

## JRC TECHNICAL REPORT

# FAO – State of the World’s Forests: Forest Fragmentation

*Algorithm Technical Basis  
Document (ATBD)*

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## **Abstract**

This document summarizes the design process, definitions, and algorithmic implementation conducted by the Joint Research Centre to support the development and implementation of FAO's global forest analysis for the thematic topics Accounting and Fragmentation. The analysis scheme and data products were designed to support the indicator Forest Fragmentation in the State of the World's Forests (SOFO) report 2020.

The spatial forest coverage is derived from the Copernicus Global Land Cover 2015 dataset (accessed in July 2019) and for 21 Global Ecological Zones (GEZ). The source data was re-projected to equal area to allow for comparable area estimates across the Globe. Spatially explicit maps and statistical summaries are derived at global level and for each of the 21 GEZ.

# 1 Introduction

The *State of the World's Forests* (SOFO) reports on the status of forests, recent major policy and institutional developments and key issues concerning the forest sector. It makes current, reliable and policy-relevant information widely available to facilitate informed discussion and decision-making with regard to the world's forests. One focal point of the State of the World's Forests 2020 assessment is to identify actions that can be taken to increase the contributions of forests and trees that are necessary to accelerate progress towards the 17 Sustainable Development Goals (SDGs) – the central framework for guiding development policies throughout the world.

Within this context, forest fragmentation plays a key role in biodiversity, ecosystem services and the ever-increasing pressure from anthropogenic land use. Forest fragmentation may lead to the isolation and loss of species and gene pools, degraded habitat quality, and a reduction in the forest's ability to sustain the natural processes necessary to maintain ecosystem health.

The goal of the indicator 'Forest Fragmentation' is to provide quantifiable and intuitive classes allowing to locate and measure various degrees of forest fragmentation at global scale. To achieve this goal, FAO evaluated and discussed various public data sets and appropriate methods for mapping and quantifying forest fragmentation. The evaluation phase concluded on the following key findings (KF):

**KF1 - Data source:** the COPERNICUS [Global Land Cover Map](#) (hereafter COP) was selected to be the most appropriate public data source within the context of the assessment. The Copernicus Global Land Service provides systematic monitoring of bio-geophysical parameters at global scale. The monitoring activity is conducted by 20+ institutes across Europe dealing with the processing of low-to-medium spatial resolution optical and radar data, data validation, data provision and product quality control. All Global Land service products are provided under the free and open access policy as defined in the European Union's Copernicus regulation ([N° 377/2014 of 3 April 2014](#)) and Commission Delegated Regulation ([N° 1159/2013](#)). In this respect, the products described in this ATBD *contain modified Copernicus Service information (2015)*. A brief summary of the COP data set is provided at <https://lcviewer.vito.be/about> with a visual online representation and download information at: <https://lcviewer.vito.be/>. Further information on COP is summarized in Buchhorn et al (2019). The global coverage of the original COP data is provided in 94 individual tiles in EPSG 4326 projection, each covering 20° x 20°. The tiles are reassembled into a single global map, and then re-projected into an equal-area projection (Goode-Homolosine Land, EPSG 54052) map with a pixel-resolution of 100 meters to allow for area estimates.

**KF2 - Definition of Forest:** the *Discrete Classification layer* of COP provides 23 individual land cover classes following the FAO UN Land Cover Classification System (LCCS). The additional layer *Forest Fractional Cover* provides the percentage of a pixel that is filled with forest/trees independent of the discrete classification. Forest is defined for pixels being either in the *Discrete Land Cover* class "Closed Forest" (Map code in [111-116]) or where the *Forest Fractional Cover* is at least 30%. Neighbouring forest pixels are considered connected if they share a common pixel border (4-connectivity).

**KF3 - Methodology:** the method "Forest Area Density" (FAD) at Fixed Observation Scale (FAD-FOS) was selected to best match the fragmentation assessment requirements stipulated by FAO. In addition, the FAD methodology is complemented by the reporting scheme "Accounting", providing geographic maps and derived statistics in six forest patch size classes [100; 1,000; 10,000; 100,000; 1,000,000; > 1,000,000] hectares.

**KF4 - Measurement scale:** because fragmentation is scale-dependent, the FAD fragmentation assessment is conducted at three individual analysis scales corresponding to a local neighbourhood area of approximately 100; 1,000; 10,000 hectares (= [1, 10, 100] km<sup>2</sup>). These three scales were found to be appropriate to capture the diverse functions of forest patches and their role in sustainable forest management, for forest naturalness and the protection of biodiversity in forests. The three analysis scales translate into closest matching square moving window sizes of 9x9, 31x31, 99x99 pixels (= 81, 961, 9801 hectares) for FAD and using COP with a spatial resolution of 100 meters.

**KF5 - Fragmentation classes:** The fragmentation scheme assumes that fragmentation is inverse proportional to forest area density (FAD). The full range of FAD is divided into the following six fragmentation classes: *Rare* (FAD < 10%), *Patchy* (10% ≤ FAD < 40%), *Transitional* (40% ≤ FAD < 60%), *Dominant* (60% ≤ FAD < 90%), *Interior* (90% ≤ FAD < 100%), *Intact* (FAD = 100%). The so-defined six classes capture meaningful degrees in forest fragmentation for management, habitat and biodiversity assessment studies.

**KF6 - Reporting style:** reporting of forest fragmentation will be conducted at the pixel level for each forest pixel. *Accounting* will be reported for each forest patch in six forest patch size classes.

**KF7 - Indicator product:** the final result of the analysis are spatially explicit maps and derived tabular statistics of forest fragmentation. Because the georeferenced maps are in equal area projection the derived statistics provide forest area and fragmentation statistics in percentage as well as actual area in hectares, allowing for a comparative analysis at different reporting scales across the World.

**KF8 - Reporting scale:** the indicator, with maps and statistics, is derived at two scales:

- 1) Global (full coverage of COP in a single equal area-projected map), and
- 2) at 21 Global Ecological Zones (GEZ), re-projected to match the equal area global COP map.

The FAO expert panel found that measuring the triple-scale ([1, 10, 100] km<sup>2</sup>) Forest Area Density (FAD) together with Accounting is well-suited to investigate the spatial integrity of forest land cover. The fragmentation indicator addresses key fragmentation aspects, such as isolation of small fragments, number and extent of perforations, and large compact forest patches.

A conceptually similar FAD approach (originally by Riitters et al. 2002; Riitters and Wickham 2012; Wickham 2008) is used for official reporting on forest fragmentation by the [US-Forest Service](#) (2012, 2016), the [US Montréal Process Report](#), (<https://www.fs.fed.us/research/sustain/criteria-indicators/>, Indicator 1.03 Fragmentation of forests), [Forest Europe](#) (indicator 4.7: Forest Fragmentation), and the [MAES](#) project. This enables common usage of the same information scheme across disciplines and locations, and permitting rigorous evaluations of the trade-offs or synergies involved in land-cover pattern management strategies.

