



EUROPEAN COMMISSION
DIRECTORATE-GENERAL
JOINT RESEARCH CENTRE
Directorate D – Sustainable Resources
Bio-Economy Unit

Quantifying Forest Fragmentation.

Available in the free software *GuidosToolbox*. This is a living document, please check for the latest version at: <https://forest.jrc.ec.europa.eu/en/activities/lpa/gtb/>

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1. Background

Fragmentation is a very complex topic. Typically, it is a summary descriptor addressing a variety of spatial attributes of a forest map (i.e., total forest area, average patch size, number of forest patches, spatial aggregation and/or dispersion of forest patches, compactness, amount of forest adjacencies, amount of forest perforations, inter-patch connectivity and distance, etc.).

A fragmentation assessment scheme should account for key aspects of fragmentation, such as the area and shape of contiguous forest, forest integrity (amount, shape, and area of perforations inside spatially intact forests), and the spatial inter-patch distance distribution of forest patches separated by non-forest lands.

- Forest fragmentation must account for the principal aspect of forest pattern, which is the amount of forest. Any other aspect of pattern (patch shape, connectivity, etc.) is necessarily constrained by forest amount. Therefore, no other aspect can be fully interpreted without also measuring forest amount.
- Forest fragmentation is scale dependent and observer dependent. There is no single scale or observer that is not arbitrary. The solution is to report fragmentation at multiple scales, in a way that different observers can make their own choices about scales and thresholds of concern.

Scope of this report and for consideration:

This report illustrates a popular map analysis methodology to describe and measure forest fragmentation and temporal changes. The methodology outlined in this document (FAD, FED, FAC) extends a [reporting scheme](#) used by the USDA-Forest Service (USFS) for reporting to the [Montréal Process](#) to provide additional features and reporting schemes. The result is a map product, with a statistical summary and a dedicated change analysis for several fragmentation classes. The fragmentation analysis scheme is available in two forms:

- a) Multiscale:** concurrent multiscale analysis at five fixed observation scales plus a multiscale summary. This is the original scheme described in section 2 to section 4.
- b) Single scale:** fragmentation analysis at a user-defined Fixed Observation Scale (FOS). A modified and new default scheme is described in section 5.

2. Forest fragmentation assessment scheme

2.1 The methodology

Technically, all analysis methodologies described in this document apply convolution filtering, also known as a [moving window](#), [focal](#) or neighborhood analysis in GIS applications. Here, a window ([kernel](#)) is overlaid on a foreground pixel of the input map, the pattern index within the window is calculated and then assigned to the same location on the output map. This process is then repeated for every pixel of the input map, hence the term *moving window*. The value of a pixel in the new output map represents an index of pattern derived from the surrounding area of the moving window coverage in the original map. This value is driven by the window dimension and the computation rule assigned to the window elements.

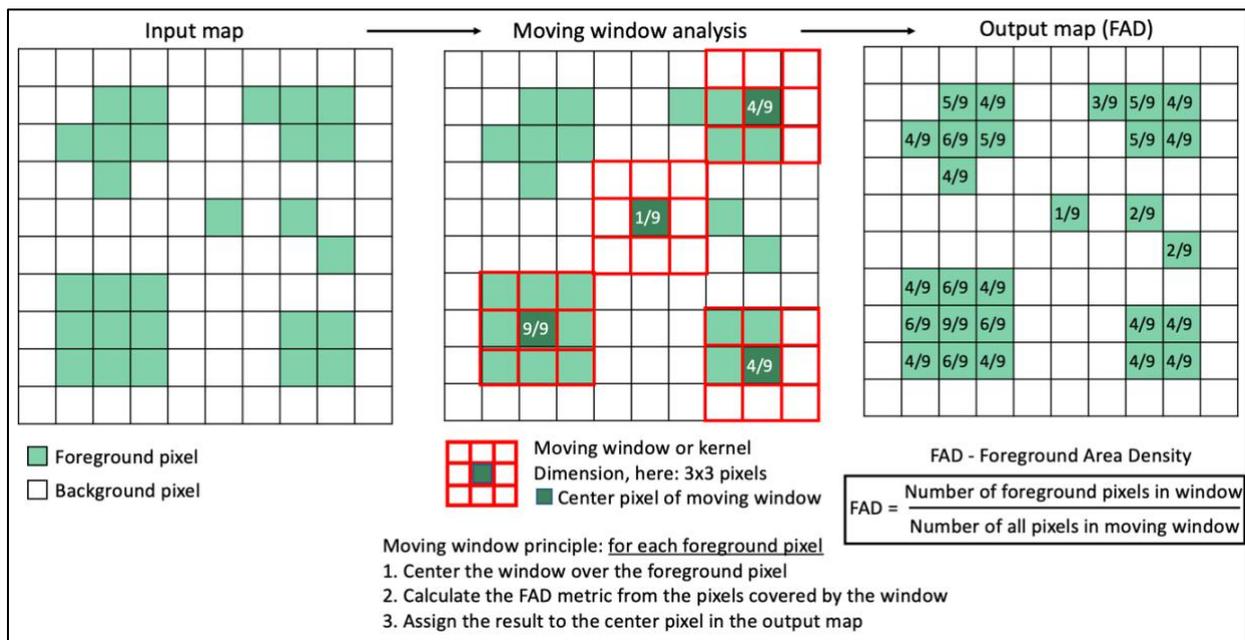


Figure 1: Moving window analysis: a moving window of size $n \times n$ (here, 3x3) is centered over a given foreground pixel, the metric is calculated, and the resulting value is assigned to the same location in the output map. The central panel shows four example locations to illustrate the process.

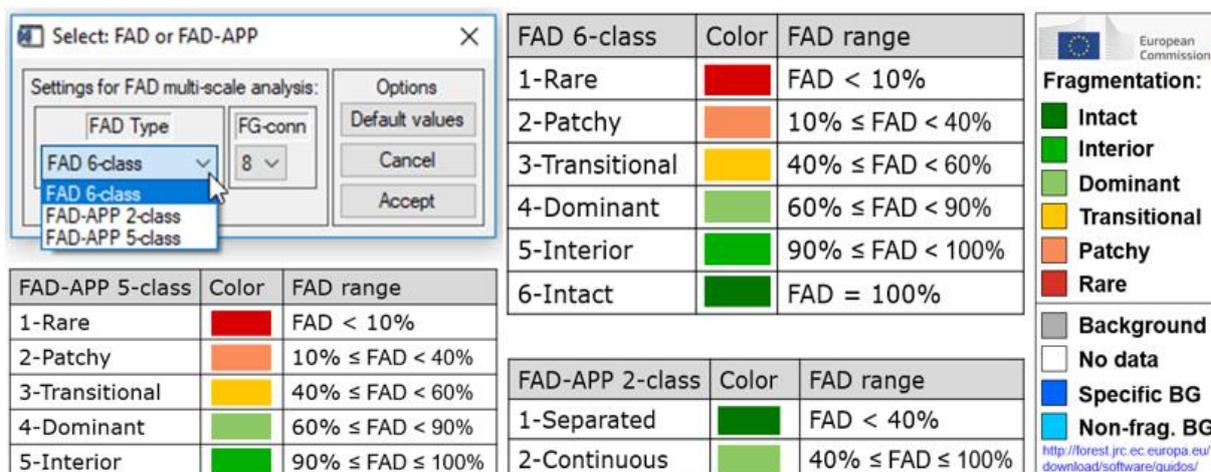
Figure 1 shows an example of a map of 10x10 pixels with foreground pixels in green color. The central panel shows the application of a moving window analysis using a 3x3 window centered on four of the foreground pixels. Within each window, Foreground Area Density (FAD), equivalent to the amount of foreground area relative to the moving window area, is assigned to the central location in the output map. After repeating these steps for all foreground pixels, the result of the computation is shown on the right panel, having identical pixel coverage as in the input map but now showing the degree of FAD for each foreground pixel and considering a local neighborhood of 3x3 pixels.

