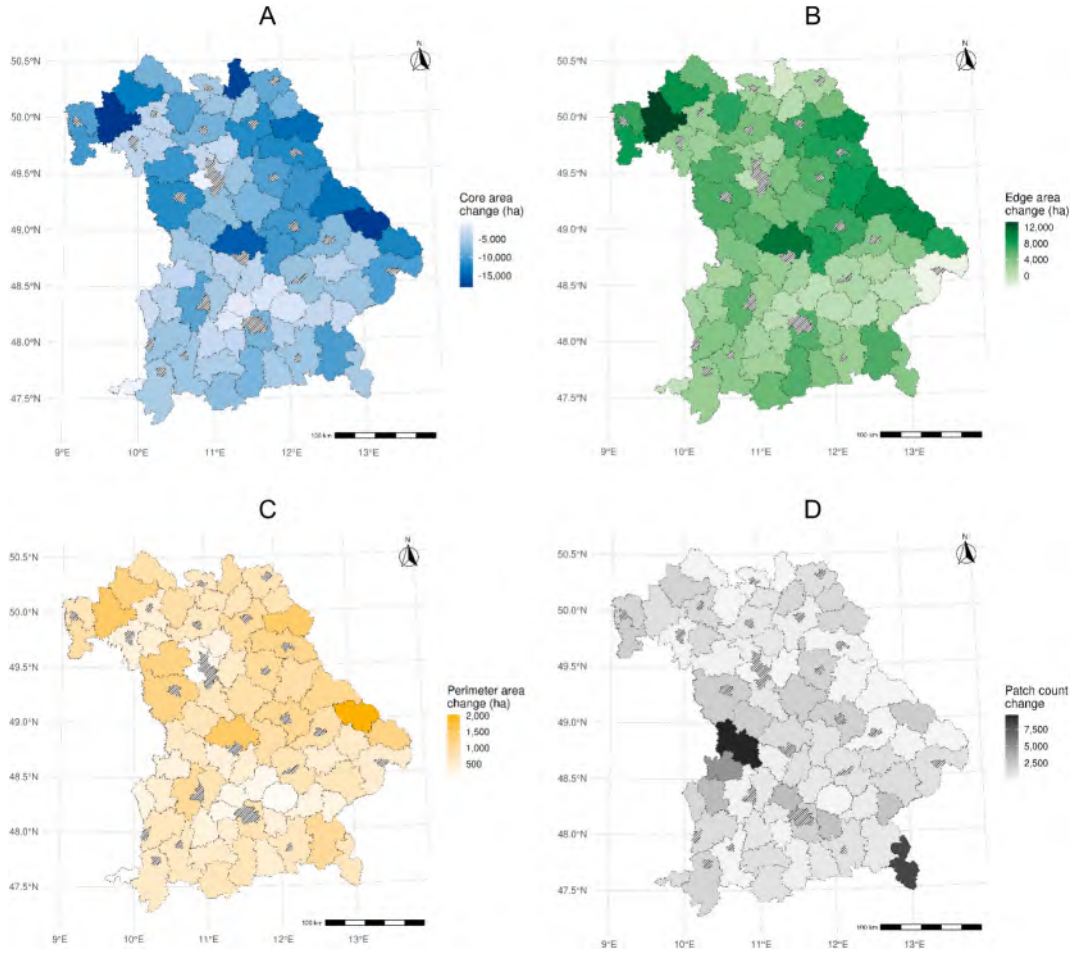


Fig. 7. Spatial distribution of total MIP (s = 100 m) change (2017–2025). Core area decreased (A) while edge area (B), combined perimeter area (C), and the number of patches (D) increased. Municipal district data is excluded from maps (hash pattern).

