Evaluating the Contribution of Unmanaged Forests to Forest Connectivity Indicators Using Spatial Analysis and GIS Data

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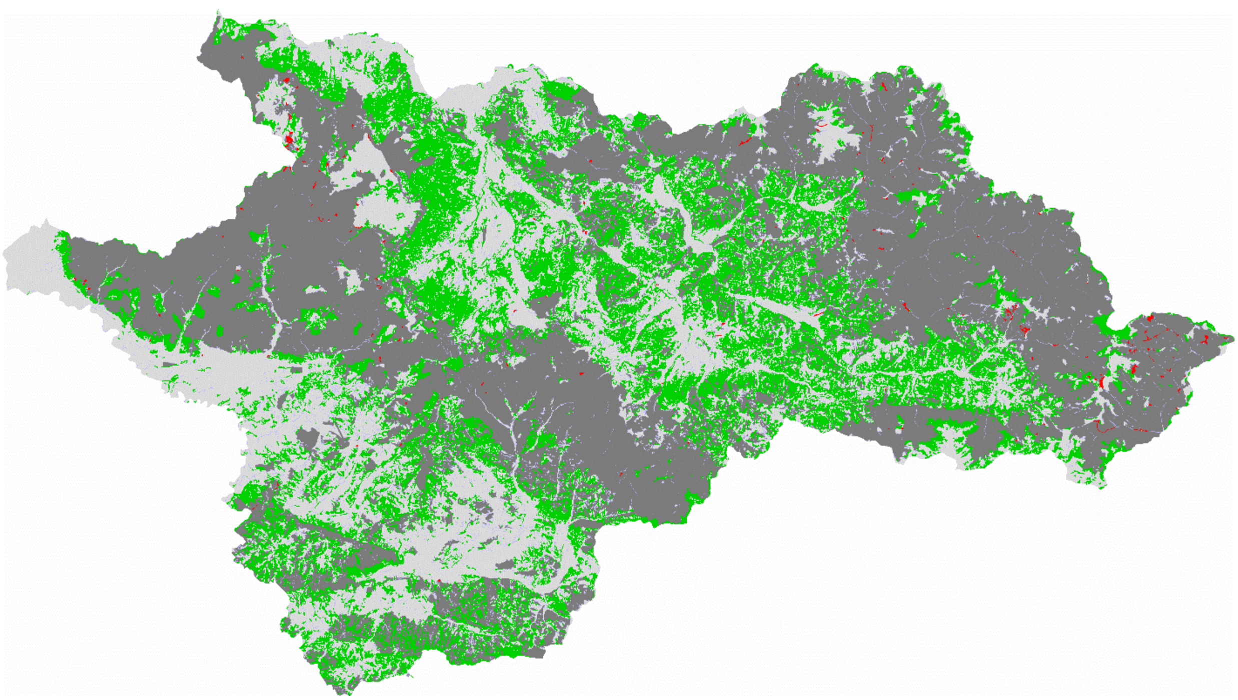

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1. Introduction

Forests are dynamic, multifunctional socio-ecological systems that deliver essential ecosystem services—from carbon sequestration and climate regulation to soil stabilisation, water filtration, and cultural identity. In Europe, the mosaic of forest ownerships and management regimes has created a patchwork of intensively managed production stands intermingled with strictly protected reserves, semi-natural woodlands, and abandoned or successional forests on marginal land. While managed forests often dominate policy discussions because they underpin rural economies and comply with national inventory reporting, unmanaged or lightly managed remnants can play a critical, yet under-appreciated, role in sustaining ecological networks.

Landscape connectivity—the degree to which the spatial arrangement of habitat patches facilitates or impedes movement of organisms and ecological processes—is a cornerstone concept in modern conservation biology. High connectivity reduces the risks of local extinction, supports genetic exchange, and buffers communities against disturbances such as wild-fire or windstorms. Conversely, fragmentation—the breaking apart of habitat into smaller, isolated patches—erodes resilience and accelerates biodiversity loss. Quantifying where a landscape sits along the fragmentation–connectivity continuum allows land managers to prioritise interventions and optimise the placement of reserves or ecological corridors.

Classic patch-based metrics (e.g. mean patch size, edge-to-area ratios) capture only limited aspects of complexity. Recent advances in spatial analysis, notably within the GUIDOS Toolbox (GTB) developed at the Joint Research Centre (JRC), provide finer-grained metrics such as Forest Area Density (FAD), Morphological Spatial Pattern Analysis (MSPA) classes, Porosity, Equivalent Connected Area (ECA), and Coherence. Together they offer a multi-dimensional assessment of forest structure at pixel-, patch-, and landscape-scale.

While several continental-scale assessments (e.g. EU Forest Observatory, FRA 2020) rely on satellite-derived forest masks, many national forest assessments focus on managed stands documented in Forest Management Plans (FMPs). The dichotomy raises a policy-relevant question: **To what extent do unmanaged forests, not included in FMP layers, influence landscape-level connectivity indicators?** If their contribution is high, conservation policies that focus solely on managed tenures may under-estimate functional connectivity and inadvertently down-play the ecological value of 'left-aside' forests.

This study addresses that gap by comparing two scenarios for Maramureș County—a mountainous region renowned for its heterogeneous ownership patterns and high conservation value forests. Scenario A includes only parcels under active management (hereafter *managed forests*). Scenario B combines those parcels with continuous satellite-derived forest cover (*all forests as land cover*). By systematically applying GTB's Fragmentation, Pattern, Accounting, and Restoration Planner modules, we quantify how unmanaged fragments alter key indicators and discuss implications for forest policy, restoration planning, and long-term monitoring.

2 Methods and Data

2.1 Study Area

Maramureș County straddles the Eastern Carpathians, encompassing altitudinal gradients from 200 m valley floors to 1 950 m alpine ridges. The climate is humid continental, with mean annual precipitation of 900–1 200 mm and mean annual temperatures ranging from 6 °C in lowlands to 0 °C at higher elevations. Forests occupy roughly 48 % of the county, dominated by Norway spruce (*Picea abies*) above 900 m and mixed beech–fir below. Socio-economically, the region features state-owned production forests, communal woodlots, private smallholdings, and strictly protected reserves (e.g. Rodna Mountains National Park). Historical land abandonment following socio-economic transition (post-1990) has allowed natural succession on former pastures, adding young unmanaged stands.

2.2 Data Sources

Dataset	Spatial Resolution	Temporal Reference	Purpose
Forest Management Plan (FMP) layers	1:5 000 (vector)	2015–2020 revision cycle	Delineation of actively managed compartments (Scenario A)
JRC Global Forest Cover 2020 v2 (GFC 2020)	25 m raster	2020	Wall-to-wall forest mask for Scenario B

Figure 1. JRC Forest data source

All rasters were re-projected to ETRS89–LAEA (EPSG: 3035) to ensure equal-area cell dimensions (25 m × 25 m). Vector FMP polygons were rasterised using the same grid. Cloud artefacts in GFC were filtered via the QA band, and a slope-based correction (> 35°) was used to adjust for potential under-canopy snow mis-classification in winter scenes.

2.3 Scenario Construction

- **Scenario A (Managed):** Raster cells flagged as 'forest' if they fall inside an FMP polygon with harvesting prescriptions during 2010-2020. Non-forest and unmanaged polygons coded as background.
- **Scenario B (All Forests):** Raster cells flagged as 'forest' if either Scenario A or GFC 2020 indicate forest cover. This additive approach ensures that Scenario B ≥ Scenario A.

