Satellite Observation Requirements of ecosystem extent and fragmentation

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Acronyms and Abbreviations

CBD	Convention on Biological Diversity
COP	Conference Of the Parties
EBV	Essential Biodiversity Variable
EEF	Ecosystem Extent and Fragmentation
EO	Earth Observation
ESA	European Space Agency
FPAR	The Fraction of Photosynthetically Active Radiation
GEO-BON	Group on Earth Observation – Biodiversity Observation Network
GPP	Gross Primary productivity
HR	High Resolution
IPBES	Intergovernmental Platform on Biodiversity and Ecosystem Services
LARCH	Landscape Ecological Analysis and Rules for the Configuration of Habitat (model)
MODIS	MODerate-resolution Imaging Spectroradiometer
NBSAP	National Biodiversity Strategy and Action Plan
RS	Remote Sensing
RS-enabled EBV	Remote Sensing enabled Essential Biodiversity Variable
PROBA-V	Project for On-Board Autonom-Vegetation
SDG	Sustainable Development Goals
SOR	Satellite Observation Requirement
SRL	Science Readiness Level
TM	Thematic Mapper

Terminology

Contextual definition of biological, ecological, remote sensing and other terms as used in the document.

Term	Definition
Accuracy	In this document, accuracy is described as the closeness of variable values estimated from remote sensing to *in situ* measurement.
Biodiversity	The variability among living organisms from all sources (including terrestrial, marine and aquatic ecosystems) and the ecological complexes of which they are part, including diversity within and between species and of ecosystems.
Biome	A biome is a specific geographic area where an assemblage of organisms is determined by large-scale climatic and vegetation characteristics. A biome can be made up of many ecosystems.
Biophysical Attributes	A biophysical attribute is a biotic and abiotic component of an ecosystem (e.g., leaf area index, ice-cover, land cover, urban footprint or vegetation height) covering the Earth that incorporates and support biodiversity and has an influence on organisms survival, development, and evolution.
Ecosystem	A functional unit or system of the earth's surface that is the whole system including the organisms, the physical factors and their interaction that form the environment (Basu and Xavier, 2016)
Ecosystem fragmentation (EF)	Ecosystem fragmentation is the process by which the division of large, continuous habitats into smaller, more isolated remnants, might result in biodiversity loss

Ecosystem function	Processes related to productivity/respiration (biomass build-up function), decomposition (biomass breakdown function), energy transfer/loss and nutrient cycling in an ecosystem (Myster, 2001).
Ecosystem structure	The minimal pattern of organization necessary for an ecosystem function to operate (Myster, 2001).
Essential Biodiversity variable	A variable that is measurable at particular points in time and space and is essential to document biodiversity change.
Satellite observation requirement	The types and detail level of a set of attributes of RS-enabled EBVs that are required by the user community for biodiversity assessment and monitoring.
Remote Sensing enabled EBVs	EBVs that are directly measurable or derived from Earth observation satellite data.
RS-enabled EBV product(s)	A product or multiple of products obtained through processing remote sensing data that potentially informs about the RS-enabled EBV.
Resolution	The ability of a remote sensing device to detect subtle variation regarding energy (radiometric resolution), space (spatial resolution) and time (temporal resolution).
Satellite RS	Remote sensing (RS) data acquired through earth orbiting satellites.
Scale	The term scale in this document refers to the scope or spatial extent of the RS-enabled EBVs observation but not to the relationship between distance on a map and a corresponding distance on the ground.
Spatial configuration	Two dimensional geographic distribution of land cover patterns
State variables	A set of variables that can be used to describe the "state" of a dynamic system. In the context of a terrestrial ecosystem, state variables are those sets of variables that describe sufficiently the ecosystem to determine its future behavior in the absence of any external forces affecting the ecosystem.
Terrestrial ecosystem	Communities of organisms and their environments that occur on the land masses of continents and islands (Chapin et al., 2002).
Thematic accuracy	The degree to which the non-positional characteristic of a spatial data entity (attributes) derived from radiometric information agree with *in situ* observations.