Increasing the dimension, or size of the moving window implies accounting for a larger local neighborhood area or using a larger analysis/observation scale.

The methodology is generic, and the definition of *foreground* is left to the user. Foreground could be forest, agriculture, protected land or any thematic area of interest, which should be analyzed for fragmentation at an appropriate local, regional, or national scale.

The original multiscale assessment scheme for reporting on fragmentation measures the spatial density of forest cover, or **Forest Area Density (FAD)** (Riitters et al., 2002, 2012), at five fixed observation scales using a moving window analysis with square neighborhood areas of length 7, 13, 27, 81, 243 pixels. These neighborhood areas were selected to span a wide range of scales representing an approximately geometric progression of window area with observation scale. For example, when using CORINE land cover maps with a spatial pixel resolution of 1 hectare, the observation scales correspond to neighborhood areas of approximately: 0.5, 1.7, 7.3, 65, 590 km². The result is a set of five maps (one for each observation scale) showing forest area density values in [0, 100] % for neighborhood areas over each forest pixel. In the next step, and for each of the five observation maps, the proportion of forest pixels in each fragmentation class is calculated and summarized in a bar plot showing forest fragmentation over observation scale. Here, the observation scales are labelled as 1, 2, 3, 4, 5 corresponding to window lengths 7, 13, 27, 81, 243 pixels, respectively. In addition, summary fragmentation statistics are saved as a text-file and a csv-file for further analysis in a spreadsheet application. Finally, the five fragmentation maps are aggregated into a summary map, showing the average FAD value calculated across all five observation scales, which is displayed color-coded into the respective fragmentation class (see Figure 4). The underlying maps always show the FAD values within their full range in [0, 100] %, which are grouped (color-coded) in one of three reporting schemes (see Figure 2):

- a) **FAD 6-class:** FAD values at pixel level and color-coded into six fragmentation classes.
- b) **FAD-APP 2-class:** per-pixel FAD values aggregated at forest patch level (see section 6). Each forest patch is assigned a single FAD value, the Average-Per-Patch (APP) FAD value, which is then color-coded into two fragmentation classes.
- c) **FAD-APP 5-class:** same as b) but color-coded into five fragmentation classes.



FAD	Color	Foreground cover	Connectivity	Fragmentation
< 10%	Red	Rare	Very low	Very high
10% ≤ FAD < 40%	Orange	Patchy	Low	High
40% ≤ FAD < 60%	Yellow	Transitional	Intermediate	Intermediate
60% ≤ FAD < 90%	Light Green	Dominant	High	Low
90% ≤ FAD ≤ 100%	Medium Green	Interior	Very high	Very low

Figure 2: Summary of the multiscale FAD/FAD-APP fragmentation: class thresholds, names, and color assignment. FAD is a per-pixel classifier while FAD-APP summarizes the average value at patch level. The bottom panel shows the relation between FAD, foreground cover, connectivity, and fragmentation.

2.2 The input data:

The input map for the FAD analysis must be a binary raster map. It must have the values 1 byte for background (non-forest) and 2 byte for foreground (forest). All background data pixels will fragment the foreground.

Optionally, the input can have the values:

0 byte – missing data: These pixels will show in white color in the output map. These pixels are excluded from the analysis.

3 byte – specific background: These background pixels (e.g., water) will show in dark blue color in the output map.

4 byte – non-fragmenting background: In contrast to all other background pixels these background pixels will not have a fragmenting effect on the foreground. They can be specifically assigned to exclude certain landcover classes or individual pixels from having a fragmenting effect on the foreground. Non-fragmenting background pixels are highlighted in light blue color in the output map.

Note: Because input data pixels with 4 byte do not have a fragmenting effect, changing background to non-fragmenting background may lead to a reduction of foreground fragmentation and consequently change the fragmentation statistics.

2.3 The output data:

The result of the FAD analysis is a set of maps and documents featuring:

1. Six fragmentation categories in decreasing order from Intact to Rare foreground cover.
2. Statistical summary indices at five different observation scales and a multi-scale assessment across all five individual observation scales.
3. Geographic maps of fragmentation categories at five observation scales + multi-scale.

The next section will illustrate the FAD methodology on an example map located in the north of Finland and derived from CORINE 2012 land cover data.

3. Example application

This section illustrates features and output examples of the multiscale FAD fragmentation assessment scheme using an example forest map in the North of Finland, derived by recoding CORINE Land Cover 2012 data with a spatial resolution of 100 m. The example below is just indicative to illustrate the features of FAD.

The following describes three options for conducting a multiscale FAD fragmentation analysis.

Option A = the standard case of analyzing a forest mask.

Option B = Option A + assigning *specific background* (3 byte) to visually focus on the interaction of this specific background and the foreground fragmentation.

Option C = Option A (or B) + assigning *non-fragmenting background* (4 byte) to land cover that will not be included in the calculation of foreground fragmentation (it will be treated the same as other missing data).

Option A: Using a forest map

In option A, the forest map is derived by recoding the CORINE classes as follows:

CORINE class	FAD input value (byte)
0, 48-50 (no data or unclassified)	0 - Missing
1 – 22, 26 – 44 (artificial, agriculture, wetlands)	1 - Background
23, 24, 25 (forests)	2 - Foreground

Table 1: Recoding from CORINE land cover to a custom forest map.

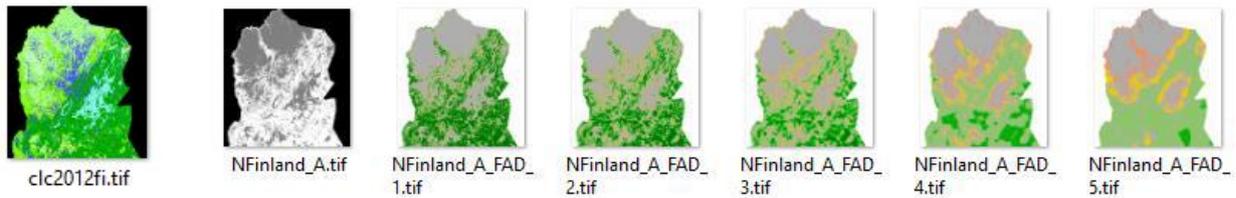


Figure 3: CORINE 2012 land cover and forest mask in the North of Finland (left) and fragmentation maps at five increasing (local to regional) observation scales.

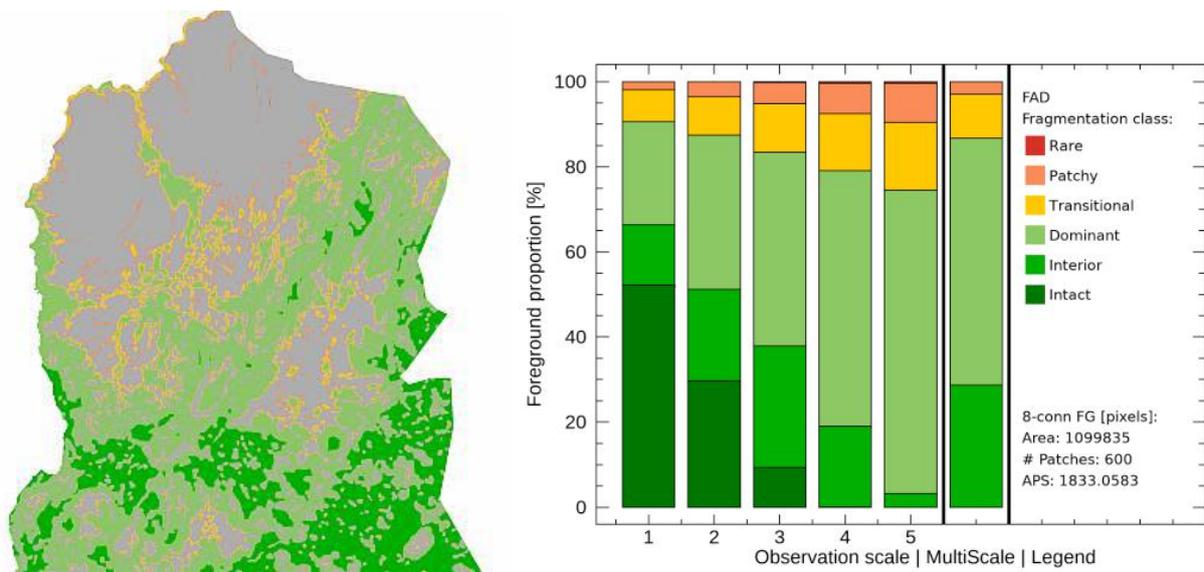


Figure 4: Aggregated (multi-scale) map of fragmentation classes over five observation scales (left) and bar plot of summary statistics (right) including total amount of forest area, number of forest patches and average patch size.

