Reporting on European forest fragmentation: Standardised indices and web map services

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ABSTRACT

This paper responds to the need of improved reporting and methodology reproducibility on forest fragmentation as underlined in the biodiversity policy context. The fragmentation of a focal ecosystem is conceptualized from a landscape pattern characterization based on three publically available landscape models (Morphological Spatial Pattern Application of the GUIDOS free-download software, Landscape Mosaic Pattern, Conefor Sensinode free open source software) that were partly combined. A set of indices were derived and organized into five main families: two indices on general landscape composition, four on forest fragmentation pattern, four on forest morphological shapes with their respective edge interface mosaic context (four indices) and three indices on connectivity. A concise array-based mathematical formulation of the indices allows their unambiguous semantic description and easier implementation, thus contributing to share concise data-transformation models. The number of indices in each family can be reduced depending on users focus and semantics. The indices were computed by using the European-wide 25m resolution forest map of year 2006 and the broad scale CORINE land cover multi-temporal data as inputs maps. A snap-shot of the European-wide data available on the status and trends of forest fragmentation over the 1990-2006 time period is shortly illustrated. Furthermore, a dedicated pattern web map viewer was developed using existing tools, free open source software and web standard technologies for data viewing and query from the European Forest Data Centre (EFDAC). The GIS layers are available as OGC WMS/WFS and could be re-used within a ModelWeb context in the near future, then being of direct benefit to GEOSS and its underlying data sharing principles.

1. Introduction

Many of Europe's habitats are highly fragmented and at risk of further fragmentation as a result of ongoing developments and land-use changes. Fragmentation results in habitat loss and degradation. It constrains natural movements of species (e.g. for foraging, breeding, migration and dispersal) but on the other hand, may prevent the spread of alien species, pests, predators and diseases. Thus, fragmentation is inherently neither good nor bad; it is matter of interpretation which is species and habitat specific. Reporting on fragmentation is first of all about identifying a generic set of indices to measure landscape pattern and their changes, which could in a second step be customized for specific species and habitats particularly vulnerable to fragmentation. It requires knowledge on the area of interior habitat, on isolation/connectivity of habitat patches within other land use forms (agricultural areas, transport infrastructures or settlements), and on edges where areas of focal habitat(s) abut modified ecosystems. Local and regional reporting units likely best capture fragmentation processes and best support decision-making processes for landscape planning and sustainable forest management.

The current study aims to support the reporting on the status and trends of ecosystem fragmentation. Its continental and regional framework of application is motivated by the need of measuring progress towards achieving global and European biodiversity policy targets on mitigating fragmentation, ensuring better connectivity and restoring degraded ecosystems (Aichi target 5 of the Convention of Biological Diversity, targets 2 and 3 of the European Biodiversity strategy for 2020 in EC, 2011), which also involve the establishment of green infrastructure at different scales (ENV, 2012). Local scale applications can be found in Estreguil *et a*l, submitted. The focus on forest is motivated by the need of harmonized forest landscape pattern information which does not exist in national inventories to compile the indicator 4.7 in Forest Europe, 2011.

Sharing information is the other two- fold concern of this study: data sharing and scientific information sharing. Primary focus is deliberately put on the later by addressing sharing unambiguous, reproducible mathematical implementation of indices, possibly based on publicly available, free scientific software. Peng (2011) noticeably highlighted reproducibility "as a minimum standard for judging scientific claims" in computational science and summarized its spectrum, ranging from non-reproducible research (publication only) up to "gold standard" of full replication. Data sharing are the underlying principles of GEOSS (Global Earth Observation System of Systems), to be implemented here for the two inter-related societal benefit areas: ecosystem and biodiversity. The effort in this paper was restricted to on line data visualization.

This study thus addresses the development of a small, generic and reproducible set of standardized fragmentation indices, the share of reproducible mathematical implementation of these indices, possibly based on publicly available free scientific software, and the on line data visualization and query. After introducing the indices, this paper shortly presents the derived European-wide forest fragmentation dataset based on available Earth Observation (EO) land cover maps, illustrates their application at regional scale and concludes with the web map viewer.

2. A standardized set of indices

The landscape pattern characterization and associated indices build upon recent research which was applied at local scale in different European environmental regions (Estreguil *et al.*, submitted). It is based on scientifically well-founded landscape ecological principles (Lindenmeyer *et al.*, 2008) and policy requirements (Kettunen *et al.*, 2007 and ENV, 2012). This paper proposes their application at continental level. It promotes the use and combination of three available landscape pattern conceptual models and contributes to the current effort of GIS and EO based models integration, which is an emerging research topic in environmental sciences (Casagrandi and Guariso, 2009; Tian *et al.*, 2008). The indices are organized into five families as described below and illustrated in **Figure 1**. They are presented in **Table 1**. The mathematical formulation of indices is available in **Table 2** of Appendix.

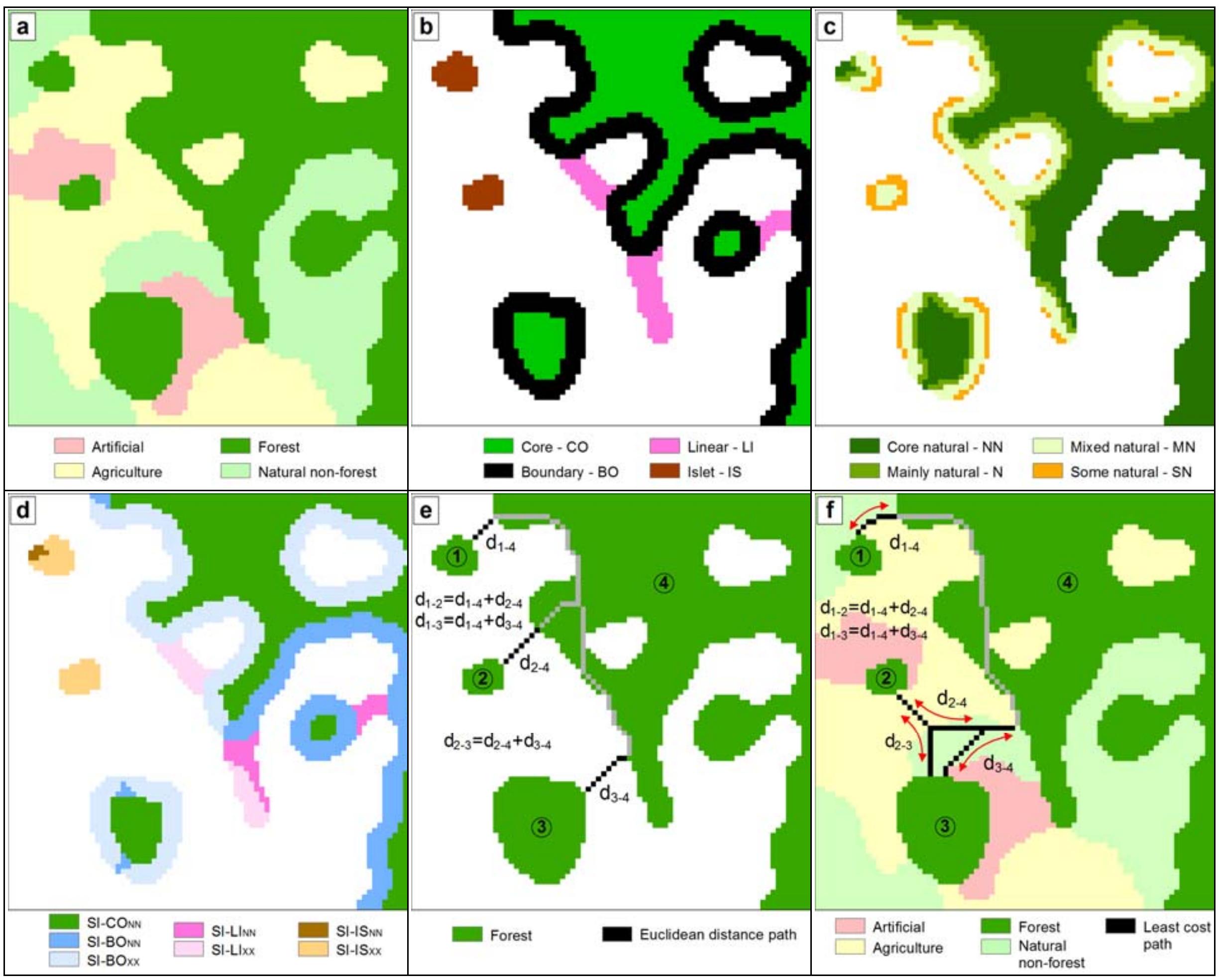


Figure 1. Conceptual illustration of model based maps to compute the index families for a focal class 'forest': (a) simplified input land cover map according to four classes of interest, (b) the morphological forest shape map (*MORPH*), (c) the mosaic forest fragmentation pattern map (*MOSAIC*), d) the forest interface map (*Interface*), e) the inter-patch connectivity based on (e) Euclidian distance and homogeneous matrix and (f) Least-cost path and matrix resistance.