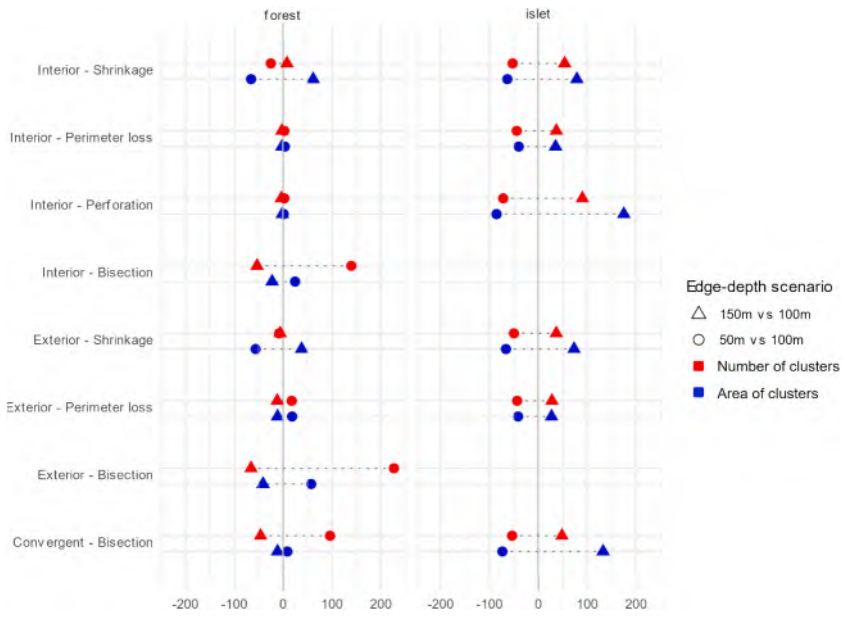


Fig. 8. Sensitivity of fragmentation process and position to edge depth, centered around the baseline condition ($s = 100$ m).

irrespective of edge depth overall.

3.4.2. *Fragmentation process dynamics and development*

Fig. 9 visualizes the development of baseline ($s = 100$ m) fragmentation spatial processes within Forests (A) and Islets (B), using the MIP class of the first pixel lost in each FCCL cluster (left column) and the spatial process observed at the end of the study period (right column). The flow colour indicates the position of each spatial process. The data represent cluster area and approximations (~) have been rounded. Notably, interior processes (perforation in particular) dominated Forest patches while interior (especially shrinkage) were the predominant processes among Islets. Initial FCCL in Forest clusters most frequently

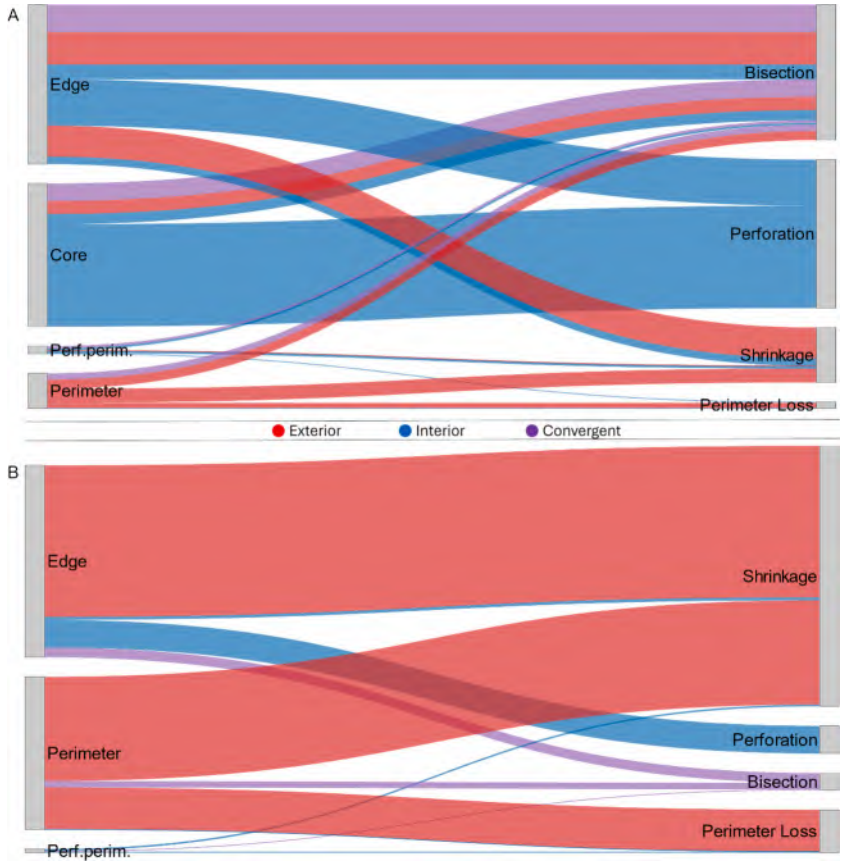


Fig. 9. Fragmentation process development for each cluster of FCCL in Forests (A) and Islets (B). The left column represents the MIP class in which processes were initiated while the right column visualizes the area covered by each process. Colors represent the position.

occurred in edge pixels (~37%). Clusters initiated in Forest core areas and perimeters accounted for approximately 32% and 26% of FCCL clusters, respectively, while perforation perimeters represented 4.5% of initial FCCL. These patterns reflect the relative distribution of MIP classes across the landscape; core and edge pixels comprise the majority of Forest area, whereas perimeter and perforation classes occupied smaller proportions.