From the maps in Figure 3, one can see the degree of forest fragmentation at any given observation scale or in Figure 4, aggregated across all 5 observation scales (multi-scale summary). The grouping in six fragmentation classes allows locating hotspots of highly fragmented forest areas (*Rare forest* – red color) or any other fragmentation classes like *interior forest*, where the forest area density is greater than 90 % (dark green). The bar plot in Figure 4 and the statistics in Table 2 summarize the forest fragmentation analysis in tabular format.

```

FAD: Foreground Area Density summary analysis for image:
C:\GuidosToolbox\data\NFinland_A.tif
=====
8-conn FG: area, # patches, aps [pixels]: 1099835, 600, 1833.0583
Fragmentation class: foreground proportion at observation scale/area:
Observation scale: 1 2 3 4 5 mscale
Neighborhood area: 7x7 13x13 27x27 81x81 243x243
=====
Rare: 0.0033 0.0242 0.2450 0.3786 0.3976 0.0186
Patchy: 1.9327 3.5649 4.9045 7.1666 9.1789 2.8774
Transitional: 7.5076 8.9589 11.3673 13.3002 15.8747 10.3957
Dominant: 24.1627 36.2559 45.5856 60.1687 71.3635 58.0553
Interior: 14.1438 21.5234 28.4999 18.8959 3.1853 28.6529
Intact: 52.2498 29.6727 9.3977 0.0900 0.0000 0.0000
=====
FAD_av: 88.4863 83.7177 78.7418 72.7682 67.8558 78.3146

```

Table 2: Statistical summary table (provided in txt and csv-format) showing percent of fragmentation classes at the five observation scales and for the multi-scale analysis.

Option B: Using a forest map + specific background (3 byte)

In option B, the forest map is derived by recoding the CORINE classes as follows:

CORINE class	FAD input value (byte)
0, 48-50 (nodata or unclassified)	0 - Missing
1 – 22, 26 – 34 (artificial, agriculture, scrub)	1 - Background
23, 24, 25 (forests)	2 - Foreground
35 – 44 (wetland, peat bogs, marshes, water)	3 - Specific Background

Table 3: Recoding from CORINE land cover to a custom forest map, including the optional class *Specific Background* (3 byte).

Motivation/Purpose: A user may be interested to highlight a specific background type, for example, wetland & water bodies to investigate the forest fragmentation near to that specific background. Specific background is displayed in dark blue color in the resulting map allowing to easily see the degree of forest fragmentation in the vicinity of the selected specific background, here wetlands.

In a similar fashion, one could assign urban as specific background to investigate forest fragmentation near urban areas, and then do the same for agriculture, then compare fragmentation near urban with fragmentation near agriculture.

Note: The additional input class *specific background* has no effect on the foreground fragmentation and the fragmentation statistics. The effect is only visual: a specific part of the background is displayed in dark blue in the resulting maps. The forest coverage and fragmentation classes are identical in Figure 5.

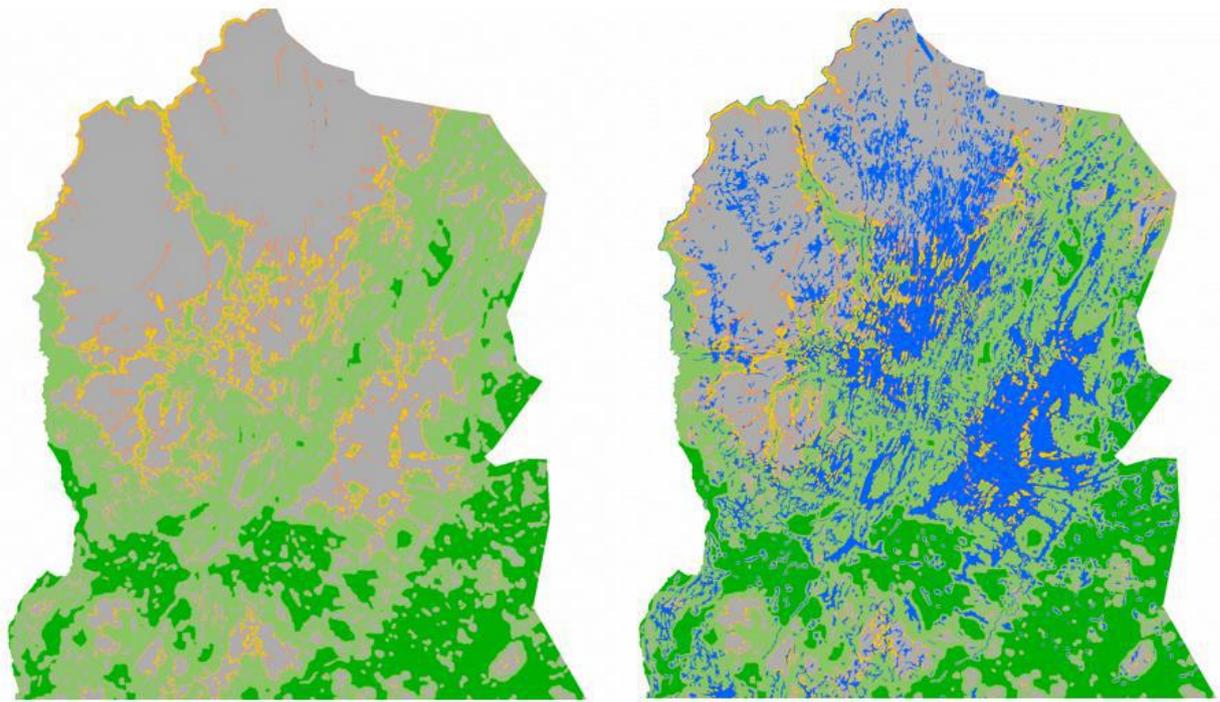


Figure 5: Aggregated Forest fragmentation map from Option A (left) and from Option B (right) with specific background (wetlands and water bodies) highlighted in dark blue.

Option C: Using a forest map + non-fragmenting background (4 byte)

In option C, the forest map is derived by recoding the CORINE classes as follows:

CORINE class	FAD input value (byte)
0, 48-50 (no data or unclassified)	0 - Missing
1 – 22, 26 – 34 (artificial, agriculture, scrub)	1 - Background
23, 24, 25 (forests)	2 - Foreground
35 – 39 (wetland, peat bogs, marshes)	3 - Specific Background
40-44 (water bodies)	4 - Non-fragmenting Background

Table 4: Recoding from CORINE land cover to a custom forest map, including the optional class *Specific Background* (3 byte) and *Non-fragmenting Background* (4 Byte).

Motivation/Purpose: A user may wish to assign a certain background type to not have a fragmenting effect on foreground. For example, water bodies within forests could be an integral part of forests and as such they should not fragment contiguous forest areas. Such a setup can be achieved by setting the related non-fragmenting background pixels in the input map to the value 4 byte (Table 4). With this setting, the amount of fragmenting background is reduced and foreground near to non-fragmenting background will no longer be fragmented. With Option C, the user can fine-tune the fragmentation analysis for any type of background. For example, one could assign lakes to not fragment forests (4 byte) while rivers will fragment forests (3 byte). In a similar fashion, and in a mountainous area, one could assign rock formations to 4 byte to ensure they will not fragment the forest cover.