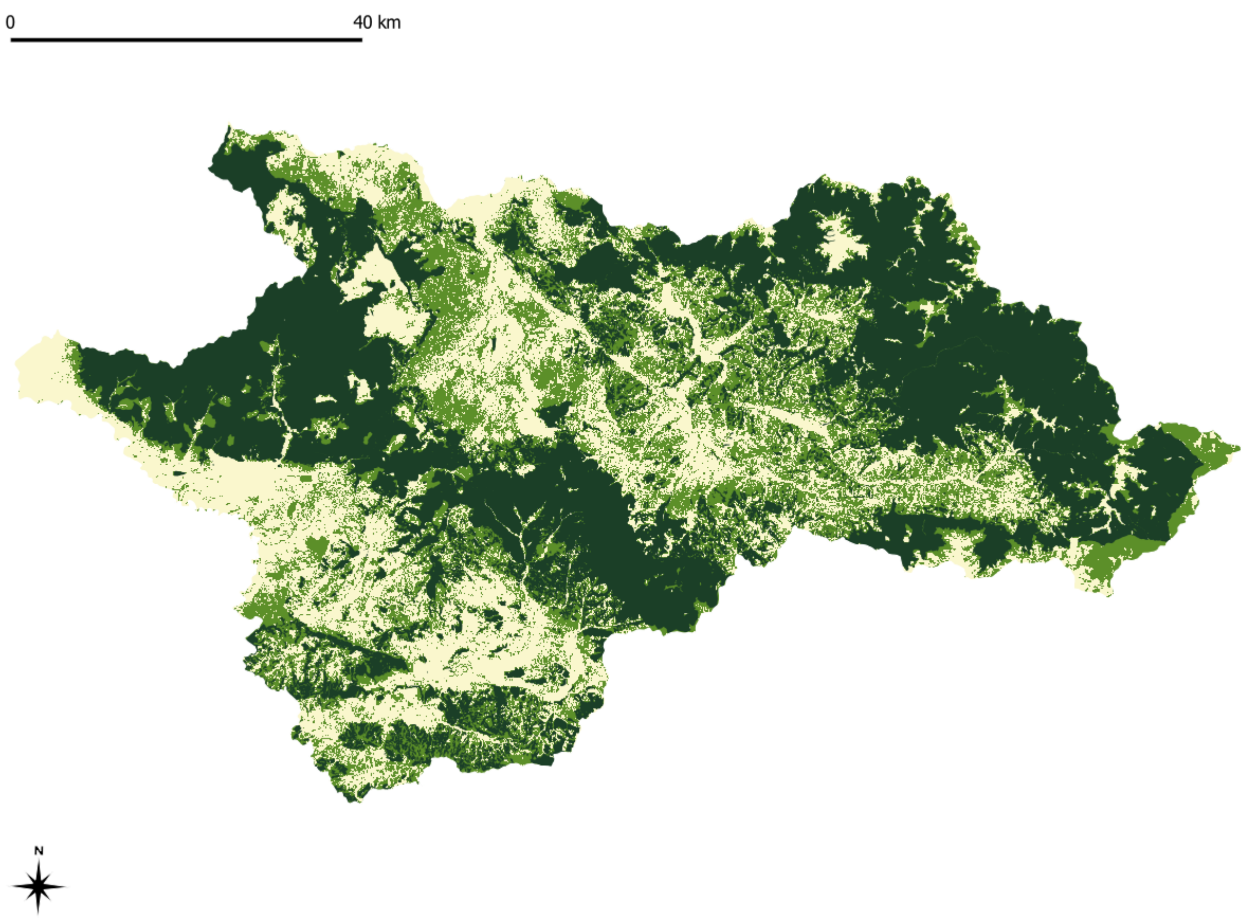

Figure 2. Managed forests (according to FMP) and Unmanaged forests (according to JRC satellite product)

2.4 Analytical Workflow in GTB

To comprehensively assess the contribution of unmanaged forests to forest connectivity, we implemented three independent but thematically grouped analytical modules in **GUIDOS Toolbox (GTB)**: (1) *Accounting* for forest area and patch sizes, (2) *Fragmentation* based on Forest Area Density (FAD), and (3) *Pattern* analysis based on morphological structure and porosity. Each module offers unique insights into landscape structure—size, distribution, continuity, and spatial morphology—thereby supporting both diagnostic and planning functions. The results from each are described in separate indicator families, ensuring clarity and comparability across the two scenarios.

2.4.1. Accounting: Forest Area and Patch Size Distribution

The Accounting module quantifies the size and frequency of forest patches by grouping contiguous pixels into discrete units. It employs **object-based segmentation**, treating each contiguous forest block (connected via 4-neighbour connectivity) as an individual patch. This is illustrated in *Figure 3*

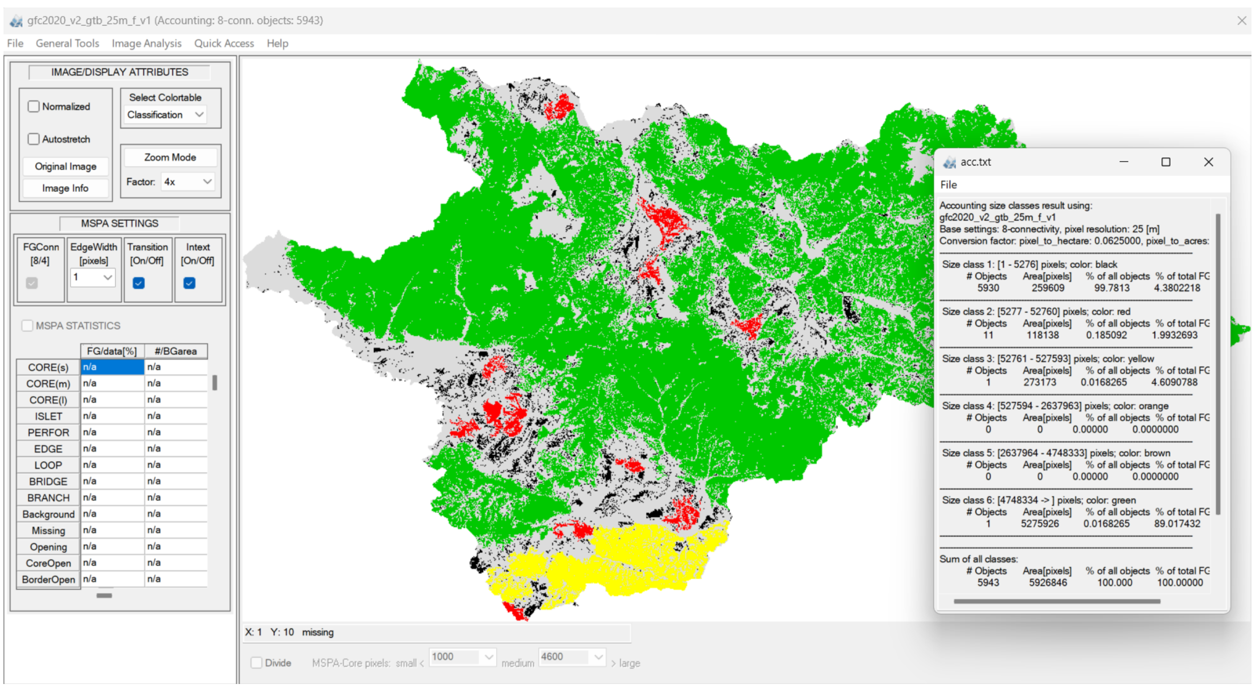

Figure 3. Accounting – Forest Area and Patch Sizes

The core methodology consists of:

- Assigning a unique ID to each forest patch based on connected pixels;
- Calculating the area (in hectares) for each patch;
- Aggregating patch sizes into predefined area classes, e.g., C1 (<10 ha), C2 (10–50 ha), up to C6 (>5000 ha).

This classification captures the hierarchical structure of the forest landscape—small patches signal fragmentation or early successional dynamics, while large patches typically correspond to mature stands or protected forest blocks. **Median patch size** is used instead of mean, as it is less sensitive to extreme values and better reflects the central tendency of patch dominance in the landscape.

Forest Area Coverage, one of the main indicators from this module, represents the percentage of forest cover in the total study area. When comparing Scenario A (managed forests) and Scenario B (all forests), a significant increase in total patch count and median patch size in Scenario B points to the spatial integration of previously fragmented or marginally visible forest units. This shift reflects both ecological gain and improved functional landscape integrity.

2.4.2. Fragmentation: Forest Area Density (FAD)

Fragmentation analysis in GTB is conducted through **Forest Area Density (FAD)**, which measures the degree of forested neighbourhood around each pixel using a moving window. The method applies a **Fixed Observation Scale (FOS)** by sliding a square window (e.g., 49×49 pixels ≈ 60 ha) over the binary forest map, calculating the local proportion of forest pixels. The output value is attributed back to the centre pixel, creating a continuous density map.

This process is visualised in *Figure 4.*

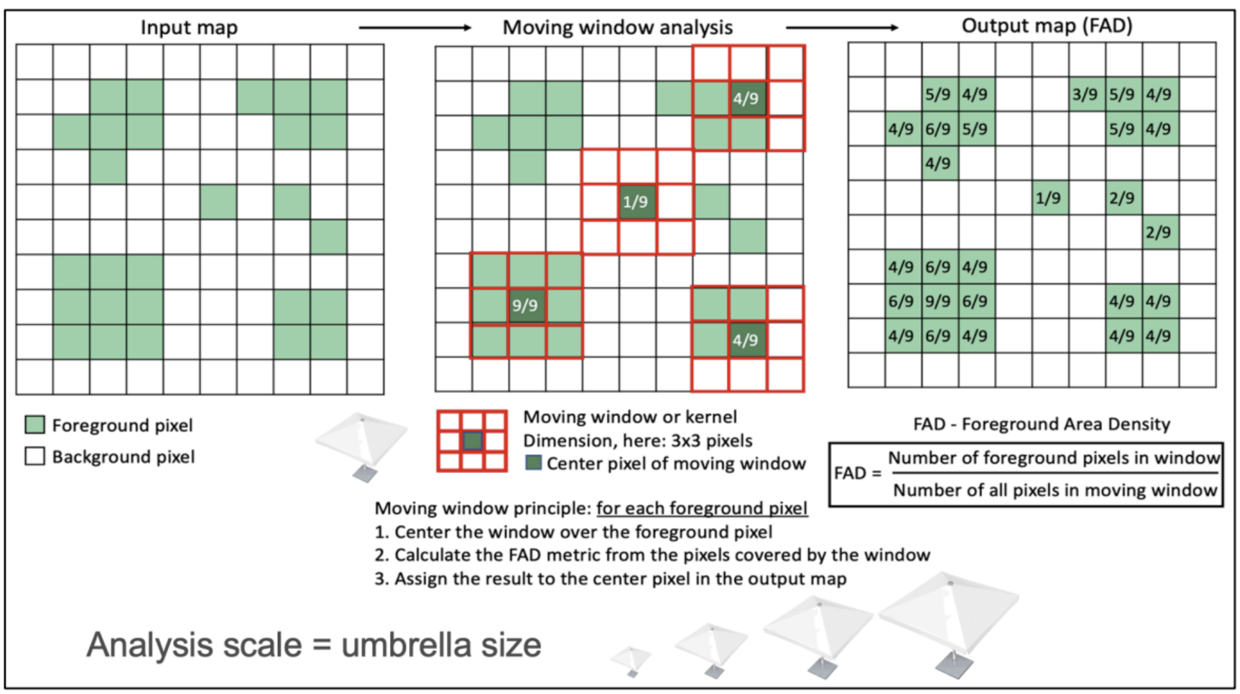

Figure 4. (Fragmentation – Forest Area Density (FAD) using moving window (Vogt) (source: GTB user manual)

where:

- The **input map** indicates forest vs. non-forest pixels;

- The **kernel window** slides across the map;
- The **output map** shows FAD values, which reflect the density of forest around each point.