Perforation was the most common process of Forest fragmentation (about 60% of clusters). Although exterior perimeter area accounted for on average ~ 4.5% of forest area across the study period, perimeter loss was the second most common process (160,168 clusters, ~24%) of which 86% were exterior processes. Islets were dominated by exterior processes. Although perimeter loss accounted for about 58% of clusters, shrinkage processes covered more area in total (~75%).

3.4.3. Temporal and spatial development of FCCL clusters

In terms of individual FCCL cluster size, there was a tendency for some disturbed areas to become larger over time. For each spatial process and in each forest type, the largest FCCL cluster began early in the study period. This could suggest that either individual clusters of disturbed forest tended to increase in area or that clusters merged over time (or a combination of both).

The largest individual clusters were classified as bisection processes. Four clusters reached an area larger than 500 ha while 25 clusters had an area larger than 100 ha. The largest cluster was nearly 1250 ha and was initiated in the first month of the study period (Sept 2017). Of the 10 largest bisection clusters, three initiated in the first month and seven initiated in the second month of the study period.

The number of new FCCL bisection clusters (aggregated annually) was highest in 2018, and declined sharply in 2019 (Fig. 10A, blue) and subsequent years experienced fewer newly formed clusters. Meanwhile the cumulative bisection area steadily increased throughout the study period (Fig. 10A, orange). Using the area of bisection clusters from July 2025, Fig. 10B visualizes the increasing fraction of the final area which is comprised of sub-cluster disturbances until the entire cluster is disturbed. Early on in the study period, the mean number of sub-clusters was around 3.5 until a sharp and steady decline began in 2021 (Fig. 10B, blue).

3.4.4. Spatial distribution of fragmentation processes

Bisection processes covered the second largest area overall (39.2%) and was relatively evenly distributed across all districts with two exceptions where clusters were notably large: Kronach (11,690 ha), and Passau (5243 ha) (Fig. 11 A).

Perforations in Forests covered the largest proportion of FCCL area (43%) compared to all other fragmentation processes. The largest perforation area was in Regen district (2133 ha) (Fig. 11 B) which includes part of the Bavarian Forest National Park (BFNP). Four additional districts experienced more than 5% of total district Forest loss to perforations: Kronach (1440 ha), Lichtenfels (978 ha), Aichach-Friedberg (911 ha) and Hof (1184 ha). The southern districts along the alpine border with Austria were among the least affected by perforations.

Forest perimeter loss (Fig. 11 D) covered the second smallest total area with respect to other process types (1.8%). However, perimeters also accounted for the smallest area of all MIP forest classes ($\leq$ 5% of total Forest area across the state). Overall, perimeter loss per district was less than 1% of total per district Forest area, with the largest total losses in Ansbach (~99 ha). The average perimeter loss area was ~30 ha per district. Schweinfurt had the highest proportional perimeter loss (~48 ha).

Shrinkage clusters (Fig. 11 C) covered 16% of total FCCL Forest area across the state. In terms of spatial distribution, Passau district had the largest overall area and the highest relative Forest shrinkage (1159 ha). Three other districts had a total shrinkage area greater than 600 ha (Kronach; 605 ha, Rottal-Inn; ~707 ha, and Hof; ~747 ha).

4. Discussion

4.1. Interior fragmentation processes: Perimeter loss, shrinkage, bisection, and perforation

Typically, forest perforations are relatively small, transient gaps in tree canopy that are often the result of windthrown trees or are created artificially by forest managers. Within these gaps, sunlight and precipitation penetrate understory plant communities, adjacent perimeters, and soil. The increase in light, moisture, heat, and wind together with freshly fallen trees creates new habitats which can encourage microbial activities that cycle nutrients, thereby facilitating a spike in localized biomass and biodiversity (Fahrig, 2013; Muscolo et al., 2014; Schliemann and Bockheim, 2011; Vichta et al., 2025). Dynamically occurring perforations across a forest patch thus modify physical structure, age distribution, and species composition. The resulting heterogeneity is generally considered to enhance resilience to future disturbances. Thus, small-scale disturbances are often implemented intentionally in managed forests to improve forest health (Caron et al., 2009; Kirchner et al., 2011; Muscolo et al., 2014). Based on a literature review, Schliemann and Bockheim recommend artificial gaps no larger than 0.1 ha (Schliemann and Bockheim, 2011).