Note: The use of the additional input class *non-fragmenting background* has two effects:

- Visual – the related part of the background is displayed in light blue color.
- Data – compared to Option A and B, Option C will change the foreground fragmentation, classes and statistics because a part of the background is now assigned to be non-fragmenting. However, the total amount of forest area is the same in all three options.

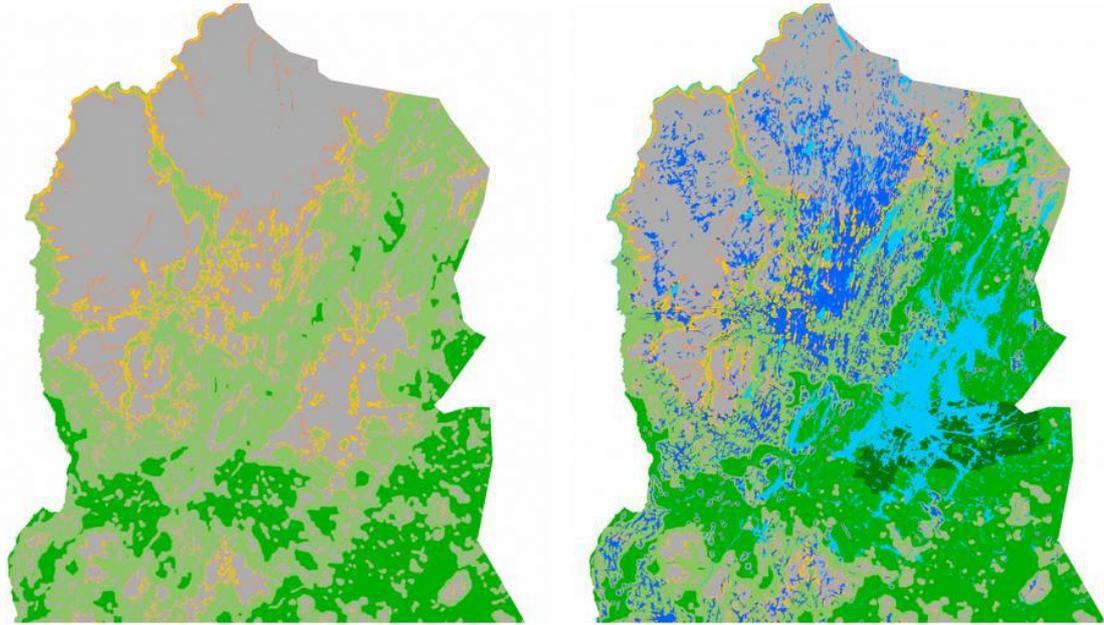


Figure 6: Multi-scale forest fragmentation map from Option A (left) and from Option C (right) with *specific background* (wetlands) highlighted in dark blue and *non-fragmenting background* (water bodies) highlighted in light blue. In the map on the right, note the difference in forest fragmentation in the vicinity of water bodies that were set to have a non-fragmenting effect on forest cover.

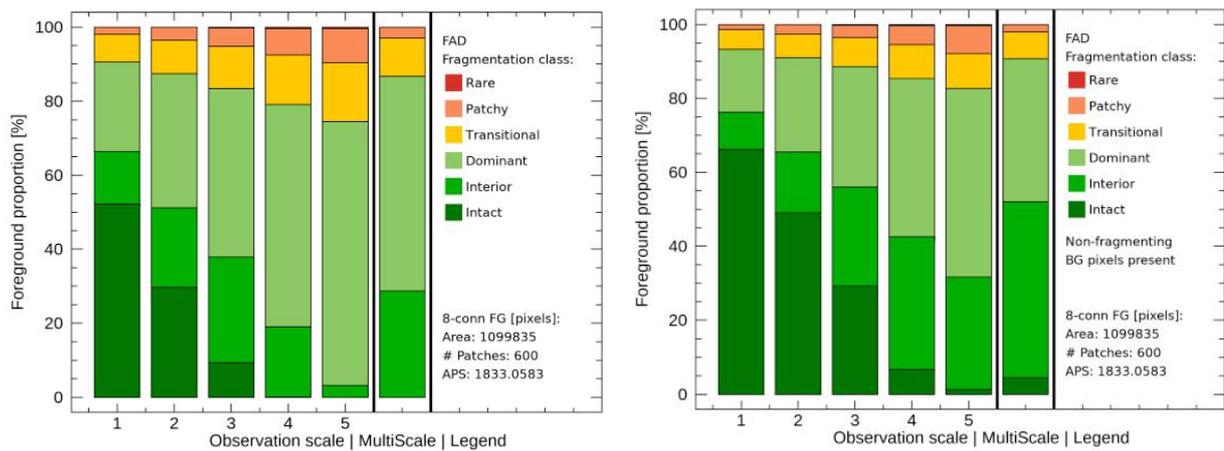


Figure 7: Fragmentation class bar plot summary from Option A (left) and from Option C (right), where the presence of non-fragmenting background changes the statistics of the forest fragmentation classes.

4. Fragmentation change analysis

A fragmentation change analysis scheme will compare two maps and summary tables of FAD. The input data sets must have the same geographic coverage, pixel dimension and alignment, and classification scheme. All changes are summarized in a bar-plot map and further detailed in observation-scale specific summary statistics provided in txt and csv-format. The features of the fragmentation change analysis are illustrated on a sample forest mask of Slovakia derived from CORINE 2000 and CORINE 2012.

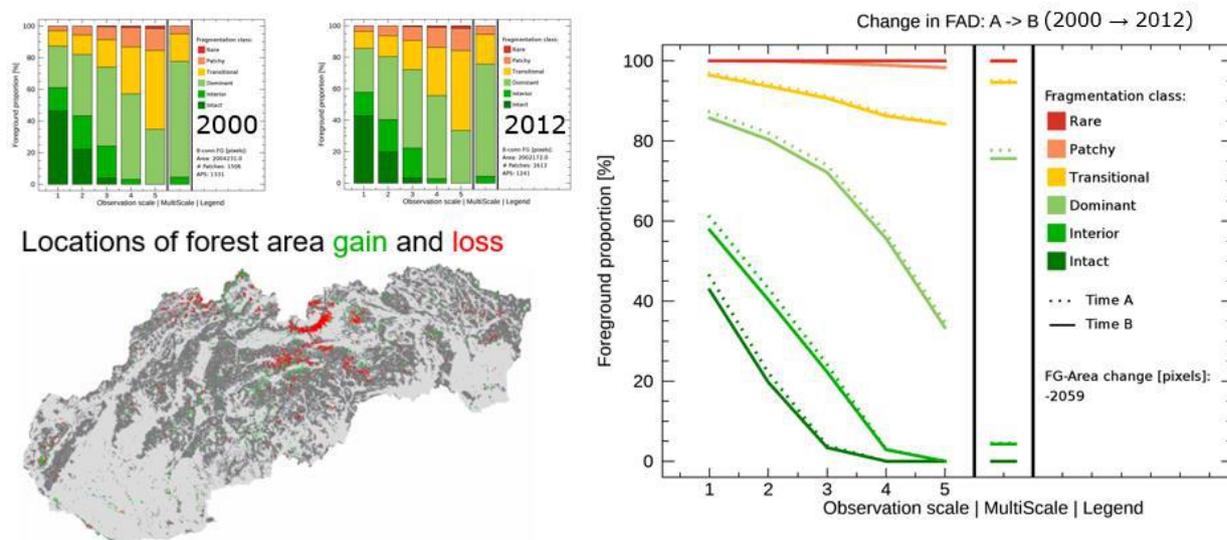


Figure 8: Top left: Fragmentation classes bar plot summary for Slovakia in the year 2000 and 2012. Bottom left: Morphological change analysis showing locations of forest area gain and loss. Right: Changes in the proportions of forest fragmentation classes for the year 2000 and 2012 for each observation scale and the multi-scale assessment.