FAD values are then classified into five fragmentation categories (*Figure 3*, "5-class scale of FAD"):

- **Rare (0–10%)** – highly fragmented forest, usually isolated pixels or narrow strips.
- **Patchy (10–40%)** – small scattered patches, often degraded or secondary growth.
- **Transitional (40–60%)** – buffer zones or ecotones between core and edge.
- **Dominant (60–90%)** – substantial forest presence, but possibly interspersed with openings.
- **Interior (90–100%)** – high-continuity, core forest.

Regarding the relationship between fragmentation and connectivity we used two core metrics: Forest Area Density (FAD) and Foreground Area Clustering (FAC), both computed using a moving window approach on a binary forest map.

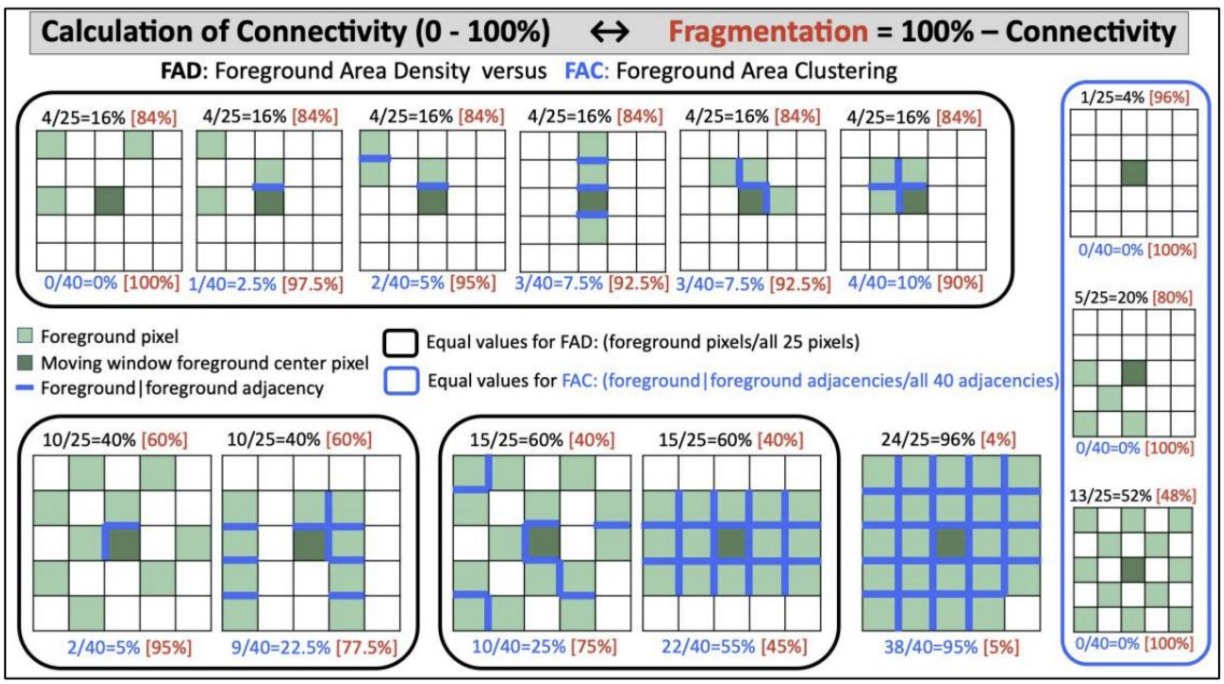

Figure 5. Calculation of Connectivity and Fragmentation (source: GTB user manual)

Forest Area Density (FAD) measures the proportion of forest (foreground) pixels within a fixed square window, typically 5×5 (25 pixels), centered on each forest pixel. It quantifies how much forest exists locally, regardless of its configuration. For example, in the top row of the figure, each grid contains exactly 4 forest pixels, resulting in a constant FAD of 16%. However, their spatial distribution differs, demonstrating that FAD alone does not capture fragmentation or clustering.

Foreground Area Clustering (FAC) addresses this limitation by accounting for how these forest pixels are arranged. It measures the number of adjacent forest–forest pixel connections out of a maximum of 40 possible adjacencies in the 5×5 window. For example, a single isolated forest pixel results in 0 adjacent forest pixels and thus FAC = 0%, while a tight cluster of four adjacent forest pixels may result in higher FAC values such as 7.5% or 10%. This reveals that FAC is sensitive to spatial structure rather than just area.

Together, these metrics allow the calculation of both connectivity and fragmentation. Connectivity is represented directly by FAD values, while fragmentation is the complement: Fragmentation = 100% – Connectivity. The bottom-left grids in the figure, for instance, show cases with FAD = 40% but with very different FAC values. A tightly grouped patch yields high FAC (e.g., 95%), whereas a scattered distribution results in low FAC (e.g., 25%). This means that even if two areas have the same amount of forest cover, their ecological function in terms of connectivity may differ substantially due to differences in structure.

The rightmost examples in the figure demonstrate nearly complete forest cover with FAD = 96% and FAC = 95%, indicating a nearly intact forest block. In contrast, the top-left grids, which also have FAD = 16%, show extreme fragmentation with FAC values ranging from 0% to 10%, depending on the clustering of pixels. This stark contrast highlights how relying solely on FAD might mislead conservation planning, as areas with identical density may exhibit drastically different ecological connectivity.

2.4.3. Pattern: Morphological Spatial Pattern Analysis (MSPA)

While FAD captures forest density, it does not describe the **form** or **position** of forest gaps relative to core areas. To address this, we applied **Morphological Spatial Pattern Analysis (MSPA)** using 8-neighbour connectivity and one-pixel edge width.

MSPA classifies each forest pixel into one of seven morphotypes and several background classes based on mathematical morphology. The morphotypes include:

- **Core** – interior forest with no adjacent gaps;
- **Edge** – pixels at the boundary of core areas;
- **Perforation** – internal openings within forest blocks;
- **Bridge** – narrow forest strips linking two core areas;
- **Branch** – one-end connections extending from core or bridge;
- **Loop** – closed or cyclic paths;
- **Islet** – small, isolated patches lacking core area.

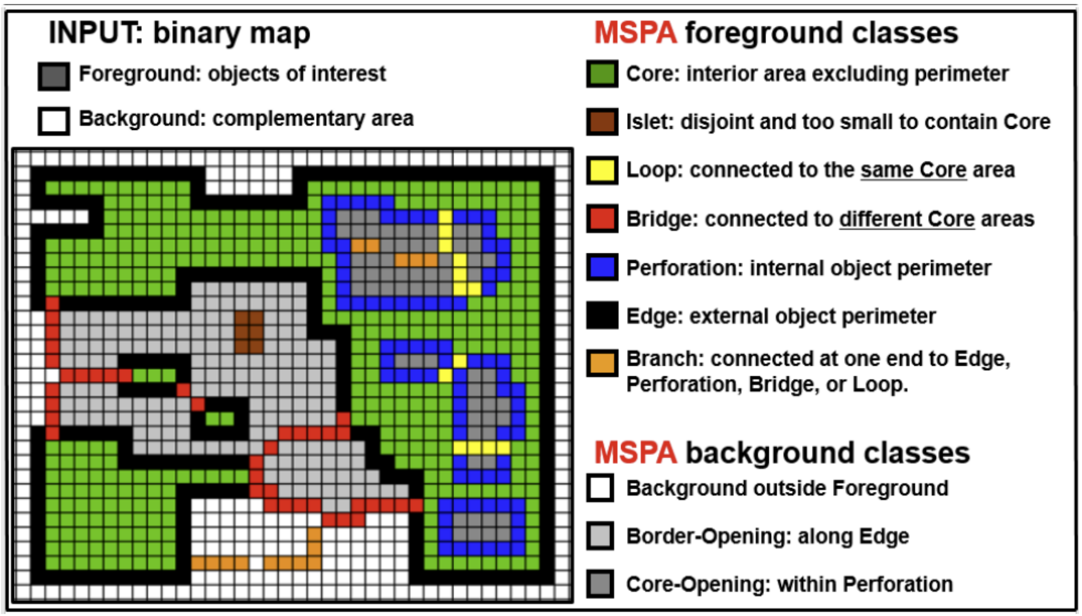

Figure 6. MSPA foreground classes

These classes are shown in *Figure 6 and Figure 7*. The distinction between **Core-Openings** (gaps within forest) and **Border-Openings** (gaps at the external edge) allows for quantifying **Porosity**—an indicator of internal fragmentation. High porosity suggests degraded interior conditions, while low porosity indicates cohesive habitat blocks.