However, in Bavaria, the average baseline perforation cluster size was 0.18 ha, and more than 113,000 clusters were 0.1 ha or larger. Meaning that at least 25% exceeded the recommended Schliemann and Bockheim gap size, and more than 200 individual perforations were at least 100 times this size. While canopy gaps are generally regarded as

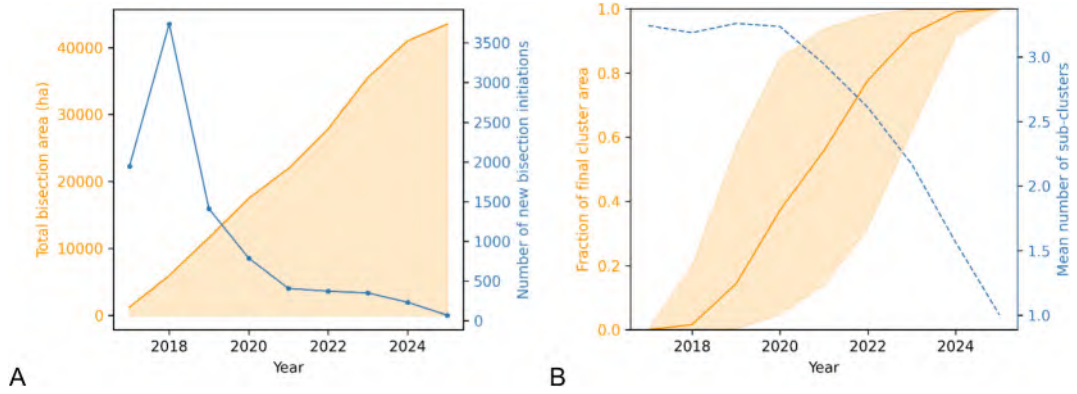


Fig. 10. Annually aggregated sub-cluster dynamics in bisection processes ($s = 100$ m). The number of newly formed FCCL clusters (A, blue) are plotted together with the cumulative area over time (A, orange), the mean fraction of 2025 bisection area disturbed by sub-clusters annually and the mean number of sub-clusters (B), (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