# pixels	B0-Background	B1-Rare	B2-Patchy	B3-Transitional	B4-Dominant	B5-Interior	B6-Intact
A0-Background	2769270	232	22492	41064	61309	2500	0
A1-Rare	18	131	98	0	0	0	0
A2-Patchy	6819	29	76506	14764	217	0	0
A3-Transitional	22052	0	7069	272923	47079	13	0
A4-Dominant	97084	1	2038	50132	1292332	24524	0
A5-Interior	3683	0	0	270	28145	58304	0
A6-Intact	0	0	0	0	0	0	0
Gross area gain (Class A0 -> Class B1-B6): 127597 pixels							
Gross area loss (Class A1-A6 -> B0): 129656 pixels							
Net area change (A->B): -2059 pixels							

Table 5: Transition matrix of forest area changes in fragmentation classes in the year 2000 (A) to the year 2012 (B) for the multi-scale summary map. The bottom part shows a summary of forest area gain, loss and net change. Fragmentation increase is found within the triangle outlined with the full orange line and fragmentation decrease within the triangle outlined with the dotted orange line.

The first table in the summary statistics (Table 5) shows the number of pixels being in one of the six FAD-classes or in the background at time A and at time B. Missing pixels at time A and/or time B are excluded from the change analysis. If the area of a pixel is known and constant throughout the map (equal-area projection) then the number of pixels multiplied by the pixel-

area corresponds to actual area measures. For example, in the case of using CORINE data 1 pixel = 1 hectare. The **gross area gain** equals to the number of pixels changing from background at time A to any foreground class at time B. Similarly, **gross area loss** equals the number of pixels changing from any foreground class at time A to background at time B. The net area change is the sum of gross area gain and gross area loss. Entries **along the diagonal** of the transition matrix show the amount of forest which is in the same fragmentation class at both times. Matrix entries below the diagonal (full orange line triangle) correspond to an increase in fragmentation where the original fragmentation class of a given forest pixel in the year 2000 has changed to a higher fragmentation class in the year 2012. Similarly, entries within the dotted orange line triangle correspond to a decrease in fragmentation.

Table 5 allows making statements on area changes in fragmentation classes and forest cover changes. For example, 50,132 hectares of forest changed from the fragmentation class *Dominant* in 2000 → *Transitional* in 2012; 217 hectares of *Patchy* forest turned into *Dominant* forest in 2012. Or, in the period from 2000 to 2012 we found a gross area gain of 127,597 hectare and a gross area loss of 129,656 hectare leading to a net forest area change of -2,059 hectare.

% change A->B	B1-Rare	B2-Patchy	B3-Transitional	B4-Dominant	B5-Interior	B6-Intact
A1-Rare	0	-0.11304	0	0	0	0
A2-Patchy	0.033073309	0	-17.029817	-0.25030279	0	0
A3-Transitional	0	8.0619041	0	-54.30417	-0.0149951	0
A4-Dominant	0.001140459	2.3242553	57.173487	0	-28.287675	0
A5-Interior	0	0	0.30792391	32.098216	0	0
A6-Intact	0	0	0	0	0	0

Table 6: Transition matrix of relative changes in forest fragmentation classes in the year 2000 (A) to the year 2012 (B). Fragmentation increase is found within the triangle outlined with the full orange line and fragmentation decrease within the triangle outlined with the dotted orange line.

The second table in the summary statistics (Table 6) shows the *relative* changes within the foreground only and normalized to each class, fragmentation increase and decrease. Entries along the diagonal of the matrix are zero because these entries correspond to pixels being in the same class at time A and B, equivalent to no change. Matrix entries below the diagonal represent fragmentation increase expressed with positive percentages of the amount at time A. Fragmentation decrease is expressed with negative percentages and found above the matrix diagonal. With this setup, the second table shows the relative contribution of each possible fragmentation class change separate for each fraction change type, fragmentation increase and fragmentation decrease.

Table 6 allows making statements on relative changes in fragmentation classes. For example, 32% of all fragmentation increase is found for *Interior* to *Dominant*. Or, 17% of all fragmentation decrease is found for the transition of *Patchy* forest in 2000 into the less fragmented class *Transitional* in 2012.

Note: The example above showed results for the multi-scale analysis only. Fragmentation change analysis consists of six files: the multi-scale change analysis shown above plus a corresponding set for each of the five individual observation scales.

5. FOS: fragmentation at user-defined Fixed Observation Scale

Alternative to the multi-scale assessment, we can conduct a fragmentation analysis at a single, user-defined *Fixed Observation Scale (FOS)*. Here, the user can choose between the following three assessment methodologies: Foreground Area Density (**FAD**, see Figure 1) and the alternative edge-counting methodologies Foreground Area Clustering (**FAC**, see Figure 9, 10) and Foreground Edge Density (**FED**, see Figure 11, 12). While FAD measures the proportion of foreground pixels within the moving window, FAC measures the proportion of *common adjacencies* (vertical or horizontal pixel edges in common) between foreground pixels with respect to the total number of adjacencies inside the moving window.

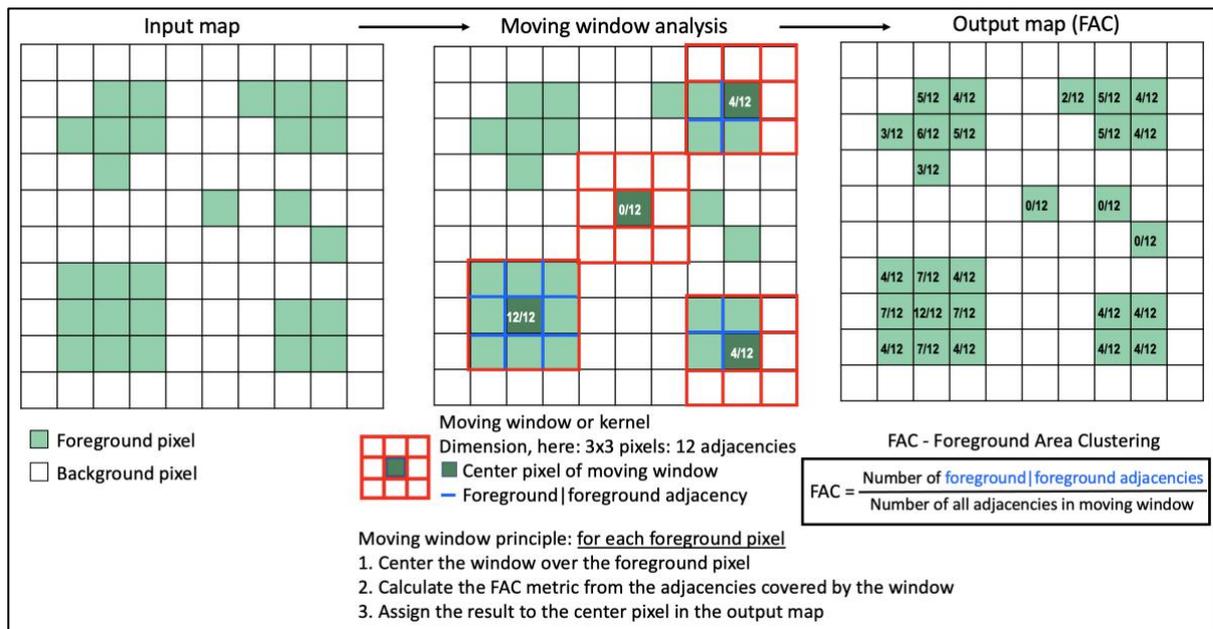


Figure 9: FAC measuring the degree of local clustering exemplified for a 3x3 moving window.