1. Introduction

1.1. Purpose

This document outlines the requirements for satellite observations of RS-enabled EBVs on the structure and function of terrestrial ecosystems. Terrestrial ecosystems are marked by high variability in bio-geophysical and optical properties, and there is no unified theory describing those properties and their changes over time. Satellite observations have a valuable contribution in providing a synoptic picture for studying and monitoring biodiversity change. Terrestrial ecosystem function and structure as characterized by habitat structure, extent, fragmentation, a composition by functional type, net primary productivity, canopy biochemical traits, FPAR, disturbance regime, etc., are recognized as RS-enabled EBVs by GEO-BON. The workhorse for monitoring of these terrestrial ecosystems structural and functional EBVs is Earth Observation data obtained from optical, thermal, Radar and LiDAR sensors, as well as *in situ* measurements. The potential contribution of satellite-based datasets and derived products have to be exploited, evaluated and benchmarked so that space agencies could provide observations for terrestrial ecosystem structural and functional RS-enabled EBVs on an increasingly routine basis. Therefore, this document focuses on identifying the required set of satellite observation requirements to assess and monitor the state/change of terrestrial ecosystem structure and function at national, regional and global scales with consistency in space and time. The following sections provide details on the datasets and products required to monitor terrestrial ecosystem extent and fragmentation.

1.2. Scope

The scope of this chapter is to assemble the satellite observation requirements for the RS-enabled EBV- ecosystem extent and fragmentation of terrestrial ecosystems. The aim is to identify the observation requirements to support scientific investigations aimed at improving our ability to assess and monitor biodiversity, particularly, ecosystem extent and fragmentation. Overall, this document provides the observational requirements needed to monitor ecosystem extent and fragmentation properties of terrestrial ecosystems that are of most significant interest concerning biodiversity change.

1.3. Target audience

The Satellite Observation Requirements document analyzes the current status and requirements of remote sensing-based EBVs. It thereby supports the efforts of the Convention on Biological Diversity (CBD), Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) and Group on Earth Observation – Biodiversity Observation Network (GEO-BON), to generate a global monitoring and knowledge base, with which to report on the status and changes in terrestrial biodiversity, ecosystem structure and ecosystem function. Additionally, this document is aimed at benefiting space agencies by identifying the key satellite observation requirement for terrestrial biodiversity monitoring and change detection within the context of EBVs. The Satellite Observation Requirements document is likewise addressed to local, national and international government and not-for-profit organizations tasked with biodiversity monitoring, assessment and target reporting. Here, it specifically demonstrates how RS-enabled EBVs and the indicators derived thereof, can be used to inform biodiversity monitoring and change detection, and simultaneously contribute towards addressing issues pertaining to minimizing the costs of *in situ* data collection, analysis and reporting.

1.4. Method

The document is assembled based on a review of the literature on terrestrial ecosystem research activities supported by experts' opinion. First, a generic template for the observation requirement was developed, reviewed and filled through a literature review. Second, the list of observation requirements considered and its content was reviewed in an expert workshop. The satellite observation requirements of the RS-enabled EBV were then synthesized after the expect workshop and revised including the experts' opinion. Finally, the observation requirement document was further improved through open review by expert groups of remote sensing and biodiversity community.

1.5. Clearing up the ambiguity

Scale: The word scale has multiple meanings in various disciplines, which leads to an ambiguous usage of the term-scale and thus an appropriate qualifier has to be used for a more productive approach (Schneider, 2001). In remote sensing, the scale might be resolution and can be thought of as the smallest objects being distinguished by sensors. For ecology, the scale is likely to be grain, which is the measured size of patches. In environmental studies, the scale could be, the area or time interval in which the parameter of interest is homogeneous. While in cartography, the scale is defined just as the ratio between the distance on the map and the ground (Wu and Li, 2009).

Wu et al. (2006) proposed a three-tiered conceptualization of scale, which organizes scale definitions into a conceptual hierarchy that consists of the dimensions, kinds, and components of scale (Figure 1). Dimensions of scale are most general, components of scale are most specific, and kinds of scale are in between the two. This three-tiered structure seems to provide a clear picture of how various scale concepts differ from or relate to each other (Wu et al., 2006). Within the hierarchical scale definitions, the scales used in this document fall under observation scale (scale of measurement or sampling) kind and presented as spatial, spectral, and temporal resolution.

i. **Spatial resolution**: refers to the size of the area covered by a pixel in a satellite image. In optical and thermal remote sensing, each pixel in an image corresponds to a patch on the Earth's surface. It is also known as 'ground resolution' and is usually expressed in meters.

ii. **Spectral resolution**: refers to the wavelength intervals. It describes the ability of a sensor to define narrow wavelength intervals. The finer the spectral resolution, the narrower the wavelength range for a particular channel or band. The following categories are used in setting the requirement for spectral resolution in accordance with the characteristics of the RS-enabled EBV:
    - Panchromatic – 1 band (black and white)
    - Multispectral – 4 to ±15 bands

- Hyperspectral – hundreds of bands

iii. **Temporal frequency (resolution)**: is the required interval between two successive instances of an RS-enabled EBV measurement in the same area and often expressed on an hourly, daily, weekly, monthly, yearly basis depending on the nature of the RS-enabled EBV.