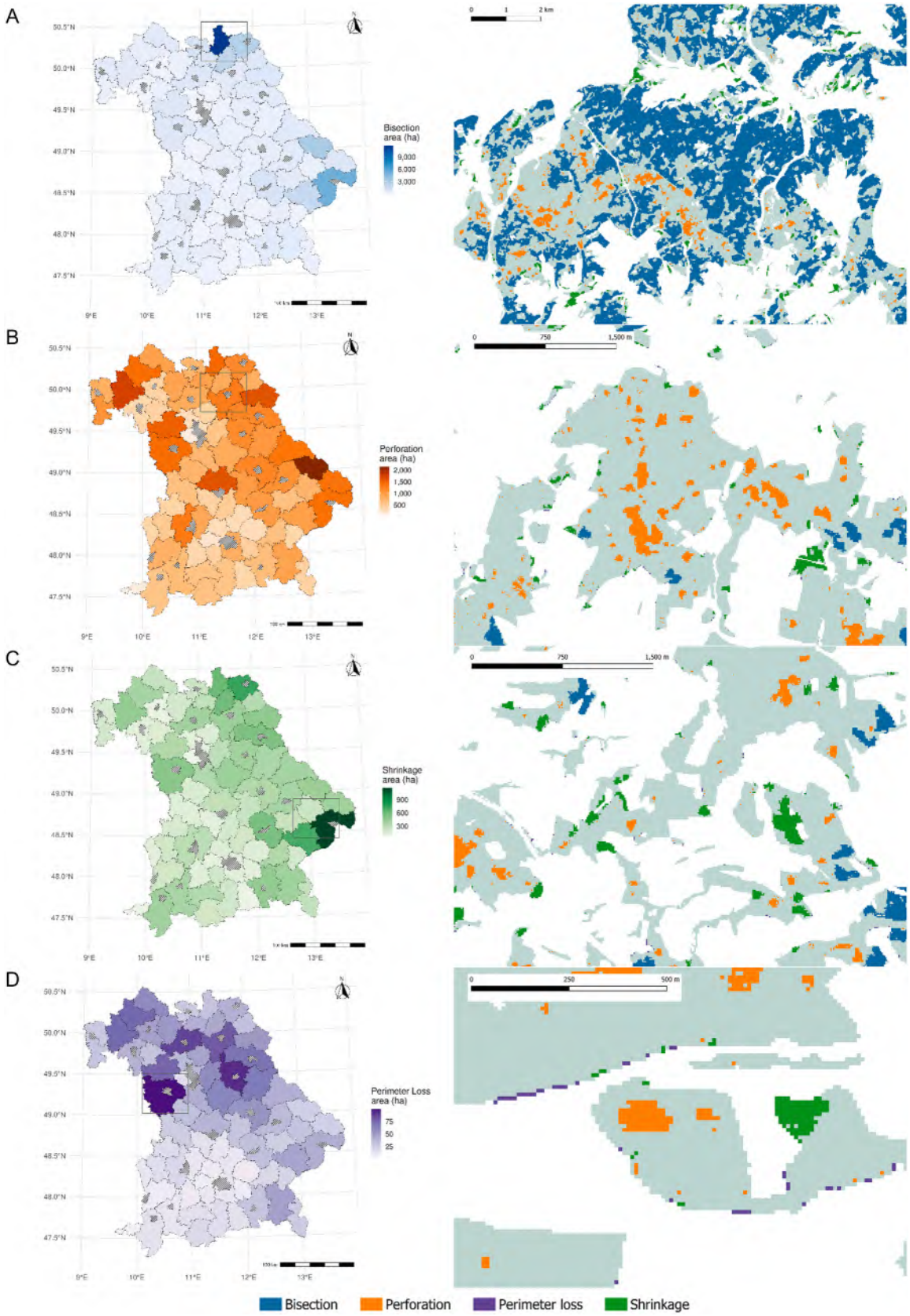


Fig. 11. Spatial distribution of fragmentation processes in Forests. Inset maps show the district with examples of each process: Bisection (A) in Kronach, perforation (B) in Bayreuth, shrinkage (C) in Passau and perimeter loss (D) in Ansbach. Undisturbed forest cover in light green. Municipal district data is excluded from maps (hash pattern). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

temporary, our results suggest that a subset of perforation disturbances may escape this dynamic. Below a certain spatial extent, perforations function as transient canopy gaps; beyond that extent, they may transition into persistent internal edges if recovery is slow or incomplete (Kern et al., 2013). Removal of deadwood can also play a key role in the spread of canopy loss of adjacent perimeters (Kortmann et al., 2026). The scale and trajectory of a perforation determine whether it introduces localized forest benefits or drives fragmentation by exceeding a spatial threshold. When perforations expand or persist, the microclimatic and structural conditions along their perimeters may increasingly resemble those of outer forest boundaries (Lenk et al., 2024). Under such conditions, gap dynamics may shift from regeneration-driven turnover to fragmentation. Therefore, the size of a fragmentation cluster may be an indication of persistent change to both local and landscape-level ecosystems.

Unusually large perforations may be a consequence of tree species composition, management, prolonged drought, and subsequent bark beetle outbreaks (Dobor et al., 2020). The enlargement of canopy perforations drives gap dynamics in unmanaged spruce forests while some perforations do not fully recover (Krüger et al., 2024). Spatial aggregation of perforations within a patch may moreover reflect intensive bark beetle outbreaks (Kautz et al., 2011). Gap closure rates can be higher in broadleaf or mixed forests (Krüger et al., 2024), which suggests that species, and therefore forest structure, understory growth, and litter inputs influence recovery trajectories. Finally, regeneration may be insufficient, particularly if fallen deadwood is removed to limit further infestation (Bače et al., 2012).