## 2 Implementation summary

This section provides an overview of data source used, necessary pre-processing steps, details on the algorithms applied, details on the output format and other documentary information on the status product of the indicator Forest Fragmentation. All status maps and related statistics are available on the JRC public data portal: <https://data.jrc.ec.europa.eu/>, using the search term “FAO” or more generic “fragmentation”.

### 2.1 Input data source

The original *Discrete Classification* layer of the COPERNICUS (COP) 2015 land cover map (<https://land.copernicus.eu/global/about>) identifies 23 land cover classes at a spatial resolution of 0.000992063492063 degrees in EPSG 4326 projection. The global coverage of 94 individual COP tiles was downloaded (date of access: July 30, 2019). The raster data files for the *Discrete-class* (land cover) and *Tree-Cover-Fraction* layers were extracted from the zip-file for each tile. The tiles for each layer were then mosaiced into a global map (ArcMap 10.5.1 Tool: “Mosaic to new raster”). Next, the global maps were re-projected into an equal-area projection (Goode-Homolosine Land, EPSG 54052) with a pixel-resolution of 100 meters to allow for area estimates (ArcMap 10.5.1 Tool: “Project raster”) (**KF1**).

Following (**KF2**), the two layers – *Discrete Classification* and *Tree Cover Fraction*, were combined into the final, 4-class forest cover map (*fm30.tif*, 400751 x 147307 pixels) using the following assignment:

- **No data** (0-byte): pixels in the *Discrete Land Cover* classes 0 (“No data”) or 200 (“Open Sea”).
- **Forest** (2-byte): pixels in the *Discrete Land Cover* classes [111-116] (“Closed Forest”) or pixels where the Forest Fractional Cover is at least 30%.
- **Inland waters** (3-byte): pixels in the *Discrete Land Cover* class 80 (“Permanent water bodies”). Inland waters are treated as non-forest land but marked separately in the final spatial maps for visual purposes.
- **Non forest land** (1-byte): pixels not qualifying for any of the other 3 classes.

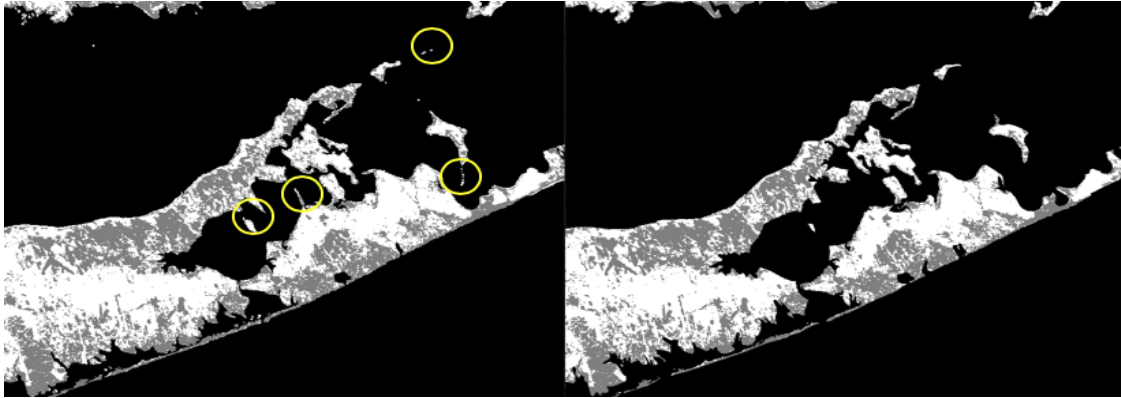
FAO provided a global polygon map of 21 Global Ecological Zones (GEZ) including the generic ‘water’ zone in equal area Goode Homolosine Land projection. This map was converted to a global raster map with a pixel resolution of 100 meters to precisely match the geoheader metadata and dimension of the forest cover map *fm30.tif* (ArcMap 10.5.1 Tool: “Polygon to raster”).

### 2.2 Differences between GEZ and forest map boundaries

The COP and GEZ raster maps can exhibit non-consistent pixel coverage near water boundaries (ocean and inland water, as defined by the GEZ map), which may be caused by (a) use of different water boundaries during the production of COP and GEZ maps, and/or (b) difference in the spatial precision of the original water boundaries of the COP and GEZ maps. As a result, the GEZ raster maps will show simplified shapes and negligence of small-scale features. This artefact is most apparent along coast lines (see Figure 1). As a direct consequence, the total area of forest for a given GEZ will be slightly smaller compared to the actual area within the global forest map (*fm30.tif*).



**Figure 1.** Example of difference in spatial detail coverage over eastern Long Island, NY: forest raster map (left) and GEZ10 (Temperate Continental Forest) rasterized vector layer (right); example differences highlighted in yellow circles.



Source: JRC, 2019.

### 2.3 Forest fragmentation assessment scheme

The methodology (**KF3**) to measure forest fragmentation applies two conceptual models, *Accounting* and *FAD*:

**Accounting:** *Accounting* is designed to provide a first overview and concise summary of the location and size class distribution of forest patches in a given forest map. The methodology provides a map product together with a statistical summary for a series of forest patch area classes (**KF3**). FAO and JRC agreed to define the following six forest patch size classes: [100; 1,000; 10,000; 100,000; 1,000,000; > 1,000,000] hectares. The forest area size classes can be used to describe the forest patch size class distribution at a given point in time or to directly compare the patch size distribution between the various GEZ. In addition, *Accounting* allows for conducting temporal analysis, which is of key importance in questions of landscape connectivity, restoration, risk assessment, habitat suitability and biodiversity studies.

The fragmentation assessment scheme *Accounting* is implemented in the free software [GuidosToolbox](#) (Vogt & Riitters 2017) and the GuidosToolbox Workbench ([GWB](#)) with further detailed in Vogt 2019b.

**FAD:** *Forest Area Density* is defined as the proportion of all forest pixels within a fixed neighbourhood area. FOS measurements (**FOS** = FAD at **Fixed Observation Scale**) are conducted via a moving window algorithm to create a new map of forest area density: the given neighbourhood - a square window of size 9x9 (or 31x31 or 99x99 pixels: **KF4**) - is centred over a given forest pixel, the forest area density within that neighbourhood is measured and assigned in a new map at the location of the subject forest pixel. This process is repeated for all forest pixels resulting in a new map of the same dimensions but showing forest area density values for the analysed neighbourhood over each forest pixel; The area density map is then stratified into six fragmentation classes *Rare* (FAD in [0, 10]%), *Patchy* (FAD in [10, 40]%), *Transitional* (FAD in [40, 60]%), *Dominant* (FAD in [60, 90]%), *Interior* (FAD in [90, 100]%), and *Intact* (FAD = 100%). Note that the fragmentation map is only color-coded into these six forest fragmentation classes while the actual degree of forest fragmentation (FAD percentage within [1, 100] %) is shown at the pixel-level (**KF6**). Statistics of the three forest fragmentation status maps are summarized with the following parameters (**KF7**):

1. Total forest area [ha].
2. Total number of forest patches.
3. APS [ha]: average forest patch size = total forest area / total number of forest patches.
4. Proportion [%] of forest in the six fragmentation classes.
5. FAD\_AV [%]: average FAD for all forest pixels in the reporting unit.