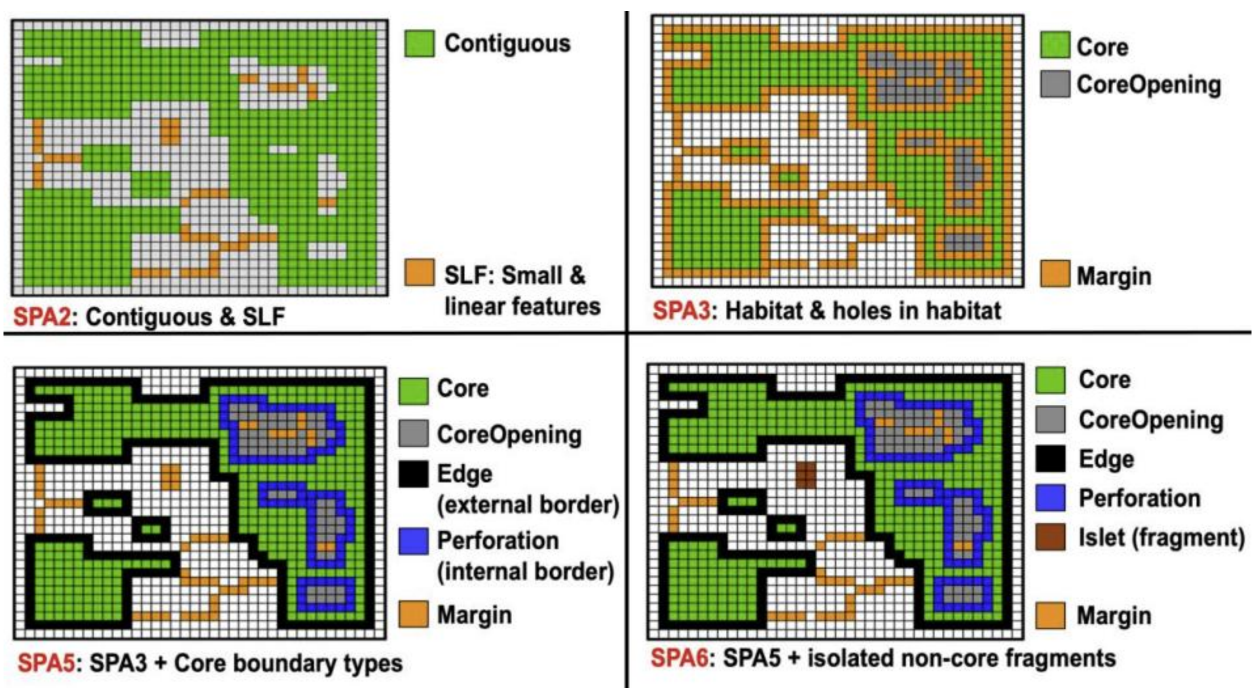

Figure 7. Internal morphology (source: GTB user manual)

In Scenario B, MSPA reveals that unmanaged forests disproportionately fill **Bridge** and **Edge** roles, enhancing network cohesion. The increase in **Core** pixels and the drop in **Perforations** and **Islets** further point to improved habitat integrity. Porosity declines sharply in these areas, showing that unmanaged forests function as ecological buffers or connectors.

In summary, the analytical workflow is structured around three independent modules:

- **Accounting** tracks size and abundance of forest units;
- **Fragmentation** measures spatial continuity using FAD;
- **Pattern** quantifies morphological roles of pixels using MSPA.

Each step builds on distinct spatial logics (area, density, shape) and contributes non-redundant information to the overall connectivity picture. When applied to two forest scenarios (managed vs. all), the workflow provides powerful diagnostics that isolate the specific spatial contributions of unmanaged forest areas. The synergy of these modules not only supports rigorous ecological assessment but also facilitates communication with policy makers and planners through intuitive maps and interpretable metrics.

3 Results

3.1 Forest Area and Patch Structure

The patch structure analysis reveals fundamental differences between the two forest scenarios—Scenario A (*only managed forests*) and Scenario B (*all forests as land cover*)—highlighting how the inclusion of unmanaged forests reshapes the spatial configuration and statistical distribution of forest patches in Maramureș County.

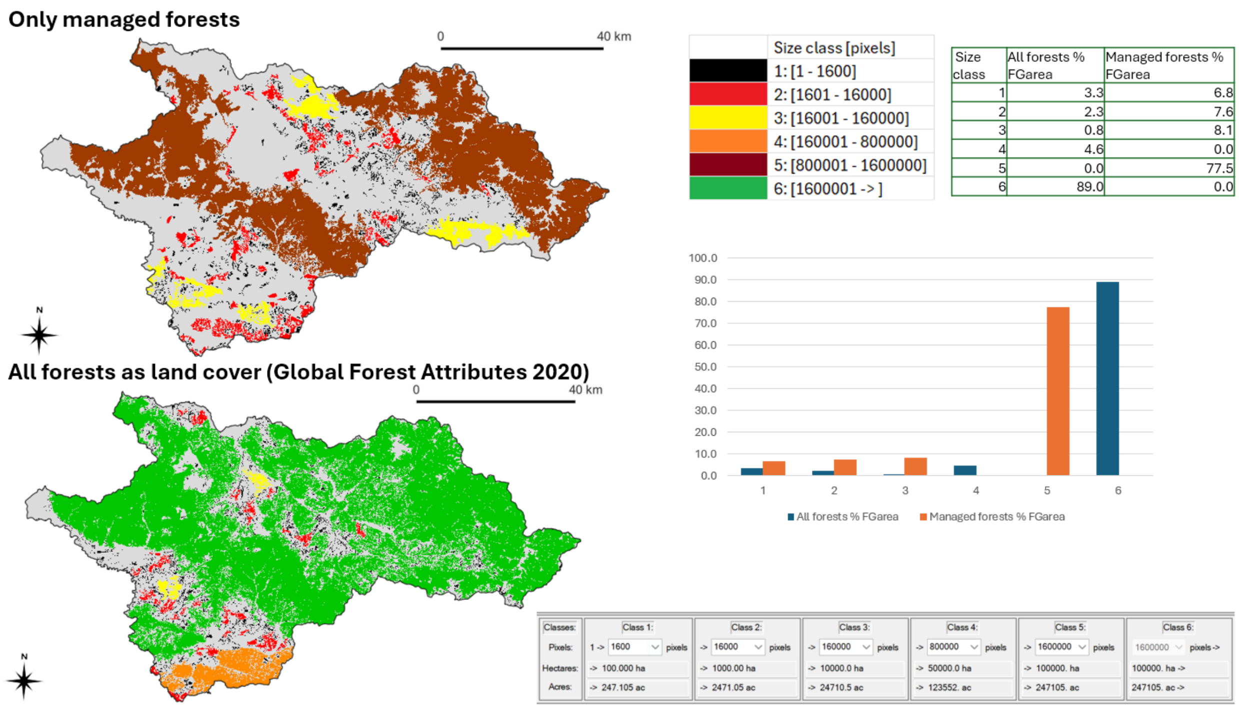

FIgure 8. Forest Area and Patch Structure in different scenarios

Scenario A contains approximately 3.88 million forest pixels, corresponding to around 24,300 hectares of forest. These pixels are confined to areas delineated in the Forest Management Plans (FMPs), representing actively managed compartments. In contrast, Scenario B adds a further 2.05 million pixels (+52.9%), derived from the Global Forest Cover 2020 layer. These newly included forest areas predominantly occur in rugged terrain—such as steep slopes and isolated valleys—that is less accessible to machinery and thus less likely to be actively harvested. These areas often represent natural regeneration zones or historically abandoned woodlands, now undergoing successional processes.

Figure 8 visualises the transformation in patch structure through spatial maps, area class legends, summary tables, and bar charts. The patch classification follows a logarithmic size scale, ranging from Class 1 (1–1,600 pixels, i.e. <10 ha) up to Class 6 (>1.6 million pixels, i.e. >10,000 ha). Each forest pixel group is assigned to a patch, defined as a contiguous set of connected forest cells using 4-neighbour connectivity.

In Scenario A, the vast majority of forest area—over 77%—is concentrated in two very large, contiguous patches (Class 5), which correspond to state-owned forest production blocks. The remaining 23% is distributed among smaller patches falling into Classes 1 through 4. These include smallholder woodlots, fragmented communal parcels, and remnant stands in the vicinity of settlements. Many of these are spatially disconnected due to logging boundaries, land use conversions, or infrastructure corridors.

The patch distribution becomes markedly more consolidated in Scenario B. The inclusion of unmanaged forests connects previously separated fragments, effectively merging isolated pixels into broader, contiguous areas. This process leads to a dramatic decline in total patch count—by roughly 38%—and a significant shift of patch sizes toward the upper classes. Most notably, 89% of total forest area in Scenario B now falls within Class 6 (>1.6 million pixels), compared to 0% in Scenario A. This means that when unmanaged stands are included, almost the entire landscape is perceived as part of a continuous ecological network, instead of a mosaic of scattered blocks.

The chart in Figure 8 (bottom-right) makes this redistribution visually evident. The dark blue bars (Scenario B) show a dominant presence in Class 6, while the orange bars (Scenario A) peak in Class 5. Conversely, Classes 1–4 represent a much smaller share in Scenario B, indicating fewer isolated or fragmented parcels. The patch structure table further quantifies this shift: small patches (Class 1) account for only 3.3% of forest area in Scenario B, compared to 6.8% in Scenario A. Similarly, the proportion of mid-sized patches (Classes 2 and 3) drops significantly.

Median patch size also provides a useful indicator of structural consolidation. In Scenario A, the median patch size is 17 ha, indicative of high fragmentation among non-industrial forests. In Scenario B, this metric increases to 42 ha, more than doubling the typical forest parcel area. This confirms that the addition of unmanaged stands does not merely increase total area but also improves structural cohesion.

Spatial patterns reinforce these statistical findings. The upper map in Figure 8 shows Scenario A as dominated by brown and orange polygons (Classes 4 and 5), surrounded by numerous red and yellow patches representing small, disconnected units. In contrast, the lower map for Scenario B is overwhelmingly green (Class 6), signalling near-continuous forest cover. The spatial continuity in Scenario B is particularly evident in the eastern and southern parts of the county, where steep terrain had previously created gaps in the FMP coverage.