- The first family (*General*) is on the availability of target habitat(s) in the landscape or region: the forest proportion (*FP*) and the natural/semi-natural habitats proportion (*NaP*).
- The second family of indices (*MORPH*) is derived from the Morphological Spatial Pattern Application (MSPA) of the GUIDOS software (Soille and Vogt, 2009) which describes and maps six morphological shapes of forest. The later were renamed and merged into four main shapes with their associated indices: the forest proportion in interior habitat (*COP*), in boundaries-edges (*BOP*), in linear forest features (*LIP*), and in islets (*ISP*). An edge size (*s*) of 100m (multiple of the spatial resolution of the input data) was used for demonstration.
- The third index family (*MOSAIC*) is derived from a moving window tri-dimensional algorithm which describes the landscape mosaic pattern around a given piece of land according to fifteen types based on proportions of artificial, agricultural and natural lands in this window (Riitters *et al.*, 2009). Two squared windows with sides as odd multiple of s (*3s* and *9s*) were used for the surroundings of each (s^2) piece of forest land (s^2=1ha in the demonstration). The original fifteen pattern types were merged into two 'un-fragmented' and two 'fragmented' forest patterns categories with their associated forest proportion related indices : 'core natural' pattern (NNP) when forest neighborhood is 100% natural, 'mainly natural' pattern (NP) when neighborhood is at least 80% natural, 'mixed natural' pattern (MNP) when forest is in natural context of at least 60% still intermingled with agricultural and artificial lands, 'some natural' fragmented patterns (SNP) when agricultural and/or artificial lands shares in forest neighborhood are above 60%.
- The fourth family (*Interface*) is obtained by overlay of the maps generated from *MORPH* (*s* edge size) and the *MOSAIC* models which is run for a square of side 3s to discriminate types of forest interface zones (forest edges with adjacent natural/semi-natural lands or more anthropogenic lands). One index (IFP) was on the proportion of forest in interior area of patches (CO) and/or along natural lands (BO_{NN}) and the other indices were from the Similarity indices ($SI\text{-}MORPH_{MOSAIC}$) on the proportion of each forest morphological shape along natural habitats ($SI\text{-}BO_{NN}$, $SI\text{-}LI_{NN}$, $SI\text{-}IS_{NN}$). Alternatively indices focusing on the anthropogenic forest interface zone can be generated like forest boundaries along agricultural or artificial lands ($SI\text{-}BO_{MN\ or\ SN}$).
- The fifth family set of indices (*Connectivity*) is derived from the original Probability of Connectivity index (PC) (Conefor Sensinode 2.6 (Saura and Torné, 2009) and the Equivalent Connected Area (ECA in Saura *et al.,* 2011). Connectivity is measured with a network-based habitat availability index that quantifies functional connectivity on the basis of the focal habitat area, its spatial configuration, inter-patch distances and specific dispersal capabilities of generic groups of focal habitat-dwelling species. Each link between every two patches a_i and a_j is characterized by a probability of dispersal p_{ij} , obtained as a function of distance (a decreasing exponential function of either the Euclidean (straight-line) edge-to-edge distance or the effective distance (least-cost), matching to a 50% probability for a specific average dispersal distance). The connectivity (or isolation) of a focal habitat in a landscape is correlated to the amount of the focal habitat in the landscape but differs from it depending on its spatial arrangement and the matrix permeability. Unlike the first four families (Table 2 of Appendix), the indices dealing with connectivity show a computational complexity which is inherently quadratic with the number of shapes (here, forest patches) because the connection between each pair of shapes has to be considered. It is possible to mitigate a further contribution to the complexity of this fifth family of indices by reducing the heterogeneity of their definition. In order to accomplish this goal, three connectivity indices – Root Probability Index (RPC), Isolation Index (IsoSI) and

Average Connectivity Index (APC) – measuring different aspects of connectivity are derived from the same family, which is referred as *Power Weighted Probability of Dispersal* (PWPD) (Estreguil *et al.*, submitted) and a simplified version of the PWPD family (s-PWPD) was formulated (Note in **Table 2** and eq. 1 of Appendix). The information on patch areas can be considered for example either by their product (as in the case of RPC) or only by one of them per each pair (IsoSi considers the destination patch area) or by even neither of them, as in the case of APC. All indices are dimensionless and range from 0 to 1. For time computing reasons, the European-wide application used the Euclidian distance and computed the RPC index for 1km, 5km and 10km average species dispersal abilities.

The compact mathematical formulation (eq. 1 of Appendix) accomplishes one of the research objectives by easing even the computational reproducibility of the more complex fifth family of indices. Connectivity indices' description is reduced to an array-based concise relationship between the vector of patch areas $A = [a_1 \ \dots \ a_n]$ and the probability of dispersal matrix $P = [p_{ij}]$ and makes straightforward the implementation of the whole fifth family using array-programming languages. For example, using either GNU Octave (Eaton *et al.* 2008) or MATLAB languages the Mastrave modelling library (de Rigo, 2012a; de Rigo 2012b), a generic index of the s-PWPD family would be computable by means of a generic reduction operator applied to a graph (whose edge- and node-weights are respectively the probabilities of dispersal P and the patch areas A) with a single line of code (eq. 2 of Appendix).

Table 1: List of indices from the five families based on the morphological, mosaic pattern models, their combination and the connectivity model (adapted from *Estreguil* et al., *submitted*)

Landscape index per reporting unit			Index family
Composition	Proportion of focal habitat forest (*f*) in reporting unit	$FP^{(f,)}$	*General*
	Proportion of natural/semi-natural lands in reporting unit	$NaP^{(nat,)}$	
Mosaic fragmentation pattern	Focal habitat forest (f) share in two unfragmented forest pattern type : - 'Core natural' NN (100% natural neighbourhood) - 'Mainly natural' N (80% natural neighbourhood)	NNP, NP	*MOSAIC*
	Focal habitat forest (f) share in two fragmented forest pattern type by agriculture or/and artificial lands : - 'Mixed natural' pattern MN in predominantly natural context (> 60%) - 'Some natural' SN in predominantly non-natural context	MNP, SNP	
Connectivity	Connectivity index value of the focal habitat forest (*f*), based on the Square Root of Probability of Connectivity (sensitive to forest area and configuration, weighted by origin and destination patch-area, Euclidian distance (*d*) between patches, prefixed average dispersal distance ($d_{50\%}$) and matrix homogeneous).	$RPC^{(f,d,d_{50\%})}$	*Connectivity (simplified Power Weighted Probability of Dispersal function (s-PWPD) of the probabilities of dispersal between*
	Idem based on Isolation Sensitive Index (sensitive to forest area and configuration, only weighted by	$IsoSi^{(f,d,d_{50\%},avf)}$	