1.6. Chapter outline

The observation requirements are structured into 11 sections and defined for each RS-enabled EBV separately. The structure and content of the parts are as follows:

1.6.1. Definition of the RS-enabled EBV

In this section, the most widely accepted and scientific description of the RS-enabled EBV is described and introduced in clear terms. For some RS-enabled EBVs, several sub-definitions might exist among the different communities, and this chapter shall include separation where needed, and relation with other similar EBVs are highlighted.

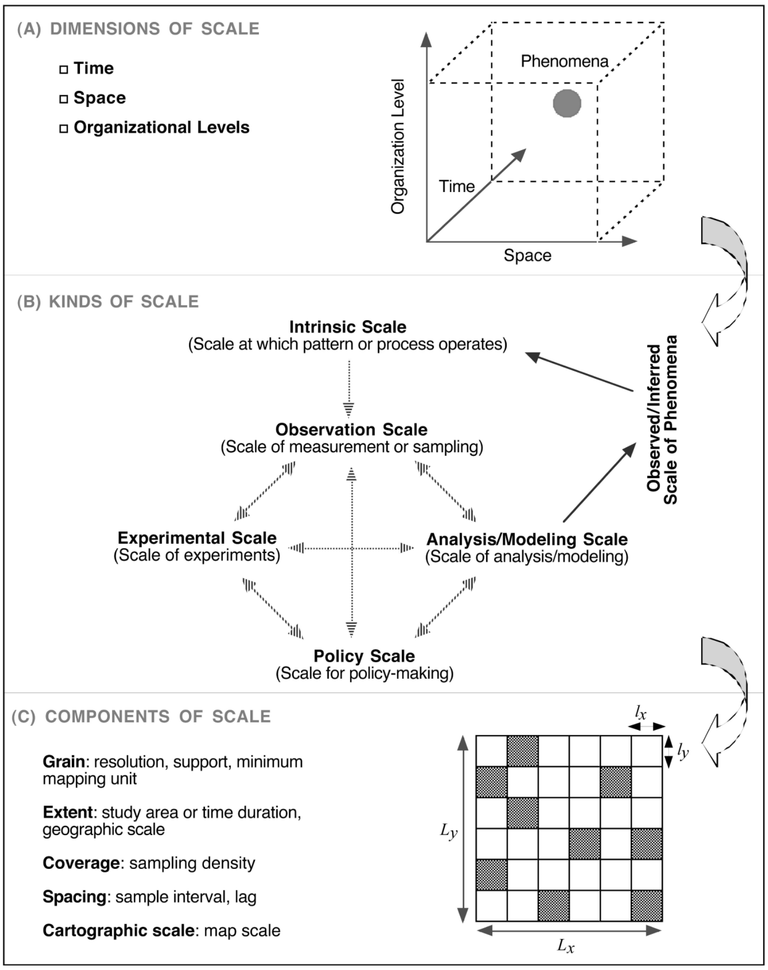

Figure 1: A hierarchy of scale concepts: (A) dimensions of scale, (B) kinds of scale, and (C) components of scale (from Wu et al., 2006).

1.6.2. The role of the RS-enabled EBV in biodiversity assessing and monitoring

Section 2 introduces the need and use of the RS-enabled EBV for biodiversity monitoring and assessment. It includes current (and future) areas of application, including the use of the data set. The contribution of the RS-enabled EBVs in assessing biodiversity targets (COP-CBD, 2010) and the sustainable development goals indicators (IAEG-SDGs, 2016) are discussed. The relationship between the RS-enabled EBV with other biological, environmental and climate variables is also reported in this section.

1.6.3. Spatiotemporal coverage

In section 3, the target geographic regions where the RS-enabled EBV is contributing to biodiversity assessment and the temporal observation coverage (inter and intra-annual observation requirements including seasonality) needed for effective monitoring is defined. Many RS-enabled EBVs cannot contribute equally to all biomes (see page 5 in part I of the SOR for biome definition) and therefore, this section shall highlight where the RS-enabled EBV's contribution to the biodiversity assessment is highest. The optimum length of observation period required is identified based on the RS-enabled EBV characteristics in order to provide reliable long-term trends and capture seasonal variability. Detailed spatial and temporal observation requirements are contained in section 1.5.5.

1.6.4. Remotely sensed EBV Products

This chapter defines the bio-geophysical and optical properties that shall be computed from remote sensing data and made available as data products to assess a specific RS-enabled EBV. One or several properties might be needed to represent the RS-enabled EBV and can include current available or future products. A matrix of properties with a short definition including units shall be listed.