The patch structure comparison reveals that unmanaged forests play a pivotal role in reducing fragmentation, enlarging forest patches, and simplifying the mosaic of land cover. Their inclusion in forest connectivity assessments transforms the landscape from one of administrative segmentation into a more unified ecological network. This has direct implications for species movement, edge effect exposure, and restoration strategy design, which are explored further in subsequent sections.

3.2 Morphological Pattern and Porosity

The structural role of unmanaged forests within the broader ecological matrix becomes particularly evident when examining their contribution to morphological spatial pattern and internal porosity. Using Morphological Spatial Pattern Analysis (MSPA), we characterised each forest pixel into functionally distinct categories that describe its position and connectivity within the forest network. These include Core, Edge, Perforation, Branch, Bridge, Loop, and Islet. These classes are not merely geometric—they reflect how forests function ecologically, particularly in relation to edge effects, movement corridors, and habitat integrity.

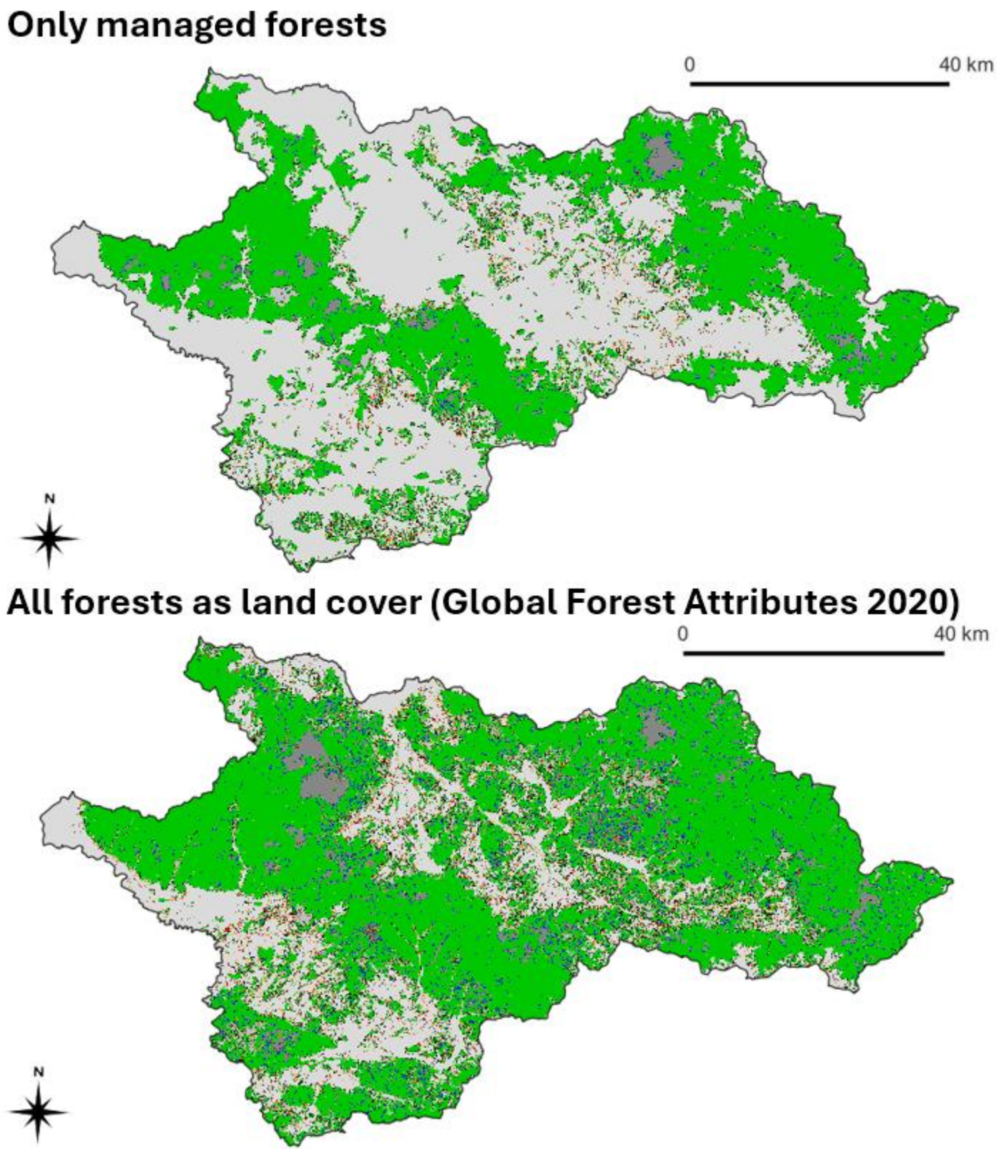

Figure 9. MSPA results in both scenarios

In the analysis, Core forest pixels—those located at least one pixel away from the edge—constitute the dominant morphological class in both scenarios. However, there is a notable difference between scenarios. In the managed forest-only layer (Scenario A), 74.2% of all forest pixels are classified as Core. When unmanaged forests are added in Scenario B, this proportion increases to 82.9% (Figure 10, upper panel). This 8.7 percentage point increase represents a significant improvement in the overall forest interior. It indicates that unmanaged forests are not just peripheral fillers or isolated remnants—they frequently connect to existing stands and extend interior forest conditions.

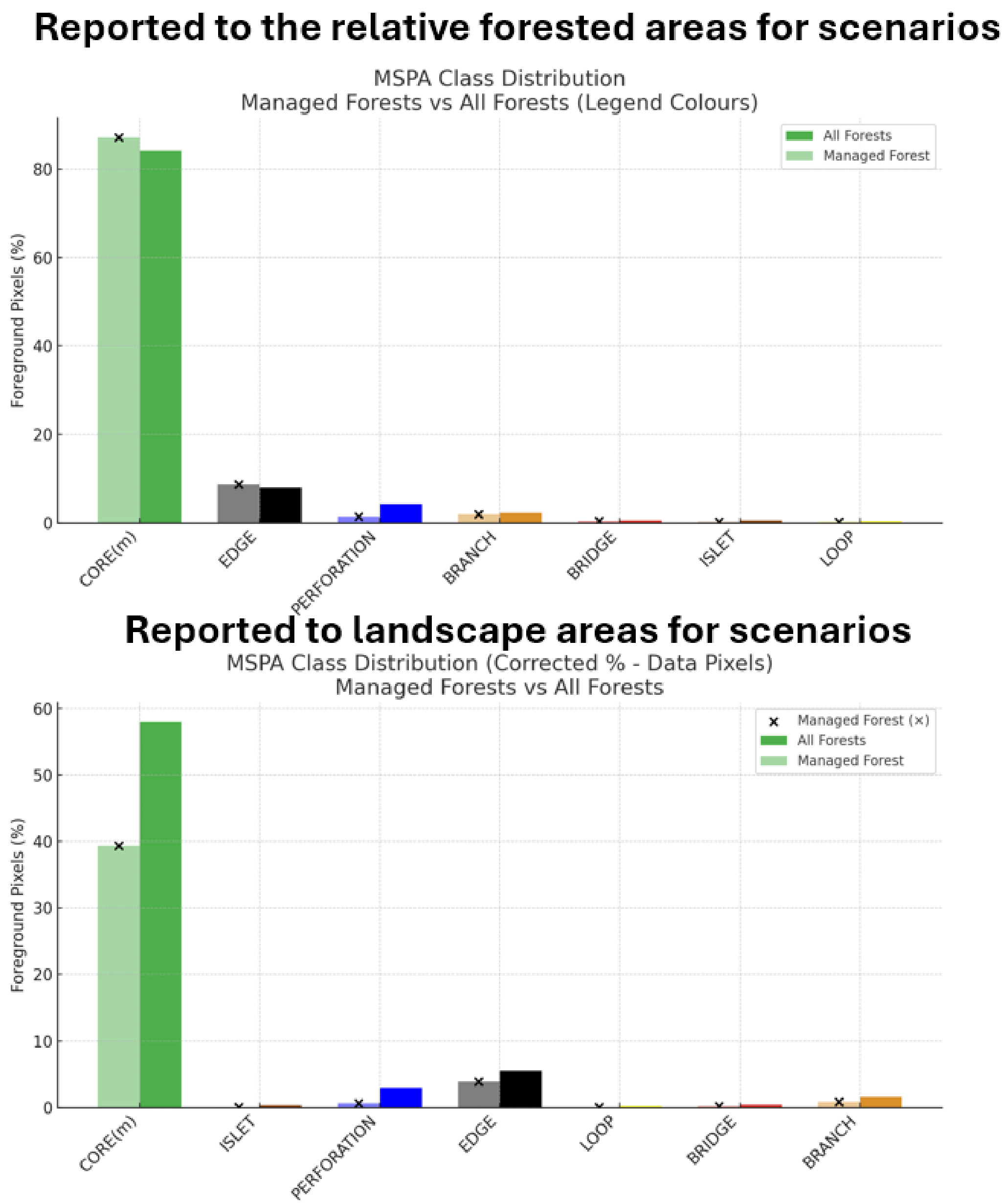

Figure 10. Comparative histograms at forest level and landscape level

This gain in Core forest area is accompanied by a simultaneous reduction in several fragmentation-sensitive classes. The share of Edge pixels decreases by 2.7 percentage points, indicating a relative contraction of abrupt forest boundaries. Perforation pixels—those located within forests but adjacent to internal gaps—also decline by 1.1 percentage points. Additionally, the proportion of Islets, which represent small, isolated forest patches below connectivity thresholds, drops by 0.6 percentage points. Collectively, these shifts suggest that unmanaged forests act as buffer zones, gap fillers, or connective tissues that reinforce the integrity of the forest network.