Perforations were the dominant spatial process in terms of frequency and covered the largest total area relative to other processes, although individual clusters were smaller than bisection clusters. Perforations were the main driver of core loss (or transition to edge) and tended to occur in regions where large forests dominate the landscape, such as Main-Spessart and Regen districts. Regen district for example, had the highest area of perforations (2134 ha, Fig. 11 B). Within the district lies roughly half of the BFNP and together with Šumava National Park (Czech Republic), form the Bohemian Forest Ecosystem, the largest contiguous protected forest in Central Europe. Within the core area of the park, which is dominated by large spruce forests, management dictates a zero-intervention policy whereby salvage logging does not occur and the forest regenerates naturally.

Recent severe drought conditions have enabled outbreaks of bark beetle infestations, which have caused widespread spruce damage in recent years (Hlásny et al., 2021). Since 2017, there has been an increase in outbreaks not only in Bavaria, but the whole of Germany and other parts of Central Europe. In Bavaria, Norway spruce forests represent the dominant tree cover (38%), so it follows that much of the losses in the state are due to infestations. Density-dependent infestations of trees like the outbreaks of bark beetles in recent years, are more likely to scale-up when aggregation of host species is spatially continuous or near-continuous. Early onset of higher spring temperatures has favored beetle activity while drought conditions stress trees and limit defensive responses to infestations (namely resin production) (Netherer et al., 2015; Öhrn et al., 2021). However, the scale and intensity of disturbances was not observed in the heavily spruce forested southern districts along the Austrian border where a cooler, wetter climate limits severity of bark beetle disturbances as forests may be less drought-stressed than other regions (Kozhoridze et al., 2024).

While some spruce-dominated districts lost more than 80% of forest core, even deciduous-dominated districts like Main-Spessart lost more than one third of core areas. Moreover, Main-Spessart was not dominated by one process but several. Severe canopy damage of deciduous forests from crown defoliation has increased sharply in recent years due to drought conditions. The annual forest condition survey is conducted in July and August to assess the crown condition of both broadleaf and needleleaf trees. Although the leaf loss declined slightly among deciduous trees since the previous year, the average was still nearly 25% despite improved weather conditions (Bavarian State Institute of Forestry (LWF), 2024).

By contrast, pre-existing gaps appeared more stable and spatially limited over the study period. Transition matrices revealed that perforation perimeters were the least affected MIP class relative to other zones, with only 4.9% transitioning to non-forest compared to 5.7% aggregated Forest loss and 7.3% for exterior perimeters. Shrinkage also covered a smaller total area and was more spatially localized. In terms of area affected, interior shrinkage was more similar to perimeter loss than to the emergence of new perforations. Because age and origin of these gaps were unknown, many may represent long-standing or permanent features. Perforation perimeters at pre-FCCL gaps may have mature borders where trees are adapted to boundary conditions. Moreover, these perimeters are oriented toward the forest interior and may experience more stable microclimatic conditions than exterior perimeters. This distinction suggests that newly created perforations and pre-existing gaps may differ in vulnerability, disturbance dynamics, and regeneration trajectories. While recent disturbances may create unstable internal edges, long-standing interior gaps may have structural and compositional characteristics that exhibit a greater resistance to drought, wind, or pest outbreaks (Pöpperl and Seidl, 2021).

By differentiating between perforation and interior shrinkage and bisection, our results suggest that interior processes are neither uniform nor always transient. Instead, their trajectory likely depends on age, size, management, regeneration capacity, and species composition. The developmental pathways of the largest perforations remain unknown.

4.2. Exterior fragmentation processes: Perimeter loss, shrinkage, and bisection

Edge disturbances are analogous to the processes of perimeter loss, shrinkage, and bisection investigated in this study. These regions are expected to experience higher relative disturbance and canopy losses due to varied microclimatic and soil conditions, and increased exposure to external pressures such as wind gusts, solar radiation, and elevated temperatures (Bernaschini et al., 2019; Ruck and Tischmacher, 2012). Edge vulnerability may also depend on contrast intensity between forest and adjacent matrix (so-called patch contrast) (Banbury Morgan and Jucker, 2025). High-contrast boundaries (e.g., built surfaces) often amplify stress gradients (Mesquita et al., 1999). Thus, classical edge theory predicts elevated disturbance susceptibility along exterior forest perimeters (Sun et al., 2025).

Although both interior and exterior perimeter loss occur at forest-non-forest interfaces, the spatial context (and therefore disturbance responses and trajectories) differs substantially. By separating pre-existing gap perimeters (perforation perimeters) from outer patch perimeters, we were able to distinguish interior-facing boundaries from true external boundaries. Indeed, we found that perforation perimeters and outer perimeters exhibited markedly different transition dynamics.