***RS-enabled EBV* property**	**Definition [unit]**
...	...

1.6.5. Spatial extent and temporal frequency requirements

This section discusses the general framework regarding the spatial and temporal resolution required for assessing and monitoring biodiversity with the RS-enabled EBV, on different geographical scales (from global to local biodiversity assessments). The application and use of products' and their dependence on the spatial resolution are discussed at different geographic scales such as global, regional, landscape, catchment, local habitat or individual (species) levels (if applicable). Temporal resolution shall be addressed in terms of how often the different products (and their related satellite observations) need to be calculated (e.g., once a year, monthly weekly, daily), what should be the frequency of observations per product and what is the temporal accuracy needed to detect changes (e.g., detect changes within a week). Please note that the temporal frequency requirements for satellite observations might be different from the temporal resolutions of the product (RS-enabled EBV property).

The section shall also indicate if these spatial and temporal observation requirements are changing between biomes or regions. Also, a critical assessment of the benefit or loss of information when changing the required temporal or spatial resolution is addressed. For instance when the temporal or spatial resolution change by a given factor (for example from daily to weekly observations or from 10 to 30m spatial resolution), the effect on the information content of the EBV products are described in this section.

1.6.6. Transferability of retrieval approaches

a) Transferability among biomes

This section highlights the possibility of the transferability of the retrieval approaches depending on biomes with the scope to produce products with global coverage (with the restrictions mentioned in Section 3). Possible hurdles occurring when one retrieval approach is transferred to another biome or ecoregion are explained.

b) Transferability across scale

Differences and adaptation needed when changing spatial resolution are discussed in this subsection.

1.6.7. Calibration and Validation

Section 7 addresses the importance of independent observations that are required for the calibration and validation of satellite data derived RS-enabled EBV. Datasets for validation or calibration might be for instance in-situ data, observation networks or airborne/ground-based remote sensing data, citizen science datasets, etc., that are suitable for the validation and calibration of global data products. Issues regarding the estimation of accuracy and precision of the RS-enabled EBV data product are addressed, and challenges when combining the different data types are discussed.

1.6.8. Existing data sets and performance

Existing datasets of the RS-enabled EBV with a focus on global products are explained in this section, including the approach for generating these RS-enabled EBV products. The part includes a brief explanation of the used input data (e.g., satellite sensors, type of satellite observations, quality level), spatial/temporal resolutions of the datasets, and use and application. The independent data that has been used for calibration/validation (e.g., *in-situ* data) is also described as well as the overall product accuracies/uncertainties. The chapter also includes an outlook of potential future (new) approaches and/or used sensors that might be developed.

1.6.9. Feasibility, scientific and technology readiness levels

A critical discussion regarding the feasibility and current limitation(s) of remote sensing to develop the RS-enabled EBV is made. The inherent limitations of using remote sensing and the combination of complementary data sets, to overcome these limitations, are assessed. The current status and the scientific and technology readiness level are estimated through analysis of the science readiness level (SRL) matrix.

1.6.10. Summary and outlook

The overall observation requirements of the RS-enabled EBV are briefly summarized. Opportunities and challenges in the future, which would extend or hinder the capacities to meet the satellite observation requirements identified and presented here. Recommendations on when and how the observation requirement should be updated are specified.

1.6.11. Specific measurement requirements summary

Summary of the satellite measurement specifications such as spatial, spectral and temporal resolutions together with delivery format, and other specific measurement requirements is presented in this section.

2. Ecosystem Extent and Fragmentation Satellite Observation Requirement Definition and Analysis

2.1. Definition of Ecosystem extent and Fragmentation

Reducing the rate of habitat loss and fragmentation, and eventually halting it, is essential to protect biodiversity and to maintain the ecosystem services vital to human wellbeing (Aichi Targets 5 and 14 respectively). Fragmentation, next to ecosystem distribution, land cover, and vegetation height (VH), is related to the EBV 'Ecosystem structure' or habitat structure (Skidmore et al., 2015). Monitoring EBV Ecosystem structure can be supported by remote sensing (RS) through the collection of information on the spatial distribution of habitats, how fragmented they are, and the impact on the distribution of species in those habitats.

Within the expert workshop with a focus on the prioritization of RS-enabled EBVs (Zurich, February 2018), the EBV fragmentation was defined as: "The EBV fragmentation should measure structural ecosystem discontinuity in a defined time-space. This can include connectivity, core, and edge characterizations, calculated across a range of scales as long as the EBV is globally applicable, scale-free, and ecologically meaningful."