The above outlined fragmentation assessment scheme (FAD 6-class) is implemented in the free software [GuidosToolbox](#) (Vogt & Riitters 2017) and the GuidosToolbox Workbench ([GWB](#)) with further details in Vogt 2019a.

## 2.4 Reporting levels

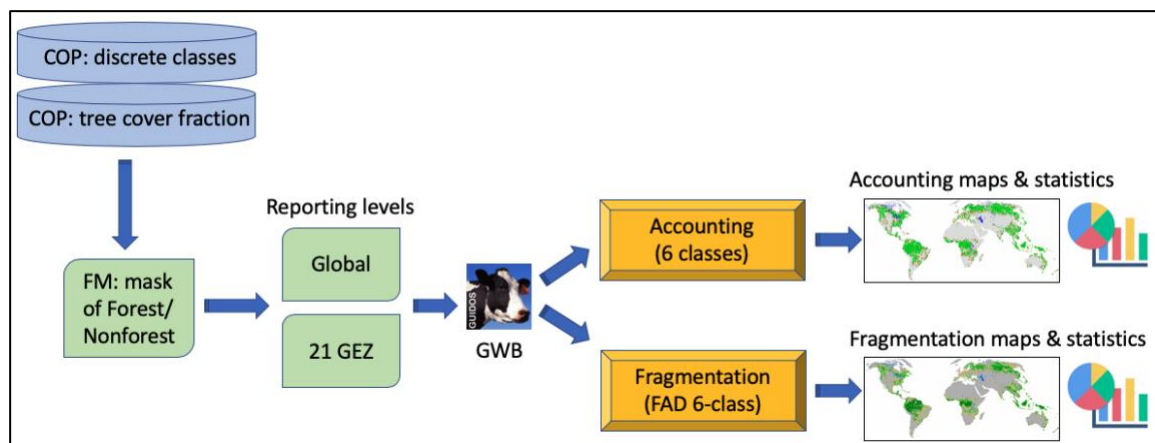
Maps & statistics for both Accounting and FAD are derived and reported at two levels (**KF8**):

1. **Global:** the entire content of the COP data coverage in equal area Goode Homolosine Land projection and with a spatial resolution of 100 meters (1 pixel = 1 hectare).
2. **Global Ecological Zones (GEZ):** 21 individual GEZ in equal-area Goode Homolosine Land projection and with a spatial resolution of 100 meters (1 pixel = 1 hectare).

## 2.5 Implementation flowchart

Figure 2 provides an overview of the processing chain to derive Accounting and Fragmentation status maps. All input & output maps and statistics are provided in a single directory “FAO” together with this ATBD. The command-line version of GuidosToolbox (GTB), the GuidosToolbox Workbench ([GWB](#)), was used to conduct batch-processing tasks of Accounting and Fragmentation. The source code of the analysis schemes is available within GWB.

**Figure 2.** Overview of the processing chain to derive Accounting and Fragmentation maps and statistics.



Source: JRC, 2019.

Details on the file hierarchy and the input and output file data assignments are summarized in the Annex at the end of this document.

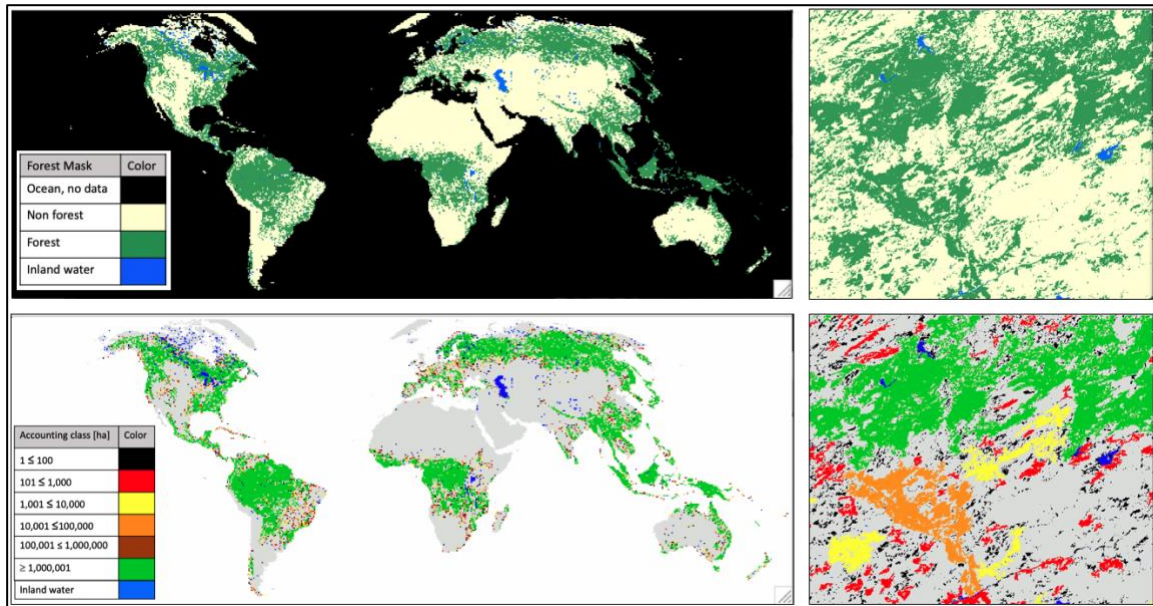
### 3 Implementation examples

This section provides examples of the individual processing steps as well as maps and details on the product.

#### 3.1 Accounting maps and statistics

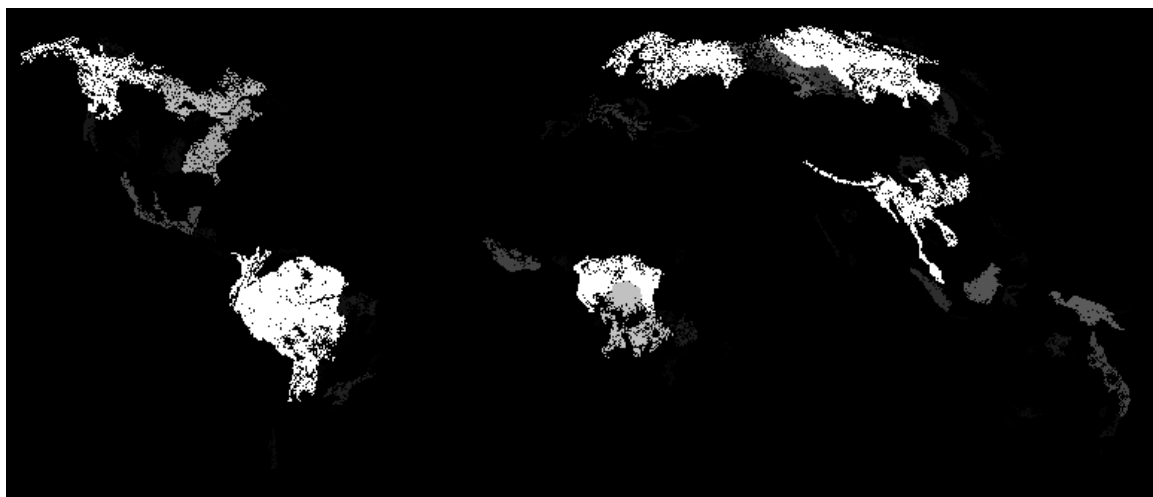
Figure 3 shows screenshots of the forest mask (fm30.tif) and the six Accounting classes at the full global extent (fm30\_acc.tif), including a zoom-in over an example area in central Portugal. For ease of orientation inland water bodies are masked in blue colour.