Importantly, these improvements are also reflected in the derived metric of porosity, defined as the share of Core-Opening pixels (internal voids) within contiguous forest areas. In Scenario A, porosity is measured at 4.6%, implying that nearly one in twenty forest pixels is adjacent to an internal clearing. With the inclusion of unmanaged forests in Scenario B, this value drops to 2.3%, effectively halving the number of such internal gaps. A lower porosity value corresponds to a more structurally intact forest interior, with greater continuity for species that are sensitive to disturbance or edge environments.

The spatial mechanisms driving these improvements are tied to the geographic positioning of unmanaged stands. Many of them occupy narrow transitional zones along valley bottoms or forest peripheries, particularly in areas where historic logging or grazing once created fragmented landscapes. By naturally regenerating in these zones, unmanaged forests often "seal" previously exposed edges and perforated zones, thereby converting pixels from marginal to interior categories. In practice, this means that former boundaries between forest and open land are now more continuous and ecologically buffered. This effect is clearly visible in Figure 9, where the additional green pixels in Scenario B visibly plug gaps in the managed-only coverage, especially in foothill regions.

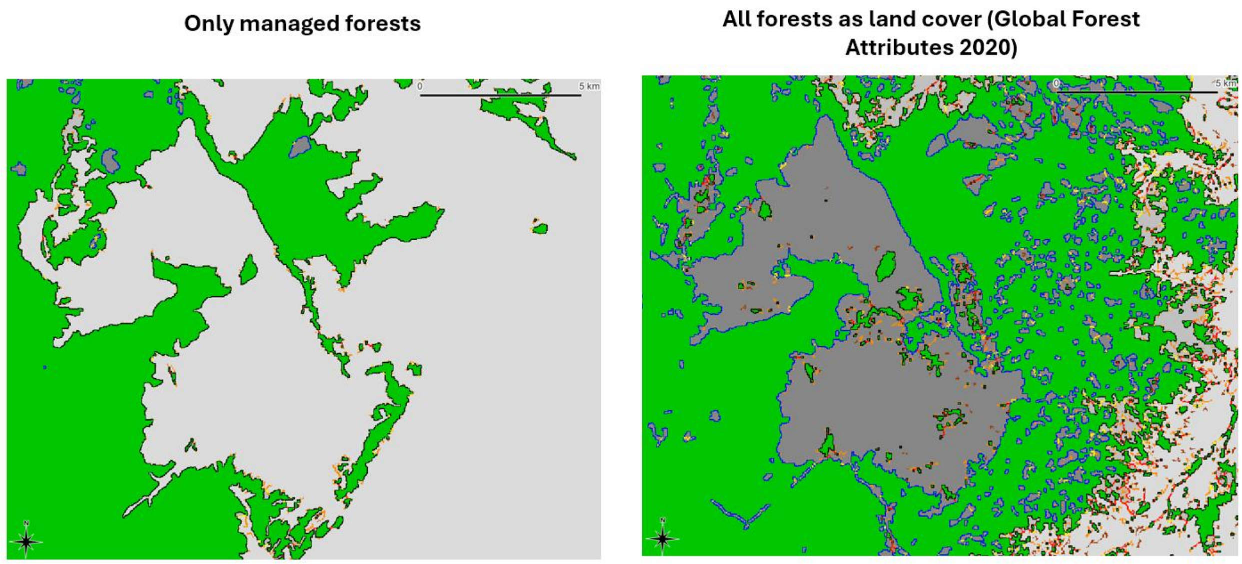

Figure 11. Effect of forest cover increase on MSPA classes

Moreover, some unmanaged patches provide lateral connectivity between larger managed blocks. For example, narrow regeneration corridors following old access roads or watercourses often form Bridge structures that connect otherwise isolated forest components. Even when small in size, such features can have an outsized ecological impact by enabling species movement and genetic exchange across fragmented terrain. Figure 12 illustrates this in a densely fragmented mosaic, where unmanaged forests link dispersed clusters into a more cohesive whole.

That said, the effect of unmanaged forests on morphological pattern is scale-dependent. When measured against total forest area, the increase in Core appears as a straightforward gain. However, when reported in relation to total landscape area (i.e. including non-forest land), Edge and Perforation classes may still rise in absolute terms. This apparent contradiction stems from the fact that Scenario B includes substantially more forest pixels overall—so even though Edge becomes proportionally less dominant within forests, the total number of Edge pixels across the landscape can still increase due to perimeter growth. This nuance is captured in the lower panel of Figure 10, where Edge and Perforation percentages shift depending on whether values are normalised by forest extent or total land area.

This shift is not just theoretical—it becomes apparent upon visual inspection. Figure 11 zooms into a landscape formerly characterised by large intact managed cores. In Scenario B, previously exposed edges become internalised, and some perforations vanish entirely due to infill from regenerating stands. Conversely, Figure 12 highlights how unmanaged forests expand the overall forest footprint, which introduces new edge zones, albeit with less rectilinear and abrupt transitions compared to managed block boundaries.

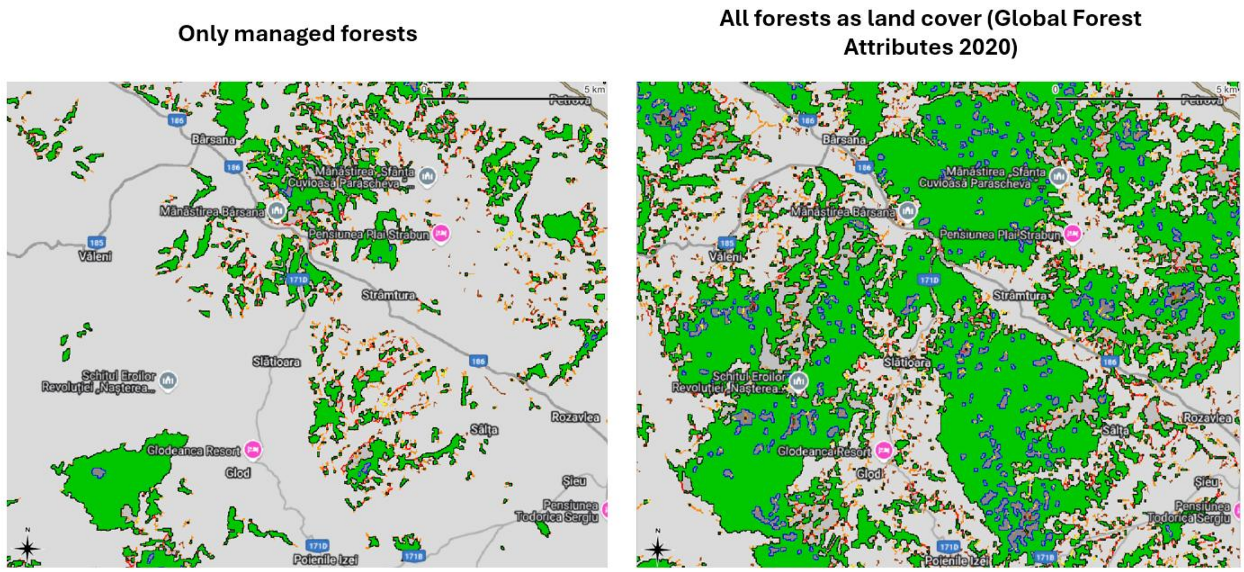

Figure 12. Effect of forest cover increase on MSPA classes

Morphological pattern analysis demonstrates that unmanaged forests significantly improve structural connectivity across the forest matrix. By increasing the extent of Core forest, reducing internal porosity, and modifying edge geometry, they support a more resilient and cohesive landscape structure. These changes have direct implications for biodiversity conservation, particularly for species that depend on large, continuous tracts of forest or are sensitive to edge-related microclimatic and predation pressures. Incorporating unmanaged forests into regional planning frameworks could thus provide an efficient, low-cost means of enhancing connectivity and mitigating fragmentation effects in Carpathian landscapes and beyond.

3.3 Fragmentation Metrics

A comparative analysis of forest structure between the two scenarios reveals important differences in fragmentation patterns and landscape connectivity. The inclusion of unmanaged forest parcels leads to a marked increase in overall forested area and to measurable gains across multiple connectivity indicators.

In the managed-only scenario, forest cover appears relatively fragmented, with many small discontinuities between compartments. This is especially evident in the spatial distribution of Forest Area Density (FAD) classes, which were computed using a fixed 49×49 pixel moving window. In this scenario, areas classified as ‘Interior’ dominate the core of large managed tracts, while peripheral zones exhibit more ‘Dominant’ and ‘Transitional’ classifications. By contrast, in the full-forest scenario (Scenario B), many formerly marginal zones shift toward higher FAD classes. This spatial trend is visible in the classified FAD maps and is supported by the quantitative class shares shown in Figure 13.