	destination patch-area, sensitive to dispersal in matrix (*avf*) with least-cost distance (*d*)).		*patches*
	Idem based on Un-weighted Average of Probability of Connectivity (proxy of matrix permeability accounting for focal habitat configuration only, sensitive to dispersal in matrix (*avf*) with least-cost distance (*d*)).	$APC^{(d, d_{50\%}, avf)}$	
Index per target morphological pattern of the focal habitat			**Index family**
Interior	Proportion of forest beyond a fixed distance to border (edge *s*)	$COP^{(f,s)}$	*MORPH*
	Proportion of forest beyond a fixed distance to border only when along anthropogenic habitats (no edge width along natural land).	$IFP^{(f,s)}$	*Interface*
Edges	Forest proportion in boundaries (fixed edge width *s*)	$BOP^{(f,s)}$	*MORPH*
	Proportion of forest boundaries along natural habitats Proportion of forest boundaries along anthropogenic habitats	$SI\text{-}BO_{NN}^{(f,s)}$, $SI\text{-}BO_{N}^{(f,s)}$ $SI\text{-}BO_{MN}^{(f,s)}$, $SI\text{-}BO_{SN}^{(f,s)}$	*Interface*
Linear features	Forest proportion in linear features	$LIP^{(f,s)}$	*MORPH*
	Proportion of linear features along natural habitats Proportion of linear features along anthropogenic habitats	$SI\text{-}LI_{NN}^{(f,s)}$, $SI\text{-}LI_{N}^{(f,s)}$ $SI\text{-}LI_{MN}^{(f,s)}$, $SI\text{-}LI_{SN}^{(f,s)}$	*Interface*
Islets	Forest proportion in islets	$ISP^{(f,s)}$	*MORPH*
	Proportion of islets along natural habitats Proportion of islets along anthropogenic habitats	$SI\text{-}IS_{NN}^{(f,s)}$, $SI\text{-}IS_{N}^{(f,s)}$ $SI\text{-}IS_{MN}^{(f,s)}$, $SI\text{-}IS_{SN}^{(f,s)}$	*Interface*

3. European-wide fragmentation data based on indices

The implementation of the set of indices to report on European-wide forest fragmentation status and trends is hampered by poorly available harmonized data. Because the observation of fragmentation is scale dependent, the exercise should be conducted at least at two different scales. Indices were implemented as follows:

- The broad scale and multi-temporal observation of pattern was based on the European-wide CORINE Land Cover (CLC) data for the years 1990, 2000, 2006 (European Environment Agency, 2011). The 25 ha minimum mapping unit enables to observe broad patterns of forest and their trends in the time period 1990-2000-2006. All indices could be implemented except the connectivity indices based on least cost path (IsoSi and APC) due to computing capacity.
- For year 2006 only, the fine scale observation of forest pattern was feasible from the European-wide JRC forest type map (FM, 25 m raster map) (Kempeneers *et al.*, 2011) where clusters of 8-connected pixels below 1ha (equivalent to 16 pixels) were removed. Spatial details up to 1 ha are relevant to identify hedgerows, woodland islets and perforations in large forest patches. This layer does not inform on non-forest classes, thus preventing the implementation of mosaic and interface indices.

In both dataset, the forested areas included broadleaves, coniferous and mixed forest, with trees higher than 5m and a canopy closure of at least 30%. Forest class includes young plantations with at least 500 stems/ha, but not other wooded lands, young plantations when below 500 stems/ha, clear cuts, burnt areas, or forest nurseries. For the *MOSAIC* model, the natural/semi-natural non forested lands from the CORINE dataset include forests, grasslands, scrublands, sparsely vegetated areas, wetlands, and other waters—both freshwater and coastal.

Because fragmentation rather occurs at local landscape scale, forest patterns were captured and reported locally per landscape units (A_L) of 25 km by 25 km, then also reported per province (A_L = NUTS2/3)[1] or per country (A_L = NUTS0). Indices based on the morphological and mosaic models allowed a direct calculation for each of these reporting units. Landscape connectivity (RPC) was first computed and reported for each of the 25 km and 25 km landscape unit (A_L). An average landscape connectivity was reported by province (NUTS2/3) or by country (NUTS0) by averaging the connectivity values of all concerned grid squares, giving weightings proportional to the unit area for grid squares occurring at province or country borders. The derived (GIS) data layers consists of European-wide vector maps for each index listed in **Table 1**, and computed for each reference year *i.e.* 1990, 2000, 2006 and reporting units (**Figure 2** and **Figure 3**). A subset of the GIS attribute shape files is illustrated for the Austrian tiles along the Danube River (**Table 3** in Appendix and **Figure 4**).

1 Nomenclature of Territorial Units for Statistics by regions and country at the Eurostat's RAMON server http://ec.europa.eu/eurostat/ramon/index.cfm?TargetUrl=DSP_PUB_WELC

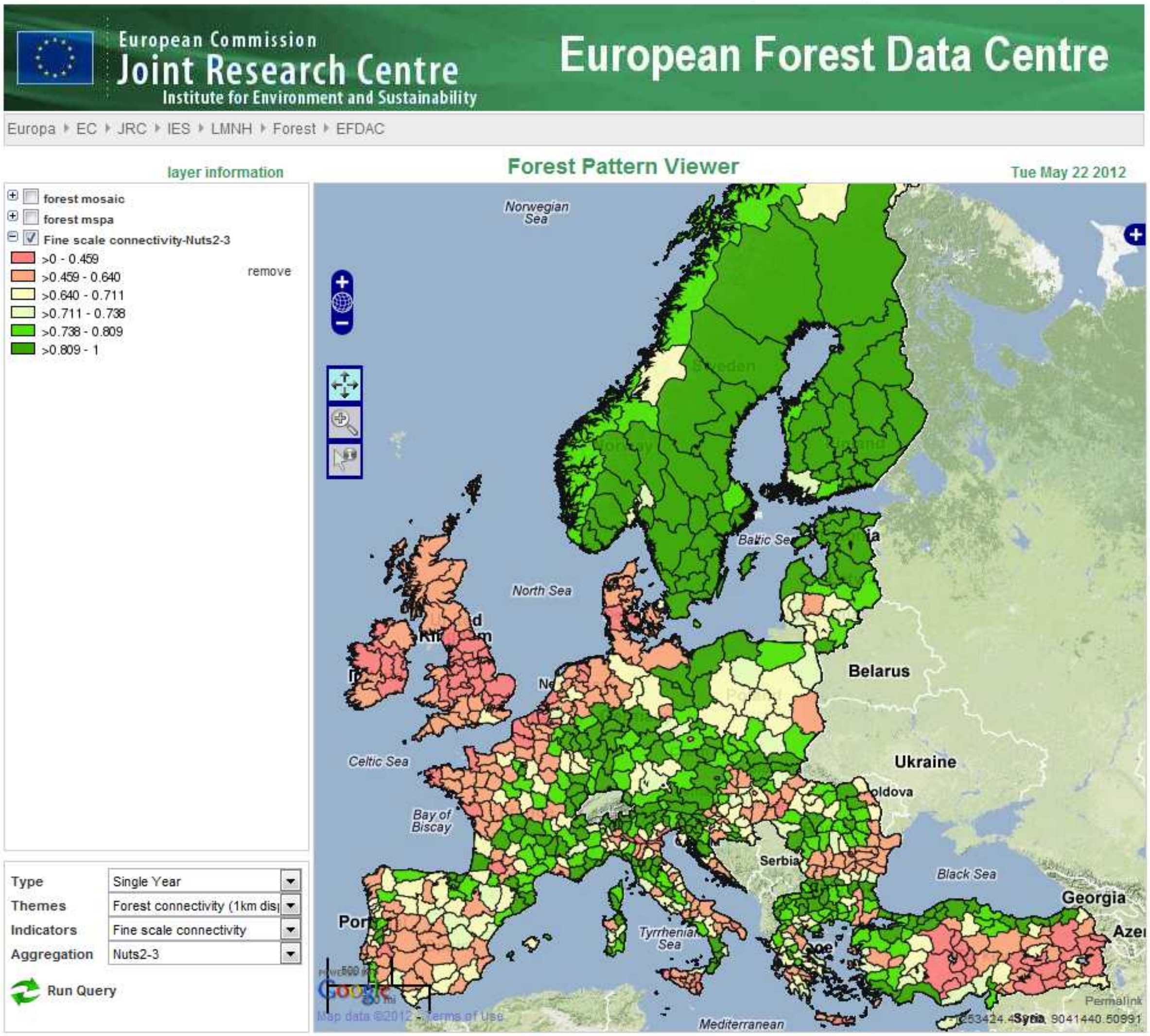


Figure 2. Example of forest connectivity index: fine scale connectivity. Year 2006, spatial aggregation at NUTS level 2 and 3. Image from the European Forest Data Centre (EFDAC) map viewer. Ground layer: Google (2012).