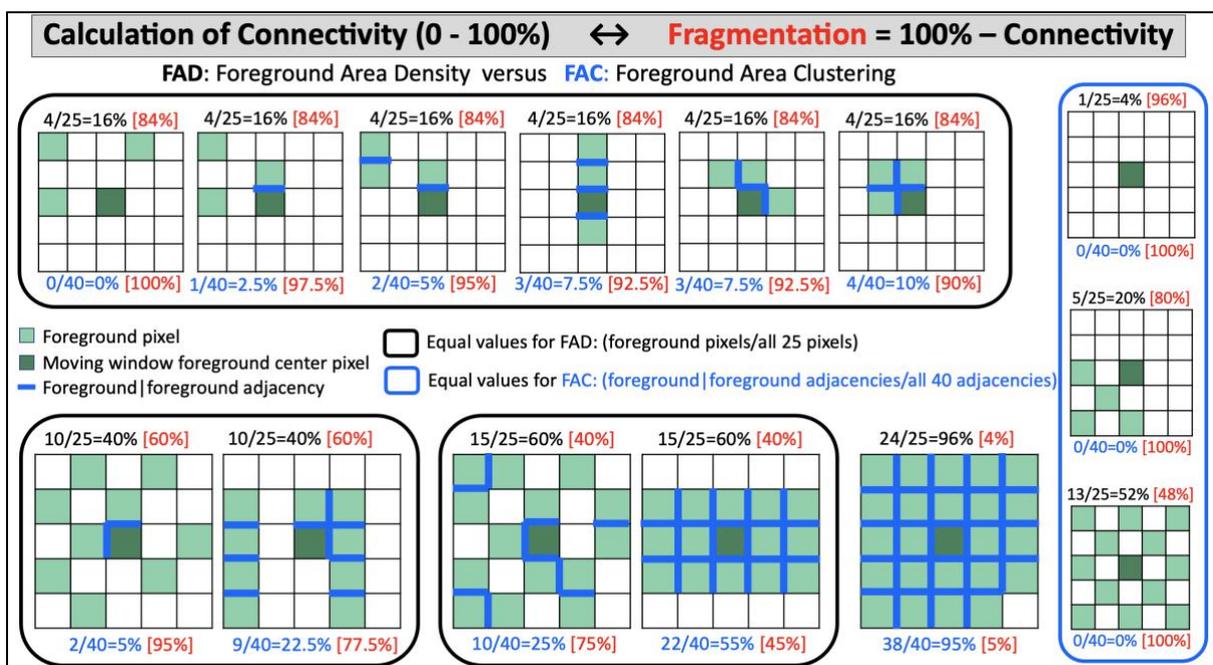


Figure 10: Comparison of FAD and FAC exemplified for a 5x5 moving window with different amount of foreground cover.

Figure 10 illustrates the difference between the two metrics for a moving window of 5x5 pixels with varying amount of foreground cover. Diagrams with the same proportion in foreground area (FAD) are surrounded by black boxes, for example where FAD = 16% (top) 40% (bottom left), or 60% (bottom center). In contrast, the right-most panel, surrounded by a blue box, shows diagrams where the degree of clustering (FAC) is constant, while the FAD values differ. In all diagrams, common adjacencies between neighboring foreground pixels are highlighted with a blue line. A moving window of size n has a total of $2n*(n-1)$ adjacencies, in the example above for $n=5$, the total number of adjacencies for a 5x5 window is 40. Adjacencies of missing pixels are excluded from the computation.

Fragmentation is expressed as the complement to connectivity and indicated in red numbers in Figure 10. Observing the sequence of the six diagrams with identical FAD = 16% (top row of Figure 10) one can see that FAC better captures *local* clustering of neighboring foreground pixels, showing increasing values from 0% to 10% for connectivity (blue numbers), equivalent to decreasing fragmentation values from 100% to 90% (red numbers).

Both metrics address connectivity of foreground pixels, each with its own focus: FAD is more focused on the amount of foreground while FAC sets more emphasis on local foreground clustering. Their results differ more for low amount of foreground and converge when the amount of foreground coverage is very high.

The third assessment option FED, or Foreground Edge Density, calculates the average value along all foreground edges, where foreground pixels are assigned full coverage (100%) and background pixels have no coverage (0%). With this assignment, FAD and FED can then also be applied to grayscale input maps, i.e., tree cover density maps in [0, 100]% (Vogt et al., 2024). When using grayscale maps, a grayscale threshold value must be specified to define background cover, which is needed to delineate foreground cover patches. Because FAC counts the same values along common foreground edges, FAC is not applicable for grayscale input maps. A comparison of FAD, FED, and FAC is exemplified in Figure 11 for a 5x5 window with binary or grayscale pixel coverage.

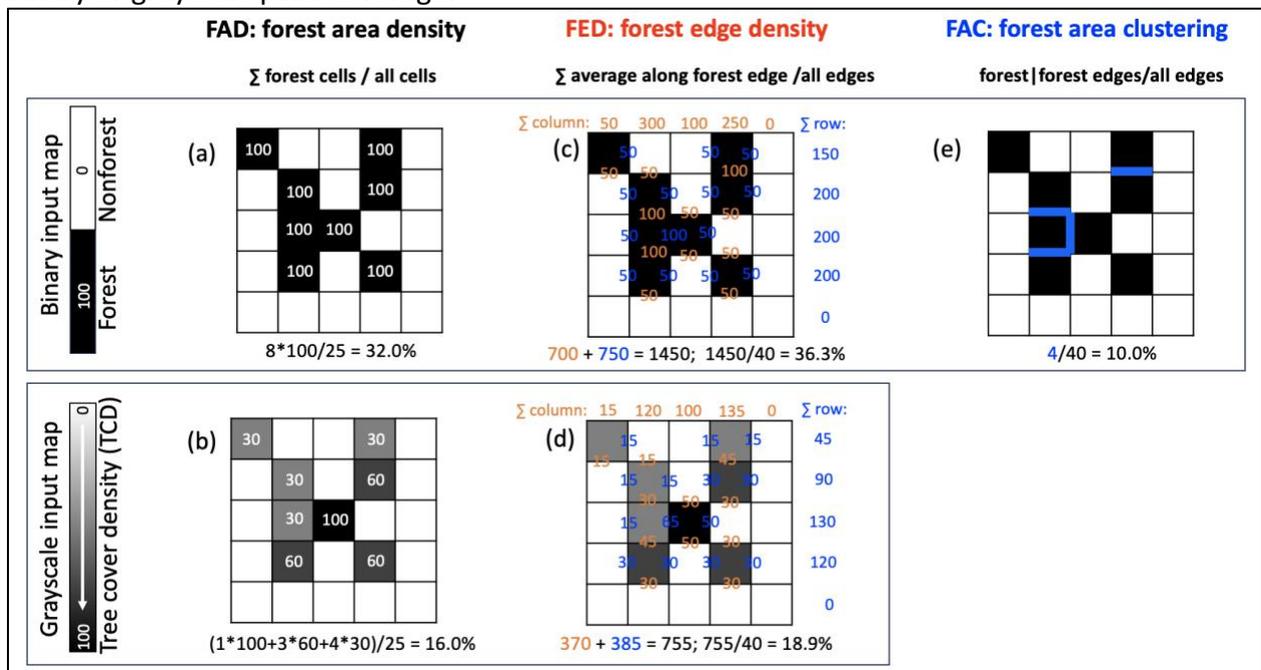


Figure 11: Comparison of FAD, FED, and FAC exemplified for a 5x5 moving window on a binary input map (top row) and a grayscale input map (bottom row).

Since FAD only counts the number of foreground pixels, it is not sensitive to their spatial configuration within the moving window (Figure 10). However, FED and FAC will change when the spatial configuration of the foreground pixels is changed (Figure 12).