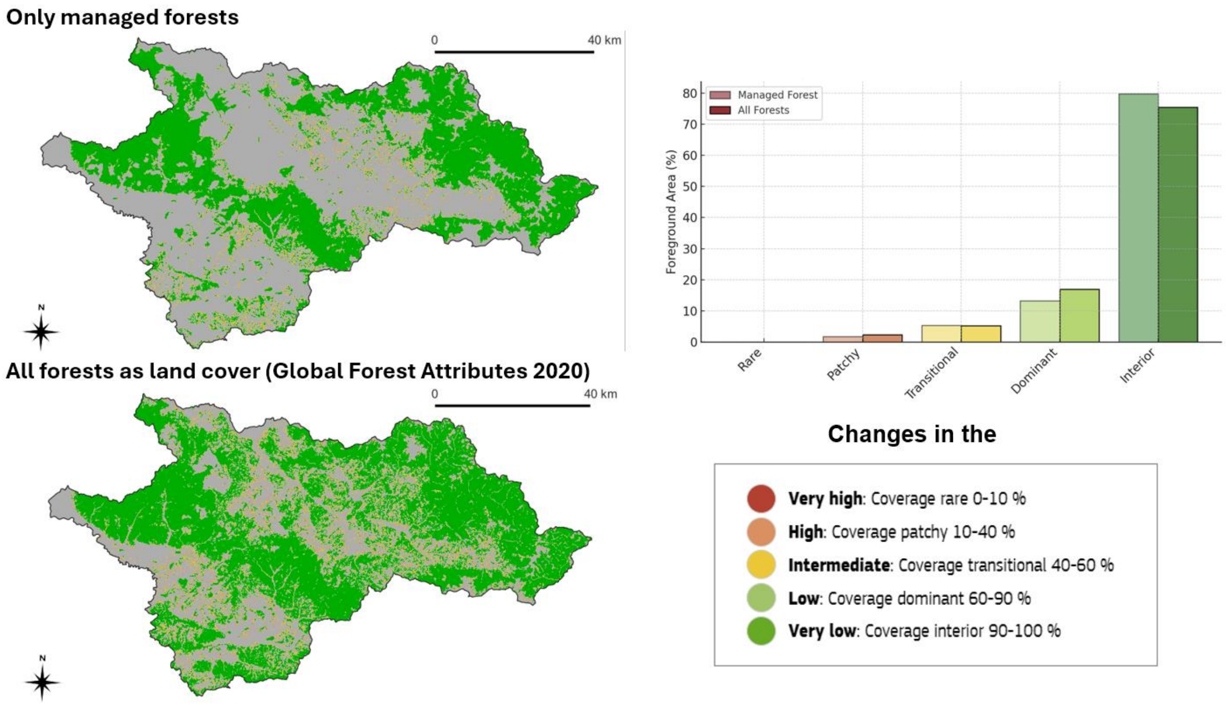

Figure 13. FAG analysis in both scenarios

The differences are further quantified in Figure 14, where the share of Rare and Patchy classes (representing low local connectivity) is reduced by more than half when unmanaged forests are included, dropping from 9.2% in Scenario A to just 4.1% in Scenario B. This change suggests that many of the small unmanaged stands serve as buffers or bridges in an otherwise fragmented managed landscape. At the same time, the share of ‘Dominant’ class pixels increases, and ‘Interior’ cover remains high, showing that the newly added forests tend to be spatially adjacent to existing large blocks.

Connectivity metrics at the forest (B3) and landscape (B4) scales confirm this trend (see Figure 15). At forest level, both scenarios are highly connected, with average FAD values exceeding 90%, although managed forests show a slight advantage of 1.3 percentage points. However, at the broader landscape scale, the addition of unmanaged stands results in a striking increase in connectivity—from 41.8% to 62.9%—which corresponds to a reduction in overall landscape fragmentation by 21.1 percentage points.

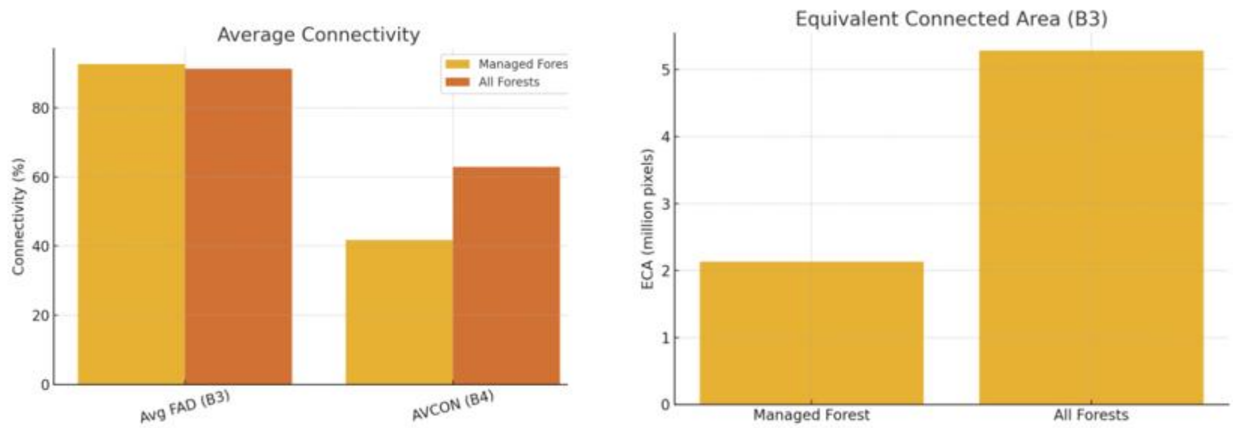

Figure 14. Connectivity and equivalent connected area

The Equivalent Connected Area (ECA) metric reinforces the role of unmanaged forests in consolidating the landscape. As shown in Figure 15, the ECA for Scenario A is 2.1 million pixels, whereas Scenario B produces an equivalent patch of 5.3 million pixels—more than double the connectivity potential. Coherence, both at the B3 and B4 levels, also improves significantly. For the forest matrix (B3), structural cohesion rises from 55% to 89%. At landscape level (B4), coherence jumps from 24.8% to 61.4%, underscoring how the unmanaged stands bolster pattern repetition across the terrain.

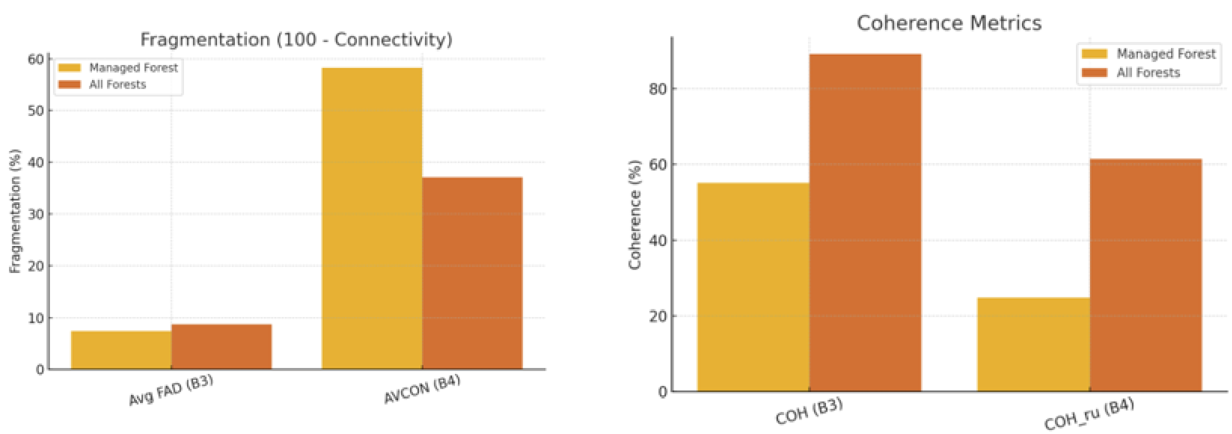

Figure 15. Fragmentation and coherence

Multiscale dynamics are illustrated in Figure 16, which charts the proportion of each FAD class across increasing observation scales. The figure reveals that connectivity gains are strongly scale-dependent. At finer window sizes (7–13 pixels), improvements are modest, likely due to increased edge effects introduced by newly classified stands. In contrast, larger observation windows (>27 pixels) show dramatic improvements in forest continuity. The most frequent class transition is from 'Dominant' to 'Interior,' and over 93.9% of the pixels that changed class did so in favour of greater connectivity.