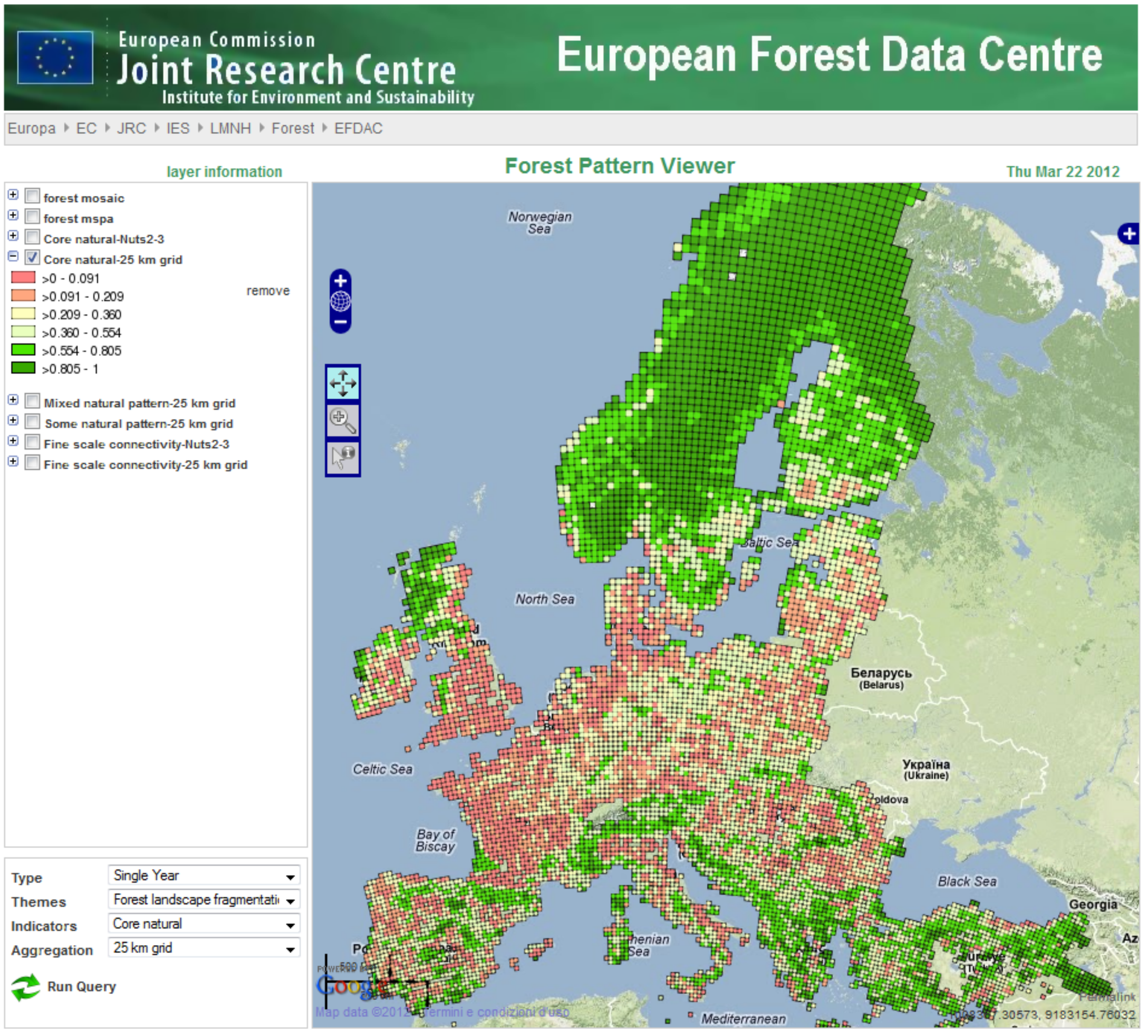


Figure 3. Example of forest landscape fragmentation index: core natural proportion. Year 2006, spatial grid INSPIRE Lambert Azimuthal Equal Area, resolution 25 km x 25 km. Image from the European Forest Data Centre (EFDAC) map viewer. Ground layer: Google (2012).