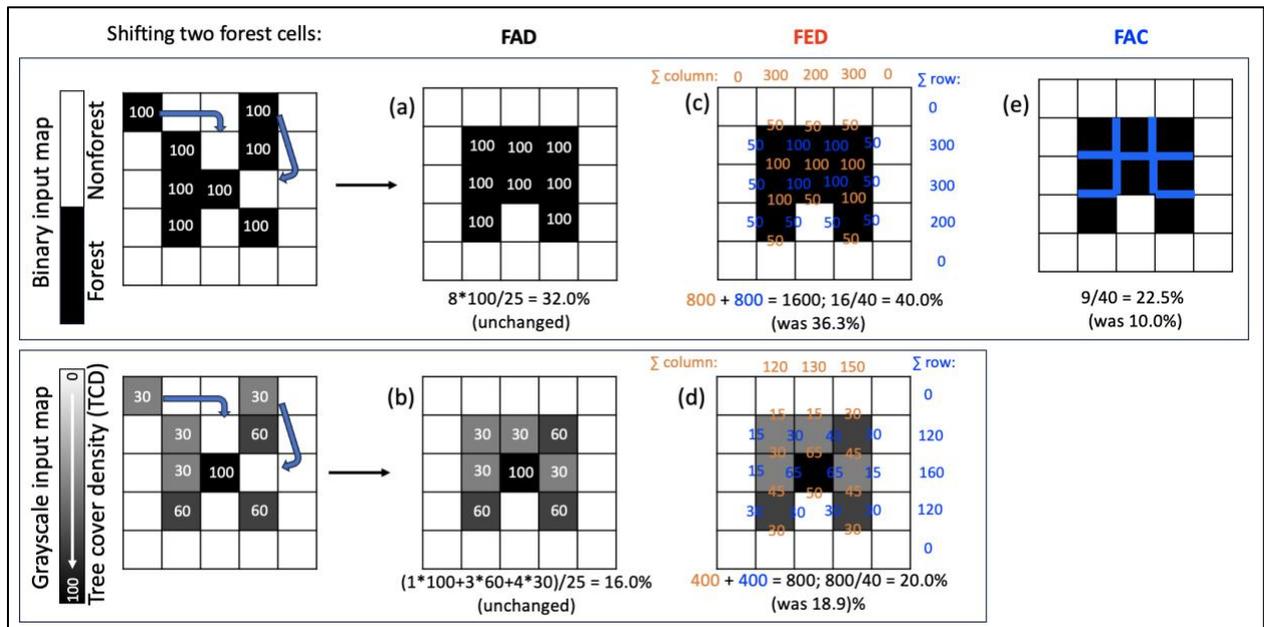


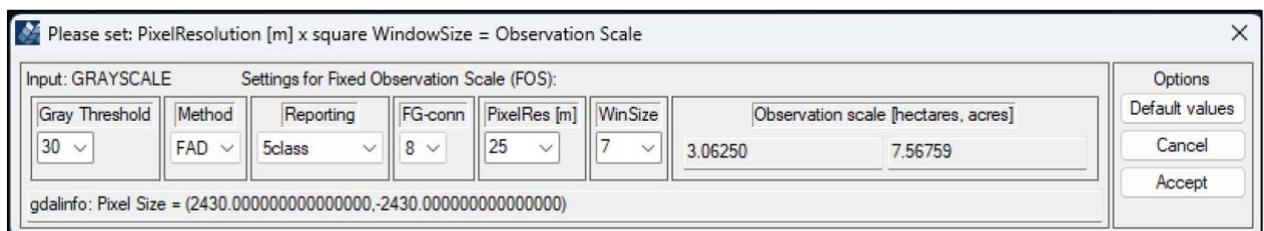
Figure 12: Comparison of shifting two foreground pixel locations for FAD, FED, and FAC exemplified for a 5x5 moving window on a binary input map (top row) and a grayscale input map (bottom row).

Four reporting schemes are available for Fixed Observation Scale (FOS) fragmentation analysis:

- FAD/FED/FAC 5-class:** shows FOS values at pixel level and color-coded into five fragmentation classes.
- FAD/FED/FAC 6-class:** shows FOS values at pixel level and color-coded into six fragmentation classes.
- FAD/FED/FAC-APP 2-class:** the per-pixel FOS values are aggregated at forest patch level (see section 6). Each forest patch is assigned a single FOS value, the Average-Per-Patch (APP) FOS value, which is then color-coded into two fragmentation classes.
- FAD/FED/FAC 5-class:** same as c) but color-coded into five fragmentation classes.

The fragmentation class names, color-codes and FOS range thresholds are identical to Figure 2. For example, the FAD 6-class setup was chosen by [UN-FAO](#) (chapter 2) to measure *Forest Intactness and Fragmentation* at 100 km² (see Vogt et al., 2019a), while EUFO chose the FAC 5-class assessment scheme (see Vogt et al., 2022).

With FOS, the user can define a custom observation scale by specifying the pixel resolution (in meters) and the side length (number of pixels) of the square moving window in a GUI:



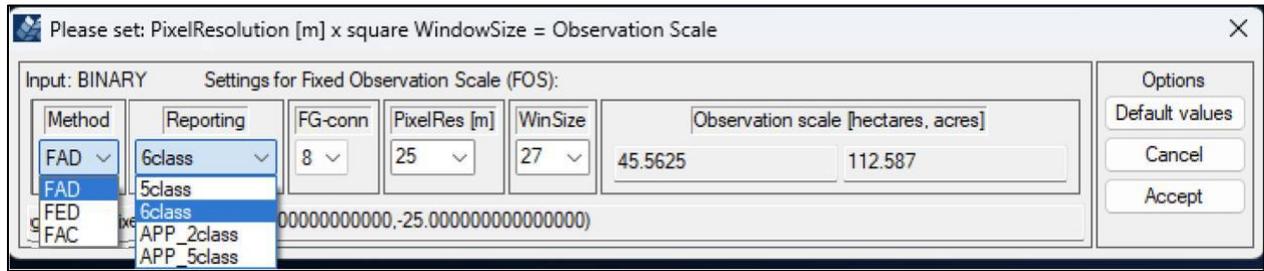


Figure 13: FOS GUI for grayscale input (top) or binary input (bottom): the user can set grayscale foreground threshold (on grayscale input only), the analysis method, reporting scheme, the connectivity rule, the spatial pixel resolution and the moving window size to define a specific observation scale for the Fixed Observation Scale (FOS) fragmentation analysis.

The custom settings are then used to calculate the area of the moving window (observation scale), which is displayed in hectares and acres. The bottom panel of the GUI provides information on the pixel size retrieved from the input map metadata. The bottom panel of Figure 13 shows a combination of pixel resolution and window size resulting in an observation scale of ~45 hectares (window side length = 27 pixels x 25m = 675m; window area = 675m x 675m = 455.625m² = 45.5625 hectare). The user can choose settings from the drop-down menu or insert custom values, followed by the Enter key. After the definition of the user-selected observation scale, click on *Accept* to apply the custom settings for the fragmentation analysis. A FOS change analysis can be conducted in the same way as outlined for FAD in section 4 above.

6. FAD/FED/FAC-APP

Section 5 described the Fixed Observation Scale (FOS) analysis using a specific square neighborhood window resulting in FOS values for each foreground pixel. As a result, the map product shows per-pixel values within a given patch. This feature may be of interest to differentiate intact areas from less intact areas inside of the same given patch. Please note that a per-pixel moving window assessment will assign lower values to pixels along the patch boundary or perforations. Users preferring to see a single and constant fragmentation value for each patch may select the option APP (Figure 2, 14). Here, the per-pixel values of a given patch are used to calculate the *Average Per Patch* (APP) value, which is then re-assigned to all pixels of the given patch. In addition, and with APP being designed as a simplified alternative reporting scheme, the number of color-classes is reduced to either five or two. The two-class APP scheme uses a threshold of 40% to distinguish *Separated* (fragmented, dark green) from *Continuous* (non-fragmented, light green) foreground cover, a setup chosen by [Forest Europe](#) for the definition of the indicator 4.7 *Forest Fragmentation* (Vogt et al., 2019a).