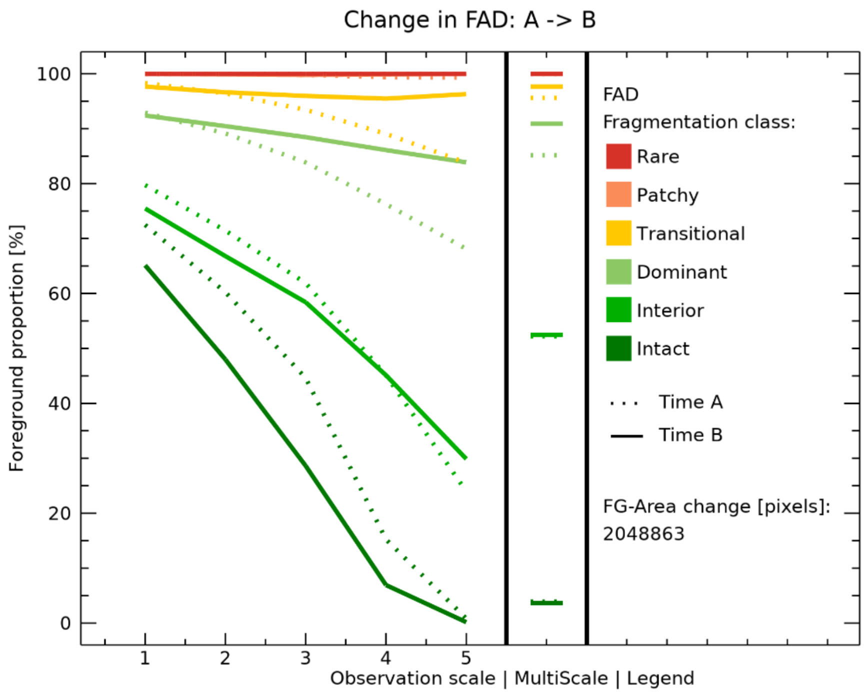

Figure 16. FAD change analysis

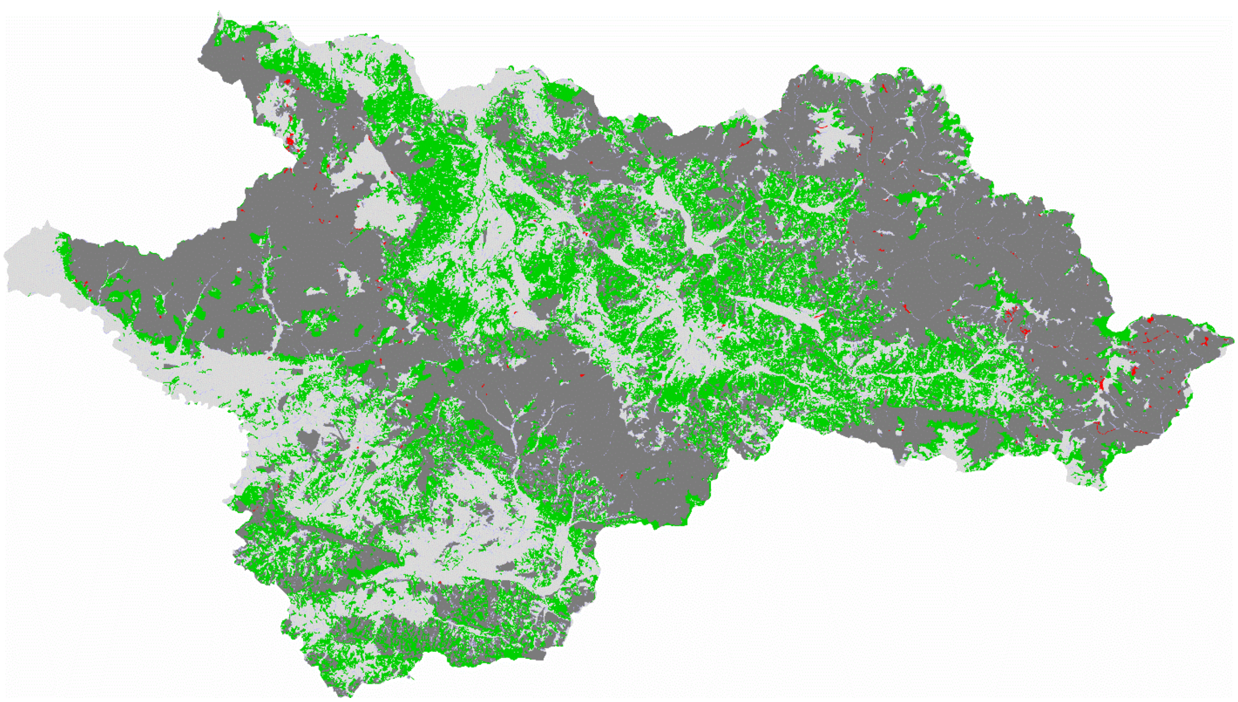

Figure 17. Changes map between FAD

Figures 17 contextualize these statistical changes by visualizing the spatial structure of the network under both scenarios.

Overall, these results indicate that the managed-only layer under-represents not only the total forest area but also the functional cohesion of the forest network. Adding unmanaged forests increases the mapped forest extent by approximately 53% and improves neighbourhood connectivity by 21 percentage points at landscape scale. Crucially, the shift in FAD classes suggests that these gains are not evenly distributed; instead, the new forest pixels act as critical connectors, converting transitional zones into dominant and interior classes. This spatial configuration suggests that unmanaged forests—despite being omitted from forest management plans—play an outsized role in maintaining ecological integrity.

From a management perspective, this has important implications. Restoration strategies focused solely on managed compartments may overlook the natural buffering and bridging roles provided by adjacent unmanaged stands. Their retention and protection could yield fragmentation reductions that far exceed the impact of isolated afforestation campaigns. As such, policy frameworks that aim to enhance connectivity should explicitly account for these 'invisible' forest patches to ensure that conservation objectives are not undermined by administrative or cadastral boundaries.

3.4 Coherence Indicators

Equivalent Connected Area (ECA) at B3 jumps from 2.1 million px to 5.3 million px (× 2.5). Coherence correspondingly increases from 55 % to 89 % (+ 34 pp). At landscape scale, COH rises even more dramatically (+ 36.6 pp), underscoring that unmanaged stands often occupy strategic locations relative to anthropogenic land uses.

Sensitivity analysis varying the dispersal threshold from 250 m to 750 m indicates that Scenario B maintains higher coherence across all thresholds, although the relative gain diminishes at > 700 m where most patches are already connected.

4 Conclusions

This study demonstrates that the inclusion of unmanaged forests—those not documented in Forest Management Plans (FMPs) but visible in satellite-derived forest masks—significantly enhances our understanding of forest structure, connectivity, and ecological functionality in Carpathian landscapes. By comparing a managed-only scenario (Scenario A) with a comprehensive forest land cover scenario (Scenario B), we highlight the underestimated yet critical role that unmanaged forests play in shaping landscape-scale connectivity.

First, in terms of total forest area and patch structure, Scenario B reveals a substantial increase of approximately 53% in forest coverage compared to Scenario A. This additional coverage is not uniformly scattered but strategically clustered in valley bottoms and steep, inaccessible slopes—areas often excluded from harvesting operations but undergoing natural regeneration. The result is a dramatic shift in patch structure metrics: the number of patches decreases by 38%, and the median patch size more than doubles, from 17 ha to 42 ha. The majority of forest area moves from intermediate patch classes (C4–C5) to the largest class (C6), effectively transforming the perceived landscape from a fragmented mosaic into a nearly continuous ecological network.

Second, morphological pattern analysis using MSPA confirms that unmanaged forests do more than just fill spatial voids—they actively contribute to structural cohesion. The proportion of Core forest pixels increases from 74.2% to 82.9%, while Edge, Perforation, and Islet classes decline. Porosity, defined as the proportion of internal openings in contiguous forests, is halved. These changes suggest a real improvement in interior habitat conditions, with unmanaged forests acting as natural buffers, connectors, and restorers of ecological integrity.

Third, fragmentation metrics derived from Forest Area Density (FAD) analysis further reinforce the role of unmanaged stands in promoting connectivity. Scenario B reduces the share of highly fragmented forest classes (Rare and Patchy) by more than 50% and raises the proportion of Dominant and Interior zones. At the landscape scale, connectivity improves by over 21 percentage points (from 41.8% to 62.9%), while Equivalent Connected Area (ECA) more than doubles, rising from 2.1 million to 5.3 million pixels. Coherence indicators show a similar trend, with structural coherence at the landscape level jumping from 24.8% to 61.4%. These metrics collectively underscore the ecological importance of unmanaged forests as connectivity anchors.

Importantly, the scale-dependency of these gains must be acknowledged. While small-scale metrics (e.g., 7–13 pixel FAD windows) show modest improvements due to edge effects, large-scale analyses (>27 pixels) reveal pronounced increases in connectivity. The strategic location of unmanaged forests—often bridging gaps between state-managed blocks—makes them disproportionately valuable for reducing fragmentation and improving habitat contiguity.

These findings carry important implications for forest policy, ecological restoration, and biodiversity conservation. Forest management strategies that focus solely on officially managed compartments risk overlooking vast areas that already function as ecological corridors or interior forest. Moreover, restoration efforts targeting connectivity could achieve far greater efficiency and impact by integrating existing unmanaged forests rather than starting from bare land. From a monitoring perspective, relying exclusively on FMP-derived layers introduces a systemic bias that under-represents forested habitat quality and misguides conservation prioritisation.

In light of these results, we recommend that national and regional forest inventories systematically incorporate satellite-derived forest layers to complement official FMP records. Policymakers should recognise the ecological contributions of unmanaged stands and consider their legal and functional integration into green infrastructure planning, Natura 2000 network expansion, and carbon or biodiversity offset schemes. Such an approach not only improves the accuracy of landscape assessments but also supports the EU Biodiversity Strategy's goals of enhancing landscape connectivity and protecting carbon-rich habitats.

In conclusion, this study underscores that the ecological structure of forests is not defined solely by administrative boundaries. Unmanaged forests, serve as critical assets for biodiversity, resilience, and functional connectivity. Their recognition and protection are vital for sustaining forest landscapes in a rapidly changing socio-ecological context.

References

1. **Vogt, P., Riitters, K.H., Estreguil, C., Kozak, J., Wade, T.G., & Wickham, J.D. (2007).** *Mapping spatial patterns with morphological image processing.* Landscape Ecology, **22**, 171–177. https://doi.org/10.1007/s10980-006-9013-2

2. **Saura, S., Estreguil, C., Mouton, C., & Rodríguez-Freire, M. (2011).** *Network analysis to assess landscape connectivity trends: Application to European forests (1990–2000).* Ecological Indicators, **11**(2), 407–416. https://doi.org/10.1016/j.ecolind.2010.06.011

3. **Estreguil, C., Caudullo, G., de Rigo, D., & San-Miguel-Ayanz, J. (2013).** *Forest landscape in Europe: pattern, fragmentation and connectivity.* EUR 25717 EN, Joint Research Centre, European Commission. https://doi.org/10.2788/77842

4. **FAO (2020).** *Global Forest Resources Assessment 2020 – Main report.* FAO Forestry Paper No. 188. https://www.fao.org/documents/card/en/c/ca9825en

5. **JRC (2021).** *Global Forest Cover Map 2020, Version 2.* European Commission, Joint Research Centre. https://forobs.jrc.ec.europa.eu/products/gfc/