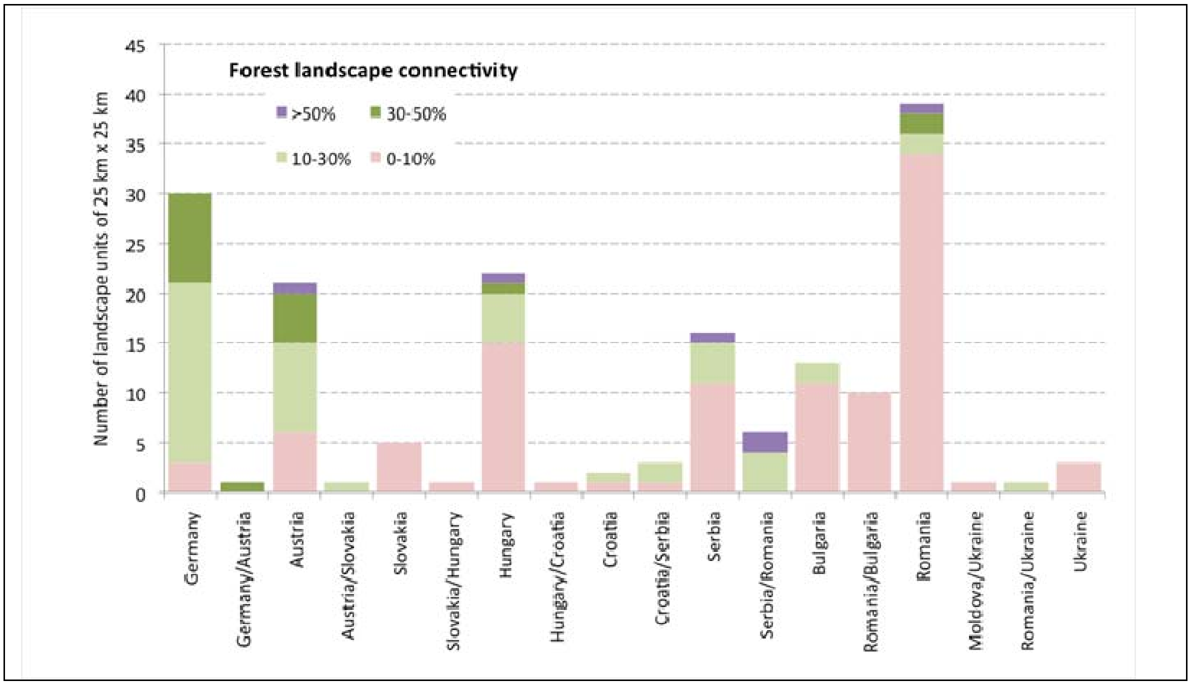
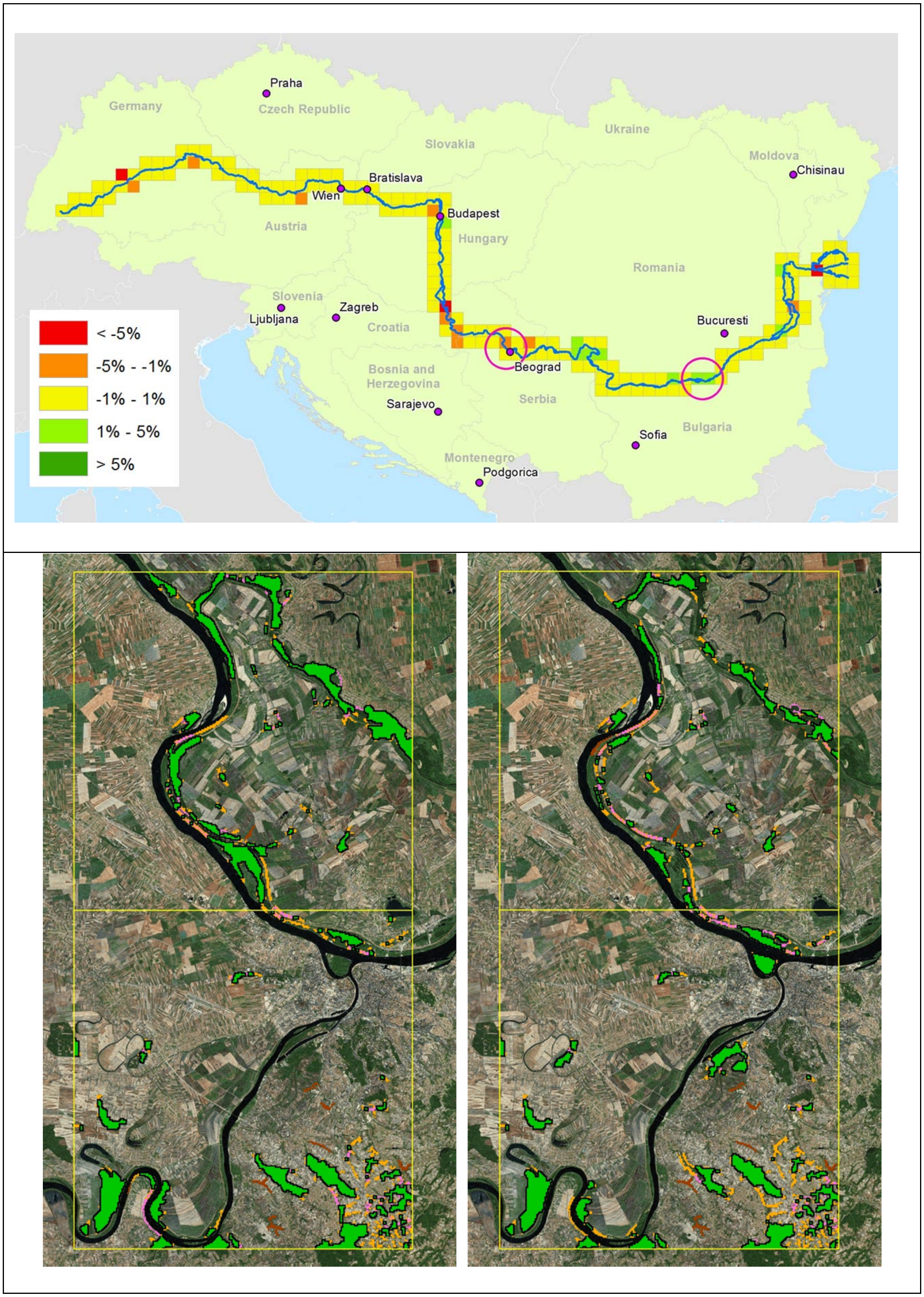


Figure 4. Country based distribution of landscapes per forest connectivity ranges at fine scale (RPC index, Euclidian distance, species average dispersal 1km, data source: JRC Forest Type map, year 2006). Forest landscapes units poorly connected (<30%) can be due to natural and/or anthropogenic driven factors and are likely more vulnerable to further fragmentation.

Trends in the time period 1990-2000-2006 were reported for two indices (NNP and RPC) and were resumed by the direction of change in between the three points in time as positive, negative, stable, unclear. Changes in the forest fragmentation landscape mosaic pattern enabled to identify landscapes or regions where forest shares in fragmented patterns have increased at the expenses of core natural pattern. Landscapes undergoing an increase of forest connectivity (positive direction) could be identified. The amplitude of relative variation for each index could be obtained as shown in the case study in **Figure 5.**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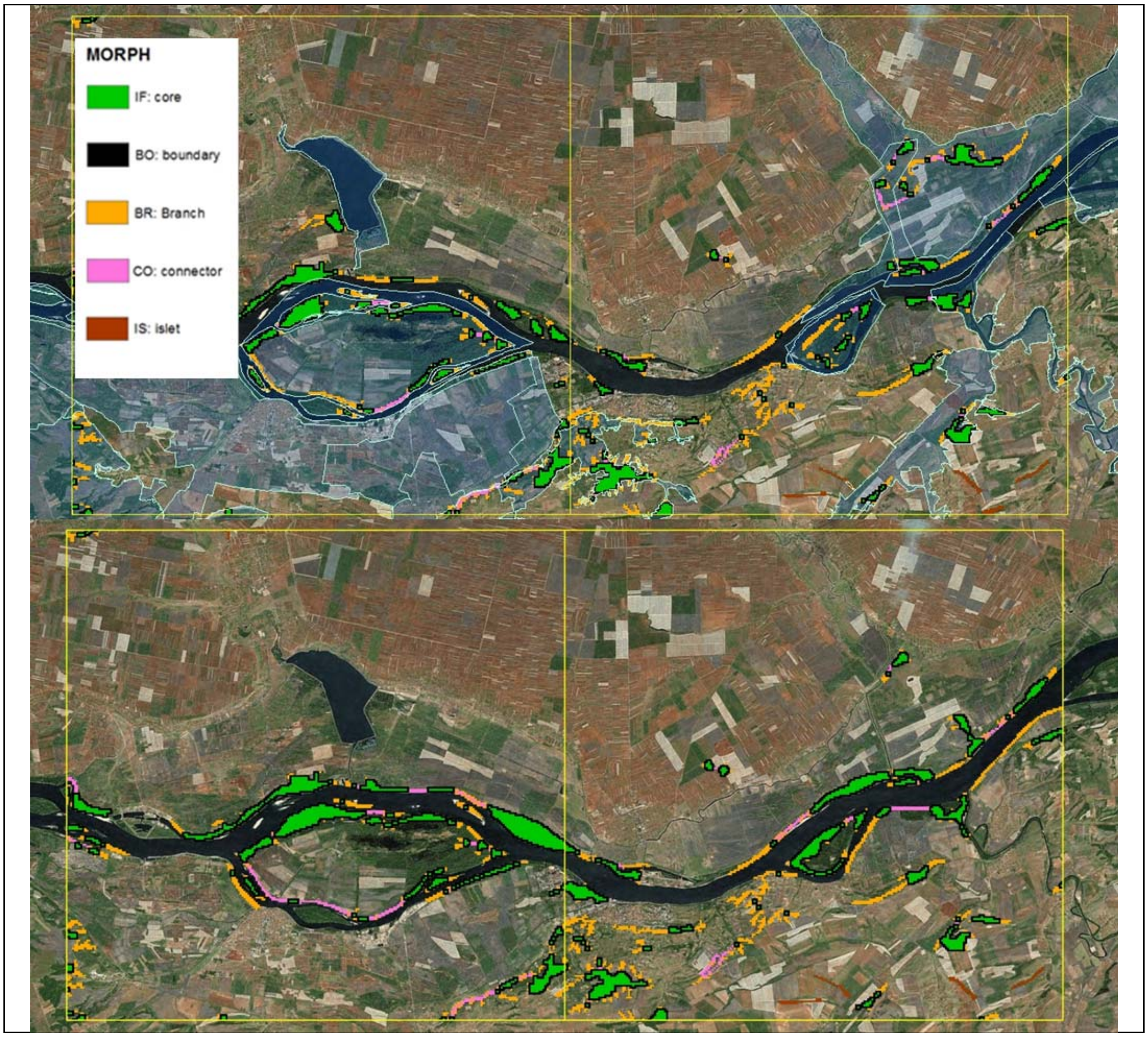

Figure 5 (a,b,c) Broad scale trend in forest connectivity along the Danube river in 1990-2000-2006 (Index RPC - Landscape unit 25 x 25 km^2 - Species average dispersal distance 1km, data source: CLC1990-2000-2006) with an insight on landscapes with (b) loss of key patches resulting in significant connectivity loss close to Beograd and (c) minor gain of forest patches resulting in a significant gain in connectivity (CLC1990-2006 processed with GUIDOS software).