**Figure 3.** Forest mask and six Accounting classes at global scale (left) and example zoom in on central Portugal (right).



Source: JRC, 2019.

**Figure 4.** Accounting showing the actual area for each forest patch of the reporting unit.



Source: JRC, 2019.

While the color-coded Accounting map (fm30\_acc.tif, Figure 3) provides a visual overview of the six Accounting size classes, the additional area map (fm30\_acc\_pixels.tif, Figure 4) shows the actual area for each forest patch

in the reporting unit. The grey-scale stretched area map can be used to get an overview of the location and size of the largest forest patches as well as to quickly retrieve the patch area of any forest patch in the image.

Detailed statistics of the global Accounting map are summarized in the accompanying text file (fm30\_acc.txt), see Figure 5. This statistic file provides information on the connectivity rule, the pixel resolution and, for each of the six size classes: the number of forest patches, total area and the proportion of each with respect to the overall number and area of forest patches. The by-class list is completed by a summary line listing the total number of objects, area and the average patch size for the reporting unit. The final section of the global Accounting statistics lists the ten largest forest patches, their area, percentage and approximate geographic location.

Figure 5. Statistical summary of the global Accounting map.

```

Accounting size classes result using:
fm30_acc.tif
Base settings: 4-connectivity, pixel resolution: 100 [m]
Conversion factor: pixel_to_hectare: 1.0, pixel_to_acres: 2.47105
-----
Size class 1: [1, 100] pixels; color: black
# Objects      Area[pixels]    % of all objects  % of total FGarea
34148956      184144076      98.2487          4.02605
-----
Size class 2: [101, 1000] pixels; color: red
# Objects      Area[pixels]    % of all objects  % of total FGarea
543080        141605572      1.56248          3.09601
-----
Size class 3: [1001, 10000] pixels; color: yellow
# Objects      Area[pixels]    % of all objects  % of total FGarea
58295         150319613      0.167718         3.28653
-----
Size class 4: [10001, 100000] pixels; color: orange
# Objects      Area[pixels]    % of all objects  % of total FGarea
6390          166315709      0.0183844        3.63626
-----
Size class 5: [100001, 1000000] pixels; color: brown
# Objects      Area[pixels]    % of all objects  % of total FGarea
784           212094815      0.00225562       4.63716
-----
Size class 6: [1000001 -> ] pixels; color: green
# Objects      Area[pixels]    % of all objects  % of total FGarea
149           3719332540     0.000428683      81.3180
-----
Sum of all classes:
# Objects      Area[pixels]    % of all objects  % of total FGarea
34757654      4573812325     100.000          100.000

Average Patch Size: 131.592

Largest patch area [pixels], percentage of global cover, location:
1) 679553813   14.85749       South-America: NW, Amazon
2) 439203845   9.60258        Russia: eastern part
3) 274513137   6.00185        Russia: western part and Scandinavia
4) 244070704   5.33626        Asia: SE
5) 215438460   4.71026        Canada: western part
6) 205889106   4.50148        Central Africa
7) 154736880   3.38311        South-Central Africa
8) 148212850   3.24047        Canada: eastern part
9) 131877633   2.88332        USA: eastern part
10) 77970898   1.70472        Russia: central part

```

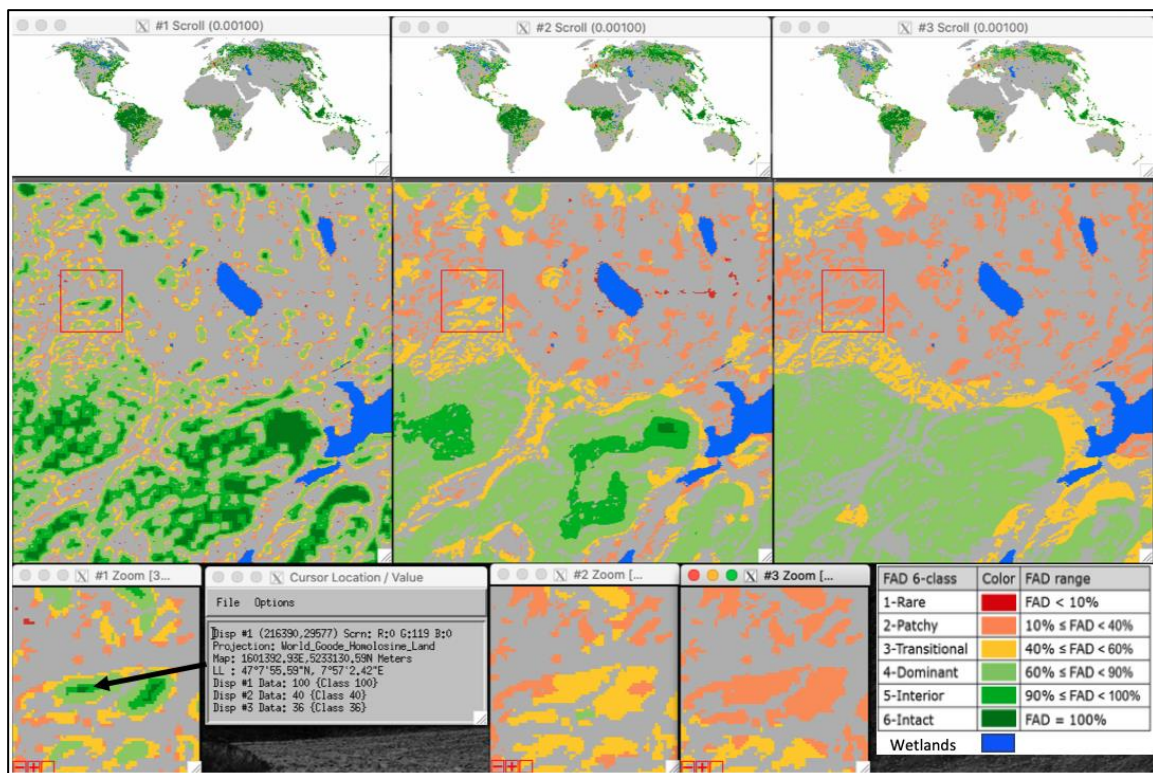
Source: JRC, 2019.

The same reporting scheme as outlined above is applied for each of the 21 GEZ layers. The only difference is that the final section of the GEZ statistical summary will list the 3 largest patches only. Please note that forest patches intersecting neighbouring GEZ layers will be divided along the GEZ boundary layer and reported individually in each GEZ layer. For this reason, the sum of all patches over all GEZ layers will be larger compared to the number of all patches reported in the global map.