Outer perimeters were the most affected MIP class. The transition of perimeter pixels to non-forest was 7.3% in Forest and 7.5% in Islets, compared to 5.7% for all classes. Moreover, perimeters were the most likely class to transition into an Islet class which is the clearest spatial signal of fragmentation. We found that 6.6% of Forest perimeters transitioned into Islet classes, which contributed to an increase in overall Islet area and an increase in the number of patches. The emergence of very small patches (Islets < 0.1 ha) contributed disproportionately to the relative amount of perimeter across the landscape at the state-scale.

The most dramatic example of this process was in Donau-Ries district, which had a 2041% increase in the number of patches over the study period. This is alarming given the ecological importance of the forests in this district which are part of the Altmühltal nature park. The park extends across the eastern half of the district, containing more than half of the forest area for all of Donau-Ries including the riparian forests of the Danube River, several small nature reserves and Natura2000 conservation sites.

Shrinkage processes covered substantially more area than perimeter loss (13% of FCCL area; more than eight times the area of perimeter loss clusters). In Forests, shrinkage was initiated in perimeters in roughly half of all clusters, otherwise beginning in edges. In Islets, most shrinkage processes initiated in perimeters, with about one-third initiating in edges. Because shrinkage occurs at existing forest-non-forest interfaces, depending on the patch-matrix contrast, it may be linked to permanent land-cover change (Fu et al., 2024; Ren et al., 2017; Sharma et al., 2019).

4.3. Convergent fragmentation processes: Bisection

Bisection is not an initiating disturbance process. Instead, fragmentation may proceed through stages: Initiation (perimeter loss or perforation), expansion (patch shrinkage or gap expansion), merging of disturbed clusters, and ultimately bisection of a formerly continuous patch (Forman, 1995). Pathways can moreover differ between natural and plantation forests (Zhang et al., 2024). Thus, bisection represents an advanced stage of fragmentation phases culminating in the division of a forest patch into spatially separated units. That is to say, bisection clusters may represent the cumulative outcome of smaller processes. The results of bisection sub-cluster analysis demonstrated additional support of this assumption. The disturbed area increased steadily over the study period while the number of new annually aggregated disturbances declined. Moreover, the number of sub-clusters was high early on but declined sharply, meanwhile the fraction of the total FCCL footprint area increased along with the number of clusters. Taken together, these results indicate that the bisection process is likely an accumulation of multiple sub-processes, which can enlarge and/or merge overtime.

While this study does not track developmental phase trajectories, spatial co-occurrence of fragmentation processes can provide additional support for this possibility. For example, in Kronach district where bisection covered the largest per-district area in the state, there was also a relatively high extent of interior shrinkage and perforation processes, alongside moderate exterior perimeter loss and shrinkage. This suggests cumulative degradation progressing toward patch bisection. Furthermore, if disturbance recovery is slow, absent, or repeatedly interrupted, these processes can accumulate until a patch loses structural continuity. Thus, bisection can indicate a structural threshold: the point at which multiple disturbances transition into landscape-level reconfiguration.

The number of Forest patches steadily declined year to year, while the number of Islet patches increased. It is unlikely that entire forest patches were eliminated, but rather subdivided. When a forest patch is bisected, the resulting fragments may fall below the spatial threshold required to retain Forest classification. Once core area is lost, these remnants are reclassified as Islets. Thus, even though bisection events were not the most common process numerically, they dominated in spatial magnitude and coincided with measurable reorganization of patch structure.

The transition of Islet perforation perimeters to perimeters was also relatively higher than other classes (12.4%). This pathway of development is classified as bisection, whereby the exterior perimeter of the islet spatially merges with a perforation, which can severely degrade interior patch habitats (Forman, 1995) and eventually cause the patch to fragment. This pathway was not as pronounced in the Forest class (5.4% of perforation perimeters transitioned into perimeters) which could be a function of patch size; perforations within the smallest patches may be closer in proximity to exterior perimeters and therefore more commonly lead to bisection processes within Islets.