Trend for each index could further be directly compared with the variation in the total amount of forest area in the landscape as illustrated for connectivity along the river bed of the Danube (**Figure 6**). Identification (where) and additional insight (how, how much) is provided on landscapes which have likely undergone forest connectivity losses (both area loss and isolation), on landscapes which acknowledged a forest gain with no benefit on connectivity (calling for a better spatial planning when re-afforestion measures), on landscape with connectivity gains due to both forest area gain and defragmentation processes or to gain in core natural forest pattern.

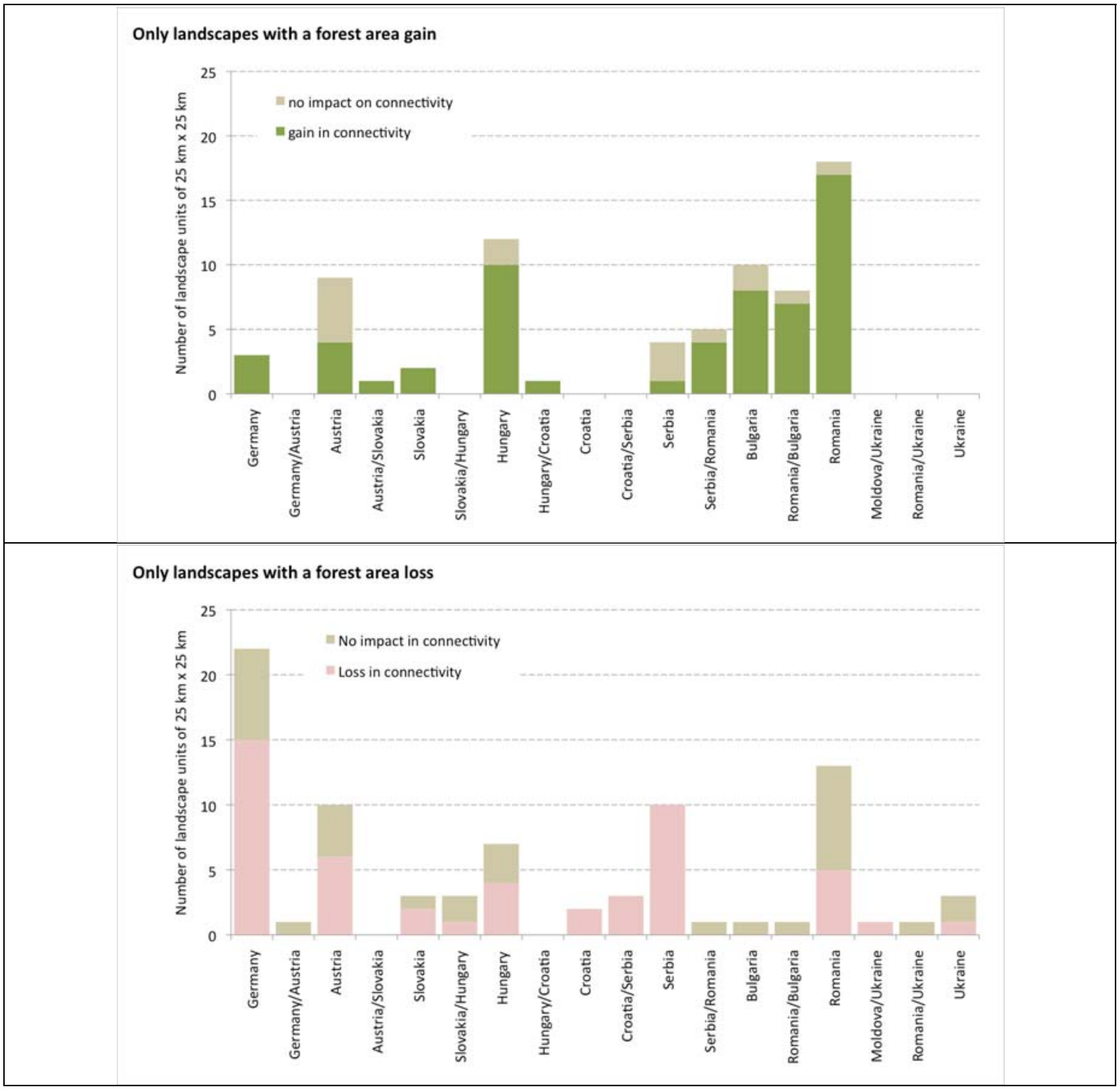

Figure 6. Forest connectivity change in 1990-2006 versus forest area change. Landscapes with a net forest area gain show in general an increase in connectivity. In few cases, this gain had no impact on connectivity (new forest areas planted too remotely from other woodland) or only a minor impact when they only enlarge an existing patch.

4. The on-line data map viewer

The European-wide fragmentation data management system framework was set up on the basis of existing tools, open source software and web standard technologies and benefited from in house expertise and existing capabilities from the European Forest Data Centre (EFDAC at http://efdac.jrc.ec.europa.eu/). Part of the static GIS layers derived from the computation of the indices listed in **Table 1** for single year (status in 2006) and trends (1990-2006) can now be viewed and queried on line from the dedicated European Forest Data Centre (EFDAC) map viewer (or from the Forest web site) (**Figure 2** and **Figure 3**). To guide the user, the indices and the derived maps are described in a downloadable pdf file and an application form can also be opened as an html file window. The query function is organised by themes, sub-divided into indices, and then proposed for three different reporting units (landscape unit, province, country) :

- 'Single year' themes (*i.e.* status in 2006) are the forest landscape fragmentation patterns in a 1km^2 surroundings (NNP, MNP and SNP indices in **Table 1**), the targeted morphological shapes with their respective interface type (interior forest - COP and IFP, boundaries-edge forest -BOP and SI-BO$_{NN}$-, linear forest features -LIP and SI-LI$_{NN}$-, isolated forest islets -ISP and SI-IS$_{NN}$-), and the forest connectivity layers for 1km dispersal distance. All themes are available to view at broad scales (derived from CLC map) while the connectivity layers are also offered for viewing at fine scale (derived from the JRC Forest type map)
- 'Change in time' themes (*i.e.* trends 1990-2006) offer two broad scale layers: trends in forest landscape fragmentation patterns and forest connectivity for 1km species dispersal distance.

Technical tasks to develop the map viewer included: a) to determine essential operational core services, b) to provide the GIS database according to agreed formatting, and c) to design data architecture and technical tools for needed services, currently restricted to data visualization and query. The spatial layers and their associated data were prepared in a common ESRI Shapefile format. They were sent to the web client using the OGC WMS standard, which were published through MapServer. Metadata and the static GIS layers, now available as OGC WMS/WFS, will soon be prepared to enable re-use in other applications, possibly in a ModelWeb context, in the near future, then being of direct benefit to GEOSS and its underlying data sharing principles. The background to the viewer uses the Google Maps. The application has been developed and managed primarily using Free/Libre Open-Source Software (FLOSS) and runs on GNU/Linux operating systems. The mapping client has been written using the Django Framework. The viewer uses the following software and licensing should be referred to: MapServer, Django , Python (Van Rossum and Drake 2011), OpenLayers, Jquery. OpenLayers, Google Maps (Google 2012) and JQuery javascript, allow the user to interact with the spatial layers.