### 3.2 FAD maps and statistics

Figure 6 shows an example of the FAD scheme from global to local scale. FAD is calculated at three scales (~100; 1,000; and 10,000 hectares) and grouped into six classes (see legend at bottom right). The top panel shows the global assessment and the centre panel a sample area northeast of Lucerne, Switzerland. The area contained in the red square is shown in full resolution in the bottom panel to illustrate local details. The pixel values indicated by the black arrow are summarized in the 'Cursor Location' window. Here, the FAD pixel value at the three observation scales is 100%, 40% and 36% and hence falling in the fragmentation class *Intact*, *Transitional* and *Patchy*, respectively. Please note that the pixel values show the actual FAD in the full range of [0, 100] %, which is then color-coded into six fragmentation classes to facilitate the visual interpretation.

**Figure 6.** Forest fragmentation (FAD): global (top), sample area northeast of Lucerne, Switzerland (centre) and at pixel level (bottom = enlarged area of red square in centre panel). FAD is calculated at observation scales 81, 961, 9801 hectares (left to right) and grouped into six fragmentation classes (bottom right).



Source: JRC, 2019.

The three FAD maps are accompanied by summary statistics. Figure 7 shows the summary statistics for the global analysis providing the percentage in each fragmentation class as well as the average FAD value at each observation scale. For example, at global level and when using the 100 km<sup>2</sup> observation scale (observation scale 3 - 99x99 pixels), the majority of forest (31.6269 %) is found in the fragmentation class *Dominant*.



Figure 7. Statistical FAD summary at global scale.

FAD: Foreground Area Density summary analysis for image: fm30_fad			
=====			
4-conn FG: area, # patches, aps [pixels]: 4573812325, 34757654, 131.592			
Pixel resolution: 100[m], pix2ha: 1.00000, pix2acr: 2.47105			
Observation scale: 1 2 3			
Neighborhood area: 9x9 31x31 99x99			
[hectare]: 81.00 961.00 9801.00			
[acres]: 200.16 2374.68 24218.76			
=====			
FAD 6-class:			
Rare:	0.3449	0.6938	0.8501
Patchy:	3.6966	6.1597	7.8750
Transitional:	6.2497	8.3029	10.4385
Dominant:	18.6345	25.9585	31.6269
Interior:	16.7868	27.1712	29.9476
Intact:	54.2875	31.7141	19.2619
=====			
FAD_av:	88.8222	83.6016	79.6330
=====			

FAD 6-class	Color	FAD range
1-Rare		FAD < 10%
2-Patchy		10% ≤ FAD < 40%
3-Transitional		40% ≤ FAD < 60%
4-Dominant		60% ≤ FAD < 90%
5-Interior		90% ≤ FAD < 100%
6-Intact		FAD = 100%

Source: JRC, 2019.

The same reporting scheme as outlined above is applied for each of the 21 GEZ layers.

### 3.3 Fragmentation summary statistics

The statistics of all reporting units (Global and GEZ) are further summarized in a single spreadsheet table (COP2015\_foreststats.xlsx), which can be sorted for a variety of attributes. This table also contains a field code definition sheet with details on each variable for further analysis in a GIS application. The summary table shows reporting unit, forest area, fragmentation classes, average patch size, number of patches and area in the six Accounting classes, the area of the largest forest patch in area (hectares) as well as proportions by forest area.

Figure 8. Statistical summary spreadsheet (COP2015\_foreststats.xlsx) with details of all reporting units. The bottom panel shows an extract of the Field Code Definition sheet.

Original sorting	UNIT	CODE	Base Statistics										FAD_1 (9x9) ~1 km2										FAD_2 (31x31) ~10 km2									
			UNIT_AREA (in ha)	FOR_AREA (in ha)	PERC_UNIT (in %)	PERC_GLOB (in %)	RARE_1 (in %)	PATCH_1 (in %)	TRANS_1 (in %)	DOM_1 (in %)	INTER_1 (in %)	INTACT_1 (in %)	FADAV_1 (in %)	RARE_2 (in %)	PATCH_2 (in %)	TRANS_2 (in %)	DOM_2 (in %)	INTER_2 (in %)	INTACT_2 (in %)	FADAV_2 (in %)												
1	Boreal_coniferous_forest	gez1	840,894,891	646,666,333	76.90	14.14	0.08	1.46	3.84	17.79	20.89	55.95	92.17	0.11	2.12	4.99	27.81	38.37	26.60	88.33												
2	Boreal_mountain_system	gez2	633,603,207	383,015,081	60.45	8.37	0.19	2.96	6.09	19.96	18.35	52.44	89.26	0.29	4.78	8.60	28.57	31.50	26.26	84.17												
3	Boreal_tundra_woodland	gez3	412,894,701	163,454,058	39.59	3.57	0.60	6.89	11.85	32.74	22.22	25.69	79.76	1.06	11.17	16.30	42.68	22.51	6.28	71.39												
4	Polar	gez4	674,589,977	12,477,187	1.85	0.27	1.99	15.80	19.52	36.81	16.32	9.57	66.74	4.23	26.90	25.31	35.36	7.31	0.82	53.60												
5	Subtropical_desert	gez5	530,947,902	17,899,133	3.37	0.39	3.43	16.41	14.36	26.20	17.69	21.90	69.99	7.24	23.02	15.93	28.12	18.83	6.62	59.92												
6	Subtropical_dry_forest	gez6	158,947,101	48,962,737	30.80	1.07	0.78	7.72	12.18	31.65	22.36	25.30	79.04	1.57	13.26	16.82	41.36	21.60	5.37	69.37												
7	Subtropical_humid_forest	gez7	466,812,375	238,076,452	51.00	5.21	0.27	3.41	6.91	24.07	22.69	42.66	87.37	0.55	5.49	9.11	35.39	36.12	13.34	81.42												
8	Subtropical_mountain_system	gez8	494,337,396	124,772,636	25.24	2.73	0.38	4.14	7.84	24.96	22.59	40.09	86.00	0.76	6.98	11.06	36.89	32.00	12.29	78.79												
9	Subtropical_steppe	gez9	472,385,580	53,115,815	11.24	1.16	1.24	10.15	13.37	28.08	17.27	29.89	77.05	2.85	17.07	17.47	33.41	17.17	11.96	66.79												
10	Temperate_continental_forest	gez10	678,317,660	320,186,227	47.20	7.00	0.35	4.50	8.10	24.01	20.94	42.10	85.87	0.85	8.28	11.27	34.63	32.08	12.87	78.12												
11	Temperate_desert	gez11	556,953,890	11,891,353	2.14	0.26	1.18	8.15	11.04	26.95	20.20	32.48	80.05	2.48	13.19	15.54	34.53	25.77	8.41	70.68												
12	Temperate_mountain_system	gez12	728,879,284	264,321,593	36.26	5.78	0.17	2.25	4.86	17.54	18.60	56.57	91.04	0.37	4.04	6.94	27.15	35.75	25.75	85.76												
13	Temperate_oceanic_forest	gez13	179,841,066	62,711,463	34.87	1.37	0.95	9.34	12.88	27.96	17.43	31.44	78.23	2.02	17.43	17.45	34.36	19.07	9.65	67.13												
14	Temperate_steppe	gez14	593,531,230	29,936,760	5.04	0.65	2.56	17.54	17.87	28.63	14.27	19.13	67.69	7.62	29.35	19.45	24.94	13.54	4.92	53.83												
15	Tropical_desert	gez15	1,300,661,038	3,221,585	0.25	0.07	7.93	34.05	22.87	24.65	7.49	3.00	48.19	19.37	46.93	17.82	13.18	1.85	0.05	32.61												
16	Tropical_dry_forest	gez16	787,660,937	250,856,640	31.86	5.49	0.84	7.19	10.09	25.06	19.48	37.35	82.10	1.55	11.55	13.22	32.16	24.95	16.54	74.68												
17	Tropical_moist_forest	gez17	1,081,737,759	497,832,278	46.02	10.88	0.54	6.46	9.99	24.74	18.59	39.68	83.09	0.99	11.16	12.95	31.37	24.89	18.64	75.87												
18	Tropical_mountain_system	gez18	445,131,152	178,108,561	40.01	3.89	0.29	2.86	4.44	12.96	13.37	66.08	91.87	0.54	4.40	5.64	17.55	25.23	46.63	88.52												
19	Tropical_rainforest	gez19	1,461,530,795	1,207,128,171	82.59	26.39	0.08	1.21	2.43	8.28	8.94	79.06	95.59	0.12	2.02	3.19	12.15	18.79	63.73	93.42												
20	Tropical_shrubland	gez20	812,475,469	50,244,885	6.18	1.10	1.57	10.83	12.67	27.10	19.23	28.60	76.76	3.37	17.26	15.56	31.94	21.27	10.50	67.44												
21	Water	gez21	86,116,753	2,628,073	3.05	0.06	0.96	9.11	13.36	25.53	16.74	34.28	78.72	2.37	15.27	17.26	28.64	21.74	14.67	69.78												
22	Global	fm30	13,449,024,906	4,573,812,325	34.01	100.00	0.34	3.70	6.25	18.63	16.79	54.29	88.82	0.69	6.16	8.30	25.96	27.17	31.71	83.60												