Compared to the per-pixel classifier APP shows the Average Per Patch value. As with FAD/FED/FAC, the APP option provides actual FOS values in [0, 100] %, just averaged by patch in an additional post-processing step. Figure 14 illustrates this fact when switching between the FOS 6-class color-table (left), the FOS-APP 2-class color-table (center), and the FOS-APP 5-class color-table (right). Please note that the center and right panel show identical average per patch (APP) values for selected patches but illustrate the difference in color-coding only when applying the FOS-APP 2-class or the FOS-APP 5-class color scheme.

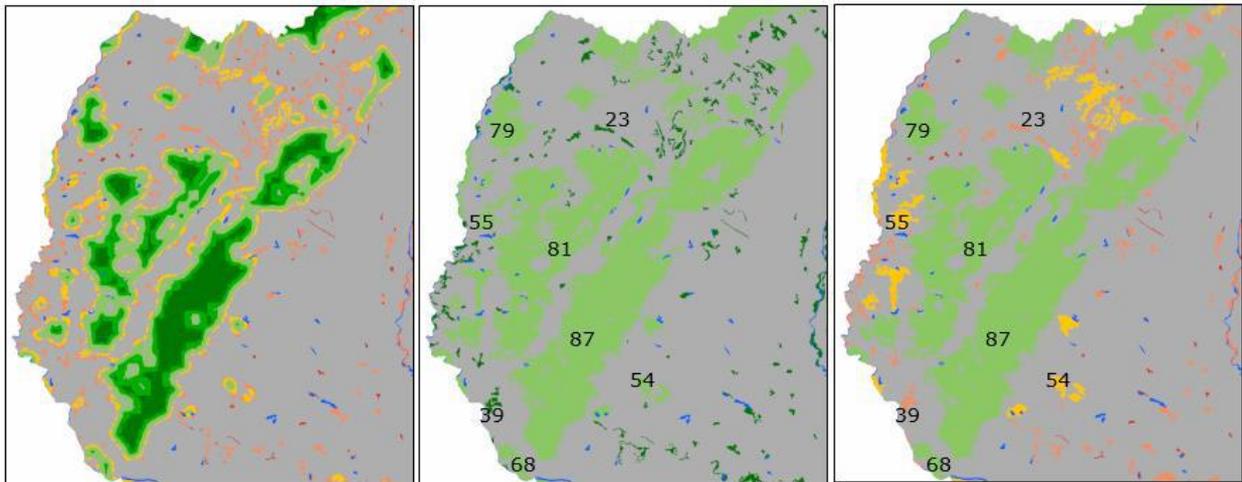


Figure 14: Forest density in the western part of Slovakia, CORINE 2012, and observation scale 23x23 pixels ~ 529 ha.

Left: FAD 6-class: FAD values at pixel level and color-coded into six fragmentation classes.

Center: FAD-APP 2-class: FAD averaged per-patch and color-coded into two fragmentation classes.

Right: FAD-APP 5-class: same as center panel but color-coded into five fragmentation classes.

7. Discussion

This document describes various ways for reporting state and trends of forest fragmentation. The assessment is based on conducting either, a multi-scale or single scale analysis. The flexible approach assures to simultaneously measure key aspects of fragmentation including, the amount of forest, the area of contiguous forest cover, perforations inside forest patches, patch shape and linear features, and the distance between individual forest patches.

An optional subsequent fragmentation change analysis provides details and a statistical summary on forest gain, loss, and fragmentation class changes over time.

The fragmentation assessment and change analysis scheme provides:

- **Generic concept:** The methodology is based on geometric principles only. As such, it can be applied to any kind of forest raster maps, independent of the definition of forest and the spatial resolution of the forest map. In contrast to many existing fragmentation schemes, the outlined methodology provides quantitative measures and is not necessarily a descriptive measure for a specific faunal species.
- **Fragmentation at different scales:** Fragmentation is perceived different at different scales, or a given landscape has a different degree of fragmentation for any given species living in that landscape. For example, the same forested landscape may be highly fragmented for a bear but not fragmented for a small bird. With reporting fragmentation at multiple scales, foresters can make their own choice and decide which scale best suits their field of application.
- **Fragmentation classes:** The intuitive naming scheme (see Figure 2) can be easily communicated and has a direct relation to habitat and biodiversity related studies. Reporting *Interior* for illustration in tables and maps may be of interest because the literature indicates FAD above 90% is a reasonable threshold for core habitat. Reporting *Dominant* may be interesting because it describes transitions from mostly forested to patchy forest landscapes. Fragmentation classes show the degree of forest fragmentation derived from a *measured* range of forest area density within [0, 100] %. Researchers will probably consult the more detailed per-pixel density distribution map while policy makers may prefer the simplified 2-class version with a clearer focus on fragmented versus contiguous land cover.
- **Fragmentation statistics and change:** The bar plot graph and the text/csv-file provide summary statistics in a tabular format. These statistics provide a concise summary on the state of forest fragmentation as well as details on changes of forest area and fragmentation classes over time.
- **Fragmentation maps:** The map product provides additional spatial information, which cannot be retrieved from indices and statistics: A geographic map of fragmentation classes is not only visually appealing, but it permits localizing hotspots of fragmentation, which is a crucial information for planning and risk assessment. Moreover, comparing maps over time can show where and how much fragmentation has decreased/increased or where it has not changed. This information is an essential requisite to localize and measure temporal changes in fragmentation. It can also be used to measure progress or the overall effectiveness of political directives; for example, and in the case of

afforestation, where the forest cover has changed from the fragmentation class *Transitional* to *Dominant*.

- **Communication:** The intuitive class names can be easily communicated and provide a clear message on a complex topic. The assessment of fragmentation is of key interest in a variety of land cover planning measures, impacting biodiversity and other environmental indicators and contributes to answering questions like:
 - **State Analysis:** How high is the degree of fragmentation in different administrative units/counties or ecological regions of the country?
 - **Trend Analysis:** Where and how much has fragmentation changed over the past decades? How are the trends? What can be expected for the future?
 - **Monitoring & Assessment:** How strong was the impact of a specific political directive or planning program in the targeted area? How big is the change outside of the monitored region? Does the result of the program merit the money spent? With these findings, what are the implications for future planning and which areas should be targeted next?

7. Conclusions

The above-described fragmentation and change analysis is available in the free JRC software *GuidosToolbox* under the menu entry: Image Analysis -> Fragmentation.

With this description, and the availability in a free software, each user can test the methodology and its settings on their own data. Additional comments:

- A *forest - nonforest raster map* as described in this document is of generic nature. It can be derived from any source such as airborne or satellite or National Forest Inventory data, rasterizing a vector map, or plot data.
- The definition of *Forest* can be based on land *use* or actual land *cover*. For example, non-stocked forested land can still be defined as Forest even if it appears as non-forest in satellite scenes.
- The user can customize the analysis by assigning dedicated non-forest land cover to *not* have a fragmenting effect on forests, e.g., lakes or small rock formations within forests.
- The user can switch between a detailed per-pixel 5 or 6-class analysis, or a per-patch averaged 2- or 5- class analysis.

The software can be downloaded and used by anybody and for any kind of digital image analysis. All data analysis schemes in *GuidosToolbox* are based on geometric principles, which permits processing forest maps of any kind, independent of the definition of forest and/or the spatial resolution. In addition to fragmentation, *GuidosToolbox* provides dedicated routines for spatial mapping and quantification of pattern, object analysis, distance and other aspects derived from land cover maps.

Further information is available in related product sheets available on the *GuidosToolbox* homepage.

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