This paper wished to contribute to the current effort of GIS and EO based models integration for an improved European-wide reporting and sharing information on forest fragmentation related issues by proposing and applying a standardised and easily reproducible set of indices. It also provided an on-line data visualization and query. Before sharing the fragmentation data, the study put emphasis on sharing scientific information and reproducibility of the complex environmental-modelling indices as suggested by Peng (2011), in our case in particular for the most computationally demanding family of indices. The next step for the coming months will be on data sharing, in particular to prepare the metadata and the OGC/WFS layers in order to be compliant with GEOSS and its underlying data sharing principles.

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Appendix

Table 2: Five families of indices based on the morphological, mosaic pattern models, their combination and the connectivity model (adapted from Estreguil *et al.*, submitted)

Notation
i, j refer to forest patches (from 1 to n, where n is the number of patches in a given analysis unit of area A_L) i' refers to morphology shapes (i' belonging to the set of morphology shapes U^{morph}) i'' refers to mosaic shapes (i'' belonging to the set of mosaic shapes U^{mosaic})   The operator $a_{\cdot}$ returns the area of the corresponding shape, so that a_i is the area of the i-th forest patch $a_{i'}$ is the area of the i'-th morphology shape $a_{i''}$ is the area of the i''-th mosaic shape $p_{ij}^{(f,avf,d)} = e^{k \cdot cost_{ij}}$ is the probability of dispersal used in the connectivity model where   • d is the Euclidian (or least cost) distance between 2 patches; $d_{50\%}$ average dispersal distance [m]   • avf is the average friction per distance unit   • $k = \dfrac{\ln(0.5)}{cost_{d50\%}}$ is a constant of probability exponential function; $cost_{d_{50\%}} = avf \cdot d$ cost at prob. 50% A_L is the total landscape area [m²] i.e. the analysis unit

Model	Index description	Index	Complexity
General	Forest (f) area $a^{(f)}$ proportion in landscape (A_L), where $a^{(f)} = \sum_{i=1}^{n} a_i^{(f)} \equiv \sum_{i' \in U^{mosaic}} a_{i'}^{(f)} \equiv \sum_{i'' \in U^{morph}} a_{i''}^{(f)} \le A_L$ Natural/semi-natural lands $a^{(nat)}$ share in landscape, where $a^{(nat)} = \sum_{i=1}^{n} a_i^{(nat)}$	$FP^{(f)} = \dfrac{\sum_{i=1}^{n} a_i^{(f)}}{A_L}$ $NaP^{(nat)} = \dfrac{\sum_{i=1}^{n} a_i^{(nat)}}{A_L}$	$O(n)$

<table>
<tr>
<td>Morphology (2)</td>
<td>Forest (f) share in a MORPH class
$U^{morph} = \left\{ CO^{(f,s)}, BO^{(f,s)}, LI^{(f,s)}, IS^{(f,s)} \right\}$
where $CO^{(f,s)}$ = core$^{(f,s)}$; $IS^{(f,s)}$ = islet$^{(f,s)}$
$LI^{(f,s)} = \text{branch}^{(f,s)} \cup \text{connector}^{(f,s)}$
$BO^{(f,s)} = \text{edge}^{(f,s)} \cup \text{edge of perforation}^{(f,s)}$

with an edge size s (multiple of the spatial resolution of input data)</td>
<td>$$\langle MORPH \rangle P^{(f,s)} = \frac{\sum_{i' \in U^{morph} \cap i' \in \langle MORPH \rangle} a_{i'}^{(f,s)}}{\sum_{i' \in U^{morph}} a_{i'}^{(f,s)}}$$
where
$\langle MORPH \rangle \in U^{morph} \vee \langle MORPH \rangle = LI^{(f,s)}$</td>
<td>$O(\#U^{morph})$</td>
</tr>
<tr>
<td>Landscape mosaic (3)</td>
<td>Forest (f) share in a MOSAIC pattern type
$U^{mosaic} = \left\{ NN^{(f,s)}, N^{(f,s)}, MN^{(f,s)}, SN^{(f,s)} \right\}$
with a moving squared window with side as an odd multiple of side s (multiple of the spatial resolution of input data)</td>
<td>$$\langle MOSAIC \rangle P^{(f,s)} = \frac{\sum_{i'' \in U^{mosaic} \cap i'' \in \langle MOSAIC \rangle} a_{i''}^{(f,s)}}{\sum_{i'' \in U^{mosaic}} a_{i''}^{(f,s)}}$$
where $\langle MOSAIC \rangle \in U^{mosaic}$</td>
<td>$O(\#U^{mosaic})$</td>
</tr>
<tr>
<td>Interface (2 and 3)</td>
<td>Forest share in interior with natural edges
$IF^{(f,s)} = CO^{(f,s)} \cup BO_{NN}^{(f,s)}$
MORPH run with edge size s and MOSAIC with a moving squared-window of side 3s

Similarity to context: Share of a specific MORPH class in a specific MOSAIC pattern type</td>
<td>$$IFP^{(f,s)} = \frac{\sum_{i' \in U^{morph} \cap i' = CO^{(f)}} a_{i'}^{(f,s)} + \sum_{\substack{i' \in U^{morph} \cap i' = BO^{(f)} \\ i'' \in U^{mosaic} \cap i'' = NN^{(f)}}} a_{i' \cap i''}^{(f,s)}}{\sum_{i' \in U^{morph}} a_{i'}^{(f,s)}}$$
$$SI\text{-}\langle MORPH \rangle_{\langle MOSAIC \rangle}^{(f,s)} = \frac{\sum_{\substack{i' \in U^{morph} \cap i' = \langle MORPH \rangle \\ i'' \in U^{mosaic} \cap i'' = \langle MOSAIC \rangle}} a_{i' \cap i''}^{(f,s)}}{\sum_{i' \in U^{morph} \cap i' = \langle MORPH \rangle} a_{i'}^{(f,s)}}$$</td>
<td>$O(\#U^{mosaic})$
+
$O(\#U^{morph})$</td>
</tr>
<tr>
<td>Connectivity (4)</td>
<td>Forest connectivity indices derived from the simplified Power Weighted Probability of Dispersal (s-PWPD) function of the probabilities of dispersal between patches, weighted on the basis of a generic function of the corresponding origin and destination forest patch-areas in the landscape A_L :

• Square Root of Probability of Connectivity (RPC) with d as euclidian or least cost path distance
• Isolation Sensitive Index (IsoSi) with d as least cost path distance
• Un-weighted Average of Probability of Connectivity (APC) with d as least cost path distance</td>
<td>$$\text{s-PWPD} = \left(\frac{\sum_{i=1}^{n} \sum_{j=1}^{n} a_i^{\gamma_1} a_j^{\gamma_2} (1 - \delta_{ij})^{\alpha} p_{ij}}{(A_L / n)^{\gamma_1 + \gamma_2} n (n - [\alpha \neq 0])} \right)^{\beta}$$
<table>
<tr><th>Index</th><th>α</th><th>β</th><th>γ_1</th><th>γ_2</th></tr>
<tr><td>RPC</td><td>0</td><td>$\frac{1}{2}$</td><td>1</td><td>1</td></tr>
<tr><td>IsoSi</td><td>1</td><td>1</td><td>0</td><td>1</td></tr>
<tr><td>APC</td><td>0</td><td>1</td><td>0</td><td>0</td></tr>
</table></td>
<td>$O(n^2)$</td>
</tr>
</table>