	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP
1	FAD_3 (99x99) ~100 km2										Six Forest Patch size classes [ha]: 1:1-100] 2:[101-1,000] 3:[1,001-10,000] 4:10,001-100,000] 5:[100,001-1,000,000] 6:[1,000,001->] >10,000 km2										
2	RARE_3 (in #)	PATCH_3 (in #)	TRANS_3 (in #)	DOM_3 (in #)	INTER_3 (in #)	INTACT_3 (in #)	FADAV_3 (in #)	NUM_PATCH (in #)	AVP (in ha)	NO_1 (in #)	HA_1 (in ha)	PERC_NO_1 (in #)	PERC_HA_1 (in #)	NO_2 (in #)	HA_2 (in ha)	PERC_NO_2 (in #)	PERC_HA_2 (in #)	NO_3 (in #)	HA_3 (in ha)	PERC_NO_3 (in #)	PERC_HA_3 (in #)
3	0.07	2.33	6.11	36.97	43.20	11.32	85.45	1,926,373	335.69	1,899,219	9,378,051	98.59	1.45	24,731	6,187,440	1.28	0.96	2,167	5,269,304	0.11	0.81
4	0.31	6.16	11.23	34.65	36.63	11.02	80.11	2,411,941	158.80	2,380,777	10,693,504	98.71	2.79	27,682	7,139,502	1.15	1.86	2,985	7,886,667	0.12	2.06
5	1.15	14.34	21.75	46.53	14.97	1.26	65.23	2,291,227	71.34	2,256,025	11,668,965	98.46	7.14	31,568	8,129,608	1.38	4.97	3,188	8,366,659	0.14	5.12
6	5.91	39.73	28.35	23.57	2.32	0.00	43.49	486,861	25.63	480,376	2,234,496	98.67	17.91	5,700	1,477,761	1.17	11.84	639	1,770,768	0.13	14.19
7	10.48	28.90	17.88	26.01	14.59	1.63	51.92	955,636	18.73	947,407	3,869,457	99.14	21.62	7,386	1,838,405	0.77	10.27	758	1,909,976	0.08	10.67
8	2.07	18.13	21.79	45.45	11.12	1.40	61.77	828,784	59.08	812,704	4,348,883	98.06	8.88	14,058	3,796,783	1.70	7.75	1,695	4,578,528	0.20	9.35
9	0.63	6.51	11.10	45.07	34.12	2.54	77.31	1,563,418	152.28	1,532,228	8,576,649	98.01	3.60	27,649	7,306,399	1.77	3.07	3,080	7,917,426	0.20	3.33
10	1.03	9.40	15.19	46.01	26.00	2.35	72.48	1,120,409	111.36	1,100,084	5,635,357	98.19	4.52	17,627	4,682,197	1.57	3.75	2,159	5,894,099	0.19	4.72
11	4.08	22.44	22.57	34.51	12.21	4.08	58.60	1,200,276	44.25	1,179,678	6,345,965	98.28	11.95	18,205	4,736,097	1.52	8.92	2,086	5,496,707	0.17	10.35
12	0.95	11.26	14.42	42.49	28.38	2.49	72.35	2,283,167	140.24	2,218,779	14,952,509	97.18	4.67	56,287	15,030,343	2.47	4.69	7,088	18,816,839	0.31	5.88
13	3.55	21.41	22.42	31.38	20.62	0.39	60.76	239,362	49.68	235,579	1,155,998	98.42	9.72	3,136	866,265	1.31	7.28	535	1,586,300	0.22	13.34
14	0.53	5.48	9.50	35.33	40.12	9.03	81.08	1,067,204	247.68	1,043,050	5,990,724	97.74	2.27	20,686	5,533,576	1.94	2.09	2,819	7,801,254	0.26	2.95
15	2.26	24.11	21.27	35.47	14.63	2.26	59.73	1,092,207	57.42	1,064,966	6,642,140	97.51	10.59	23,628	6,408,502	2.16	10.22	3,166	8,430,415	0.29	13.44
16	12.08	38.07	18.32	20.77	9.63	0.72	44.63	965,544	31.01	943,349	6,285,810	97.70	21.00	19,883	5,113,621	2.06	17.08	2,110	5,457,940	0.22	18.23
17	30.77	51.60	11.40	4.01	0.01	0.00	23.26	336,152	9.58	332,874	1,456,155	99.02	45.20	2,984	753,465	0.89	23.39	282	692,451	0.08	21.49
18	1.91	15.19	16.77	36.83	22.30	6.95	68.63	4,462,104	56.24	4,395,584	21,609,181	98.51	8.61	58,397	15,387,432	1.31	6.13	7,010	18,464,854	0.16	7.36
19	1.02	14.18	15.87	36.27	24.14	8.50	70.91	6,280,997	79.26	6,154,828	35,772,026	97.99	7.19	112,608	29,470,408	1.79	5.92	11,905	30,760,539	0.19	6.18
20	0.65	5.44	7.11	22.49	33.01	31.29	85.54	1,103,655	161.38	1,085,317	5,929,734	98.34	3.33	16,036	4,125,177	1.45	2.32	1,762	4,955,660	0.16	2.78
21	0.11	2.27	3.88	15.75	28.23	49.76	91.81	2,786,501	433.21	2,730,247	15,579,266	97.98	1.29	49,370	13,029,153	1.77	1.08	5,880	15,483,161	0.21	1.28
22	4.82	22.79	18.70	34.36	16.09	3.06	59.72	1,373,278	36.59	1,355,004	6,602,430	98.67	13.14	16,122	4,220,857	1.17	8.40	1,836	4,880,479	0.13	9.71
23	2.92	20.07	23.15	34.16	16.39	3.20	61.37	65,197	40.31	63,582	461,305	97.52	17.55	1,499	346,507	2.30	13.18	94	254,661	0.14	9.69
24	0.85	7.88	10.44	31.63	29.95	19.26	79.63	34,757,654	131.59	34,148,956	184,144,076	98.25	4.03	543,080	141,605,572	1.56	3.10	529	150,319,613	0.17	3.29