Bisection is considered the most intensive pattern of fragmentation as core pixels become exposed to the outer matrix following FCCL disturbances (Li and Yang, 2015; Ren et al., 2017; Sathyakumar et al., 2025). Therefore, the ecological consequences of bisection are likely disproportionate relative to its frequency. Because bisection directly disrupts spatial continuity, this process of fragmentation may reduce or eliminate core-specific habitats, decrease patch connectivity, increase edge-to-core ratios, facilitate colonization by generalist or invasive species, alter species interactions and trophic dynamics, and in some cases increase human-wildlife and disease-vector interactions (Collinge, 2009).

4.4. Limitations and future work

Tracking individual clusters through time would clarify how localized conditions (species, elevation, soil, climate, aspect) influence recovery versus expansion. In particular, understanding why pre-existing gaps were comparatively stable may provide insights into the structural or compositional characteristics that promote a buffering capacity during drought, storm, or pest outbreaks.

There is ample room for future studies to investigate the directionality of fragmentation processes in the context of merging events, cluster size thresholds, topographical interactions, and recovery. Evaluating fragmentation in the context of management could shed light on the localized development pathways of forest fragmentation processes, especially with regards to natural versus anthropogenic disturbances.

It is well-established that species composition, canopy structure topography, and environmental conditions modulate forest edge effects, implying that edge width vary across landscapes. Although 100 m is supported by empirical studies and widely applied in large-scale fragmentation analyses spanning multiple forest types, future work should focus on development of a unified framework for defining species- or biome-specific zones of edge influence.

5. Conclusion

Disturbance-driven fragmentation processes have collectively altered forest landscapes in Bavaria. In this investigation, we quantified fragmentation processes from September 2017 – July 2025. Our novel approach was based on the intersection of a morphological image processing (MIP) classification and forest canopy cover loss (FCCL). MIP classification resulted in two forest sizes (‘Forest’ and ‘Islet’) and four spatial regions (perimeter, edge, core, perforation perimeter). Unlike approaches that summarize fragmentation using aggregated landscape metrics (e.g., geometric indices from FRAGSTATS or class-based outputs from conventional MIP like MSPA), the method presented in this analysis identifies and delineates individual disturbance clusters, classifying each as a spatially-explicit process of fragmentation. This framework allows disturbed clusters to be analyzed directly rather than inferred from changes in summary statistics.

In total, 762,602 individual clusters of FCCL were delineated and the classification sensitivity was analyzed using an edge depth gradient (50-150 m).Core Forest area declined while edge area increased, becoming the dominant class overall. FCCL was unevenly distributed among forest regions in terms of total area however, corresponding MIP regions in Forest and Islet patches exhibited similar relative disturbance rates. This indicates that disturbance processes have comparable effects on structural regions irrespective of patch size.

We investigated four spatially explicit processes of fragmentation: Perimeter loss, shrinkage, perforation, and bisection in three positions relative to the forest patch: interior, exterior and convergent. With respect to the baseline condition (100 m edge depth), the formation of perforations in forest interiors was the most common; 33.7% of Forest cores transitioned into edge regions due to perforations. Our results further suggest that Forest fragmentation by way of perimeter loss was likely responsible for the 167.9% increase in the number of Islet patches. Meanwhile, bisection may have driven the 12.62% decrease in the number of core Forest patches. Often initiated with an interior process (perforation) or an exterior process (perimeter loss, shrinkage) at multiple locations within a single patch, the result of co-occurring processes can reconfigure individual forest patch geometry and connectedness. Moreover, this investigation uncovered a tendency for disturbance clusters to expand and merge overtime.

Although forest disturbances are generally regarded as transient and often beneficial, our results suggest that a small subset of FCCL may exceed a spatial threshold resulting in more persistent internal edges. Expansion and merging of disturbance clusters can drive persistent forest loss, which is modulated by changes in climate regimes and spikes in severe weather events, in rare circumstances resulting in bisection of forests. The bisection pathway was not widespread but may however, account for the largest FCCL clusters in this study. Collectively, these findings indicate a transition toward increasingly edge-dominated and fragmented forest landscapes in Bavaria, driven by spatially-explicit fragmentation processes.

CRediT authorship contribution statement

Kjirsten Coleman: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marco Wegler:** Writing – review & editing. **Sarah Asam:** Writing – review & editing. **Claudia Kuenzer:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

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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.

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Data availability

The data analyzed in this investigation is publicly available at https://doi.org/10.15489/ef9wwc5sff75

Forest Canopy Cover Loss (FCCL) (Reference data) (EOC Geoservice)

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