<u>Additional note for the Connectivity family of indices:</u>

Whilst the first four families (Table 2 of Appendix) show a computational complexity which is linear with of shapes (forest, morphology or mosaic patches), the indices dealing with connectivity are inherently quadratic with the number of forest patches because the connection between each pair of shapes has to be considered. The *Power Weighted Probability of Dispersal* (PWPD) (Estreguil *et al.*, submitted) family of indices harmonizes their definition. A simplified version of the PWPD family (s-PWPD) can be formulated as:

$$\text{s-PWPD} = \left(\frac{\sum_{i=1}^{n}\sum_{j=1}^{n} a_i^{\gamma_1} \cdot a_j^{\gamma_2} \cdot (1-\delta_{ij})^{\alpha} \cdot p_{ij}}{(A_L/n)^{\gamma_1+\gamma_2} \cdot \sum_{i=1}^{n}\sum_{j=1}^{n} (1-\delta_{ij})^{\alpha}} \right)^{\beta} = \left(\frac{\sum_{i=1}^{n}\sum_{j=1}^{n} a_i^{\gamma_1} \cdot a_j^{\gamma_2} \cdot (1-\delta_{ij})^{\alpha} \cdot p_{ij}}{(A_L/n)^{\gamma_1+\gamma_2} \cdot n \cdot (n - [\alpha \neq 0])} \right)^{\beta} \qquad \textbf{(Equation 1)}$$

where a_i , a_j , p_{ij} refer to the area of the i-th and j-th forest patch and to the probability of dispersal between them, δ_{ij} is the Kronecker's delta and $[\alpha \neq 0]$ uses Iverson bracket. Different values of the exponents γ_1 and γ_2 can generically transform the information on patch areas to consider for example either their product (as in the case of RPC) or only one of them per each pair (IsoSi considers the destination patch area) or even neither of them, as in the case of APC. While all indices are dimensionless and range from 0 to 1, the exponent β allows correcting the distribution of values, as for example RPC does with regard to PC. Finally, the exponent α allows including or excluding autocycles (paths whose endpoints are the same patch).

Connectivity indices' description is reduced to an array-based concise relationship between the vector of patch areas `A` = $[a_1 \dots a_n]$ and the probability of dispersal matrix `P` = $[p_{ij}]$.
Implementing the whole fifth family is straightforward using array-programming languages. For example, using either GNU Octave [Eaton *et al.* 2008] or MATLAB languages with the Mastrave modelling library [de Rigo, 2012a, 2012b], a generic index of the s-PWPD family would be computable by means of a generic reduction operator applied to a graph (whose edge- and node-weights are respectively the probabilities of dispersal `P` and the patch areas `A`) with a codelet composed by a single line of code:

```
graph_reduce( A, P, @(Ai,Aj,Pij)Ai.^g1.*Aj.^g2.*Pij, @()(AL/n)^(g1+g2), @mean, ~a )^b
```

(Equation 2)

which corresponds to the pseudo-code:

$$\texttt{graph\_reduce}\Big(\texttt{ A, P, } @f_1 : (a_i, a_j, p_{ij}) \rightarrow a_i^{\gamma_1} \cdot a_j^{\gamma_2} \cdot p_{ij},\ @f_2 : () \rightarrow (A_L/n)^{\gamma_1+\gamma_2},\ @\texttt{mean},\ \neg\alpha \Big)^{\beta}$$

(Equation 3)

where $@f_1$, $@f_2$, and $@\texttt{mean}$ respectively $\mathbf{R}^3 \rightarrow \mathbf{R}$, $\mathbf{R}^0 \rightarrow \mathbf{R}$ and $\mathbf{R}^{n\,(n-[\alpha\neq 0])} \rightarrow \mathbf{R}$ functions. This extremely compact implementation also enables improving the provenance metadata associated with the indices' data-transformation model (e.g. enhancing the accuracy of INSPIRE lineage field).

$$\text{s-PWPD} = \left(\frac{\sum_{i=1}^{n}\sum_{j=1}^{n} \boxed{a_i^{\gamma_1} \cdot a_j^{\gamma_2}} \cdot (1-\delta_{ij})^{\alpha} \cdot \boxed{p_{ij}}}{(A_L/n)^{\gamma_1+\gamma_2} \cdot \sum_{i=1}^{n}\sum_{j=1}^{n} (1-\delta_{ij})^{\alpha}} \right)^{\beta} = \left(\frac{\sum_{i=1}^{n}\sum_{j=1}^{n} a_i^{\gamma_1} \cdot a_j^{\gamma_2} \cdot (1-\delta_{ij})^{\boxed{\alpha}} \cdot p_{ij}}{\boxed{(A_L/n)^{\gamma_1+\gamma_2}} \cdot n \cdot (n - [\alpha \neq 0])} \right)^{\boxed{\beta}}$$

```
graph_reduce( A, P, @(Ai,Aj,Pij)Ai.^g1.*Aj.^g2.*Pij, @()(AL/n)^(g1+g2), @mean, ~a )^b
```

Table 3: Subset of indices values for the 22 landscape units along the Danube River in Austria at year 2006. They are based on the broad scale CLC data apart for the RPC Connectivity index which is also provided at fine-scale from the European Forest map.

N°	FP	NaP	COP	BOP	LIP	ISP	NNP	MNP	SNP	IFP	SI-BO_{NN}	SI-LI_{NN}	SI-IS_{NN}	RPC CLC	RPC FM
1	0.108	0.113	0.278	0.366	0.320	0.036	0.000	0.272	0.694	0.294	0.044	0.190	0.000	0.045	0.038
2	0.152	0.175	0.319	0.326	0.273	0.082	0.068	0.252	0.608	0.363	0.133	0.200	0.010	0.068	0.058
3	0.267	0.279	0.331	0.342	0.258	0.068	0.032	0.301	0.602	0.346	0.043	0.197	0.000	0.164	0.168
4	0.302	0.305	0.477	0.333	0.169	0.022	0.064	0.404	0.410	0.477	0.001	0.259	0.005	0.219	0.215
5	0.211	0.244	0.795	0.147	0.054	0.004	0.553	0.171	0.175	0.800	0.030	0.144	0.000	0.156	0.140
6	0.056	0.157	0.486	0.345	0.169	0.000	0.076	0.316	0.502	0.486	0.000	0.175	0.000	0.028	0.029
7	0.151	0.154	0.352	0.397	0.217	0.034	0.012	0.301	0.630	0.354	0.006	0.166	0.000	0.090	0.100
8	0.234	0.258	0.336	0.380	0.249	0.035	0.042	0.351	0.513	0.388	0.136	0.189	0.004	0.188	0.175
9	0.291	0.311	0.372	0.350	0.250	0.029	0.051	0.347	0.521	0.390	0.052	0.283	0.002	0.256	0.245
10	0.356	0.365	0.321	0.370	0.295	0.014	0.020	0.385	0.537	0.329	0.020	0.299	0.000	0.303	0.282
11	0.627	0.638	0.662	0.221	0.112	0.005	0.383	0.289	0.221	0.677	0.066	0.283	0.000	0.609	0.615
12	0.492	0.516	0.649	0.259	0.090	0.002	0.236	0.366	0.236	0.657	0.031	0.185	0.000	0.429	0.501
13	0.333	0.346	0.724	0.212	0.063	0.001	0.400	0.271	0.192	0.745	0.097	0.146	0.000	0.274	0.247
14	0.329	0.348	0.668	0.255	0.070	0.007	0.279	0.342	0.199	0.695	0.104	0.126	0.080	0.197	0.230
15	0.360	0.387	0.752	0.210	0.037	0.002	0.321	0.346	0.108	0.764	0.057	0.154	0.206	0.333	0.378
16	0.136	0.160	0.564	0.325	0.107	0.004	0.252	0.336	0.274	0.647	0.255	0.252	0.054	0.095	0.066
16	0.295	0.326	0.727	0.210	0.054	0.009	0.448	0.243	0.148	0.779	0.245	0.271	0.048	0.209	0.216
18	0.383	0.398	0.472	0.317	0.193	0.018	0.182	0.301	0.449	0.484	0.039	0.239	0.000	0.289	0.304
19	0.434	0.443	0.590	0.294	0.113	0.004	0.136	0.421	0.274	0.604	0.048	0.199	0.112	0.402	0.454
20	0.396	0.406	0.656	0.244	0.096	0.004	0.266	0.331	0.235	0.667	0.045	0.261	0.000	0.366	0.365
21	0.125	0.125	0.591	0.272	0.124	0.013	0.196	0.329	0.338	0.592	0.005	0.091	0.000	0.069	0.073
22	0.239	0.240	0.747	0.197	0.056	0.000	0.395	0.269	0.180	0.754	0.031	0.110	0.000	0.138	0.138