	AQ	AR	AS	AT	AU	AV	AW	AX	AY	AZ	BA	BB	BC	BD
1	10,001-100,000] 5:[100,001-1,000,000] 6:[1,000,001->] >10,000 km2												Largest Patch Statistics	
2	NO_4 (in #)	HA_4 (in ha)	PERC_NO_4 (in #)	PERC_HA_4 (in #)	NO_5 (in #)	HA_5 (in ha)	PERC_NO_5 (in #)	PERC_HA_5 (in #)	NO_6 (in #)	HA_6 (in ha)	PERC_NO_6 (in #)	PERC_HA_6 (in #)	MAX_HA (in ha)	MAX_PERC (in #)
3	200	4,948,320	0.01	0.77	33	10,293,827	0.00	1.59	23	610,589,391	0.00	94.42	163653147	25.31
4	428	12,472,241	0.02	3.26	53	14,544,307	0.00	3.80	16	330,278,860	0.00	86.23	166098007	43.37
5	366	10,127,916	0.02	6.20	61	17,037,598	0.00	10.42	19	108,123,312	0.00	66.15	18777114	11.49
6	130	3,461,775	0.03	27.74	16	3,532,387	0.00	28.31	0	0	0.00	475540	3.81	
7	80	2,188,788	0.01	12.23	4	1,092,768	0.00	6.11	1	6,999,739	0.00	39.11	6999739	39.11
8	268	8,401,819	0.03	17.16	52	12,565,754	0.01	25.66	7	15,270,970	0.00	31.19	3815839	7.79
9	390	10,287,719	0.02	4.32	49	10,985,316	0.00	4.61	22	193,002,943	0.00	81.07	70624162	29.66
10	422	11,950,775	0.04	9.58	97	24,420,070	0.01	19.57	20	72,190,138	0.00	57.86	11423593	9.16
11	269	7,360,362	0.02	13.86	33	8,697,215	0.00	16.37	5	20,479,469	0.00	38.56	7433649	14.00
12	859	23,578,942	0.04	7.36	127	40,336,436	0.01	12.60	27	207,471,158	0.00	64.80	36853379	11.51
13	101	2,567,413	0.04	21.59	10	1,522,928	0.00	12.81	1	4,192,449	0.00	35.26	4192449	35.26
14	506	14,035,781	0.05	5.31	116	37,453,808	0.01	14.17	27	193,506,450	0.00	73.21	60136619	22.75
15	398	10,084,382	0.04	16.08	40	13,936,976	0.00	22.22	9	17,209,048	0.00	27.44	4039016	6.44
16	179	4,338,368	0.02	14.49	22	5,886,706	0.00	19.66	1	2,854,315	0.00	9.53	2854315	9.53
17	12	319,514	0.00	9.92	0	0	0.00	0.00	0	0	0.00	0.00	57884	1.80
18	910	24,592,229	0.02	9.80	176	51,541,988	0.00	20.54	27	119,360,956	0.00	47.56	30473070	12.14
19	1,381	37,476,408	0.02	7.53	223	65,550,448	0.00	13.17	52	298,802,449	0.00	60.02	69256517	13.91
20	408	13,389,619	0.04	7.52	107	28,033,125	0.01	15.74	25	121,675,246	0.00	68.32	29791294	16.73
21	775	21,738,683	0.03	1.80	176	49,038,246	0.01	4.06	53	1,092,259,662	0.00	90.48	405112845	33.56
22	283	7,651,375	0.02	15.23	30	7,411,637	0.00	14.75	3	19,478,107	0.00	38.77	12198924	24.28
23	16	536,032	0.02	20.40	6	1,029,568	0.01	39.18	0	0	0.00	0.00	218,978	8.33
24	6,390	166,315,709	0.02	3.64	784	212,094,815	0.00	4.64	149	3,719,332,540	0.00	81.32	679,553,813	14.86

	A	B	C	D
1	ARCMAP_FIELD_CODE	ALIAS	DEFINITION	UNIT
2	Names & Codes			
3	UNIT	Name of reporting unit	See ATBD	String
4	CODE	Code of reporting unit	See ATBD	String
5	Base Statistics			
6	UNIT_AREA	Land area including inland waters but excluding ocean	See ATBD	Hectare
7	FOR_AREA	'Forest Area' inside or at the edge of the reporting unit	See ATBD	Hectare
8	PERC_UNIT	Percentage of forest inside the reporting unit	See ATBD	Percent
9	PERC_GLOB	Percentage of forest inside the reporting unit with respect to the global forest area	See ATBD	Percent
10	Fragmentation Statistics: 1/2/3 - window: 9x9/31x31/99x99 - neighborhood area: 0.81/9.61/98.01 km2			
11	RARE_1/2/3	Percentage of Forest fragmentation in class 'Rare' (FAD: [0, 10] %)	See ATBD	Percent
12	PATCH_1/2/3	Percentage of Forest fragmentation in class 'Patchy' (FAD: [10, 40] %)	See ATBD	Percent
13	TRANS_1/2/3	Percentage of Forest fragmentation in class 'Transitional' (FAD: [40, 60] %)	See ATBD	Percent
14	DOM_1/2/3	Percentage of Forest fragmentation in class 'Dominant' (FAD: [60, 90] %)	See ATBD	Percent
15	INTER_1/2/3	Percentage of Forest fragmentation in class 'Interior' (FAD: [90, 99] %)	See ATBD	Percent
16	INTACT_1/2/3	Percentage of Forest fragmentation in class 'Intact' (FAD: [100] %)	See ATBD	Percent
17	FADAV_1/2/3	Average FAD value over all forest pixels	See ATBD	Percent
18	Forest Patch Statistics			
19	NUM_PATCH	The 'Number of Forest Patches': a forest patch is composed of adjacent forest pixels sharing a common pixel side or pixel corner (8-connectivity, see graphic example on the bottom-right).	See ATBD	Integer
20	AVP	The 'Average Forest Patch Size': the total 'Forest Area' of the reporting unit divided by the 'Number of Forest Patches'.	See ATBD	Float
21	NO_1	# of Forest Patches in Class 1: 1-100 ha	Count	Integer
22	HA_1	Area of Forest Patches in Class 1	Area Sum Patch-Size: 1 ≤ 100	Hectare
23	PERC_NO_1	# of Forest Patches in Class 1 / Total Number of Forest Patches		Percent
24	PERC_HA_1	Area of Forest Patches in Class 1 / Total Forest Area		Percent

Source: JRC, 2019.

## 4 Conclusions

This document describes a methodology to map and quantify forest fragmentation. The approach is based on measuring (a) *Accounting*: a set of forest patch size classes and (b) *FAD*: the forest area density at three different observation scales. The concept assures to simultaneously measure key aspects of fragmentation including, the amount of forest, the area of continuous forest cover, perforations inside forest patches, patch shape and linear features, and the distance between individual forest patches.

**The purpose of the map product** is to exploit the spatial information, which cannot be retrieved from summary 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 source for planning and risk assessment. The map product is useful to address spatially explicit assessment questions (**where**) such as:

- Where are forests most fragmented?
- Where in the reporting unit are the small (large) forest patches?
- How far apart are the forest patches?
- Where are large forest patches close to each other (making this location a prime target for restoration)?
- Where are, or which forests patches are in high risk areas (comparing/intersecting the forest map product with other environmental data layers in a GIS)?
- Trend analysis: if comparable map products over time are available, a change map allows to delineate areas of improvement/degradation or locating areas where the situation is stable. Such geographic detail is essential in landscape management, biodiversity assessments and policy planning. It may also be used to control and measure progress of locally applied political directives.

**The purpose of the summary statistics** (*COP2015\_foreststats.xlsx*) is to provide a concise and comparative overview allowing to answer essential quantitative assessment questions (**how much**) such as:

- In which GEZ is forest most fragmented when observed at a local neighbourhood of 100 km<sup>2</sup> (i.e., in Figure 8 sort column AB to find lowest FAD\_AV)?
- Which GEZ has the most forest area (i.e., in Figure 8 sort column F)?
- Which GEZ has the highest proportion of small/large forest patches?
- In which GEZ is forest mostly contained in large forest patches?
- Which GEZ exhibits the most intact forest distribution?
- Which GEZ show a consistent degree of fragmentation from local to regional observation scale?
- Which GEZ shows a similar distribution of forest patch size classes compared to the global situation?

The above, and other similar questions, can be easily addressed by using the filter function in the summary spreadsheet (*COP2015\_foreststats.xlsx*). The accompanying map product provides additional information on the location of the topic of interest.



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## List of acronyms

APS	Average Patch Size
ATBD	Algorithm Technical Basis Document
COP	COPERNICUS Land Cover Map
FAD	Forest Area Density
FAD_AV	Average FAD value of all forest pixels
FOS	FAD at Fixed Observation Scale
FAO	Food and Agriculture Organization of the United Nations
GEZ	Global Ecological Zone
GIS	Geographic Information System
GTB	GuidosToolbox
GWB	GuidosToolbox Workbench
SDG	Sustainable Development Goals
SOFO	State of the World's Forests

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## Annex

This section describes the file hierarchy and input and output formats in the various sub-directories of the base-directory **FAO**. Files are shown in *italics* and directories in **bold**.

- **global**: directory with input/output data for fragmentation analysis:
  - **fm**: global forest mask used for the Accounting and FAD analysis.
  - **acc**: Accounting map and statistics of the global forest mask.
  - **fad**: FAD maps and statistics of the global forest mask.
- **gez**: directory with 21 GEZ-specific input/output data for fragmentation analysis:
  - **fm**: forest masks used for the Accounting and FAD analysis.
  - **acc**: Accounting maps and statistics for the 21 GEZ.
  - **fad**: FAD maps and statistics for the 21 GEZ.
- **docs**: directory with general documentation:
  - *TechnicalReport\_FAO\_frag.pdf*: current ATBD document
  - *COP2015\_foreststats.xlsx*: searchable summary statistics with field code definitions.
  - *COP\_LC\_Manual.pdf*: COP manual, version 2.1, downloaded October, 10 2019  
(source: <https://land.copernicus.eu/global/documents/products>)

**Note:** to keep the file size of the base-directory **FAO** to the minimum, intermediate data sets and the original COPERNICUS 2015 land cover data set are not included in the results.

All map products are provided in geotiff format and in the data type byte besides the images showing the Accounting area (\*\_acc\_pixels.tif), which are in data type long integer. Details of the geo-header information can be retrieved with the gdalinfo command or from your preferred GIS application. Details on the input and output pixel values are summarized in the following figures:

COP Maps: Directory: global/ Goode-Homolosine re-projected COP data			
File name: gl-dc.tif and gl-tcf.tif			
Value	Class	RGB – Color Code	Description (see section <b>Error! Reference source not found.</b> )
See: <a href="https://lcviewer.vito.be">https://lcviewer.vito.be</a> and <a href="https://lcviewer.vito.be/about">https://lcviewer.vito.be/about</a>			

Forest Masks: Directory: global/fm/ or gez/fm/			
File name: fm30.tif or gez#_fm.tif			
Value	Class	RGB – Colour Code	Description (see section <b>Error! Reference source not found.</b> )
0	Missing	0/0/0	Ocean, No data or outside reporting unit
1	Background	255/255/210	Nonforest
2	Forest	50/150/85	Forest cover
3	Water	0/100/255	Inland waters

Accounting: Directory: global/acc/ or gez/acc/gez#_fm_acc/ File name: <reporting-unit>_fm_acc.tif			
Value	Class	RGB – Colour Code	Description (see section <b>Error! Reference source not found.</b> )
0	Background	220/220/220	Nonforest land cover
103	Size class 1	0/0/0	Forest patches: $1 \leq 100$ ha
33	Size class 2	255/0/0	Forest patches: $101 \leq 1,000$ ha
65	Size class 3	255/255/0	Forest patches: $1,001 \leq 10,000$ ha
1	Size class 4	255/140/0	Forest patches: $10,001 \leq 100,000$ ha
9	Size class 5	160/60/0	Forest patches: $100,001 \leq 1,000,000$ ha
17	Size class 6	0/200/0	Forest patches: $\geq 1,000,001$ ha
129	Missing	255/255/255	No data or outside reporting unit
105	Water	0/0/255	Inland waters

Fragmentation: Directory: global/fad/ or gez/fad/gez#_fm_fad/ File name: <reporting-unit>_fad_<9, 31, 99>.tif			
Value	Class	RGB – Colour Code	Description (see section <b>Error! Reference source not found.</b> )
0 - 9	Rare	214/49/39	Forest patches in class: Rare
10 - 39	Patchy	249/139/89	Forest patches in class: Patchy
40 - 59	Transitional	254/199/0	Forest patches in class: Transitional
60 - 89	Dominant	139/199/99	Forest patches in class: Dominant
90 - 99	Interior	0/174/0	Forest patches in class: Interior
100	Intact	0/119/0	Forest patches in class: Intact
101	Background	175/175/175	Nonforest land cover
102	Missing	255/255/255	No data or outside reporting unit
105	Water	0/100/255	Inland waters

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