2.2. The role of the RS-Enabled EBV in assessing and monitoring biodiversity

There is broad recognition that fragmentation affects both biodiversity and ecosystem functioning (Haddad et al., 2015). The fundamental role of habitat in limiting species richness is emphasized by the fact that habitat loss is the main cause of declining biodiversity worldwide (DAVIS, 2006, Hanski, 2015, Assessment, 2005, Pimm et al., 2014, Haddad et al., 2015). Habitat loss usually is causing habitat fragmentation (Tscharntke et al., 2012), and according to Hanski (2015), the fragmentation poses an extra threat to biodiversity, in addition to and on top of the threat posed by the declining total amount of habitat. The effect of direct habitat loss is larger than changes in habitat configuration (Fahrig, 2003). However, Didham et al. (2012) show that indirect and interaction effects may be the dominant cause of the ecological changes, which are mostly solely assigned to the loss of habitat.

Natural habitats in most parts of the world continue to decline in extent and integrity, although there has been significant progress to reduce this trend in some regions and habitats. This decline at landscape scale of habitat loss and increased isolation is widely known to be important to forecast the dynamics of species populations and communities (Macarthur and Wilson, 1967, Diamond, 1982, Caspers, 1984, Schoener and Spiller, 1987). A synthesis of fragmentation experiments spanning multiple biomes and scales, five continents, and 35 years demonstrates that habitat fragmentation reduces biodiversity by 13 to 75% and impairs key ecosystem functions (Haddad et al., 2015). Even more, the effects of habitat fragmentation on populations, communities, and ecosystems can take up to decades before being significantly evident, indicating that current shrinking habitats will continue to lose species and see declines in ecosystem functions (Krauss et al., 2010, Hanski, 2011, Wilson et al., 2016).

Wilson et al. (2016) summarized the latest key findings related to the loss and fragmentation of habitat. As habitat fragmentation ultimately is a derivative from habitat loss, "three broadly defined mechanisms mediate the ecological consequences of fragmentation:

1. Effects related to the loss of habitat area.
2. Effects related to changes in the spatial configuration of the landscape, such as isolation.
3. Effects related to indirect or interaction effects of habitat loss and changes in spatial configuration, and to the interaction of fragments with the non-habitat areas surrounding it."

There is no scientific evidence that, at global and landscape levels, human-induced fragmented natural- and semi-natural ecosystems, will show higher biodiversity values, compared to comparable non-fragmented systems (Haddad et al., 2015, Liu et al., 2018, Wilson et al., 2016). To a specific extent fragmentation of original natural habitats is creating opportunities through the creation of new habitat types[1] for species related to more fragmented ecosystems. E.g., species bound to forest edges will, up to a certain amount of fragmentation, see an increase of their habitat "forest edge." However, correspondingly, the habitat related to species needing a vast amount of forest interior will decline. Unfortunately, much of the literature testing for the influence and dependency between the effects of edge and area has been confounded, which makes a single deduction very difficult (Fletcher et al., 2007).

Biodiversity can be measured on the basis of the population viability of species related to the quality and extent of habitats (Opdam et al., 2003, Verboom and Pouwels, 2004). The fragmentation of habitats plays a paramount role in the viability of species since populations in small patches are more likely to go extinct than those in large patches (Caspers, 1984, Diamond, 1982, Hanski, 1994a, Schoener and Spiller, 1987). Many empirical studies have demonstrated that isolated habitat patches are less likely to become colonized than well-connected patches (Hanski, 1994b). At the landscape level, the fraction of available habitat that is occupied by a species in a certain time-space is an important indicator of its viability. This "metapopulation" concept is based on the dynamics of animal species with a shifting occupation over habitat patches in fragmented landscapes (Hanski, 2011, Opdam et al., 2003). It applies most naturally to highly fragmented habitats, such as networks of small meadows, but the processes of local extinction and colonization occur in any kind of habitat. When the habitat is continuously distributed, movements of individuals are unrestricted, and many species can be expected to occur practically everywhere. Since habitat loss and fragmentation impair free movements, it has adverse consequences for the distribution and abundance of species, and so for the prediction of their occupation of the remaining habitat fragments (Hanski, 2011). As a resultant Hanski (2015) explains that to be ecologically meaningful, the

[1] "habitat type" can be defined as a unit of land or water, consisting of an aggregation of biotic and abiotic characteristics having equivalent structure, function, and responses to disturbances

fragmentation analysis of landscapes should focus on the effects of habitat configuration, isolation, and dispersal capacity on the persistence of organisms across habitats types

EBV fragmentation can be used by stakeholders such as governments, NGOs, research centers, ecosystem service providers, that are concerned by the decline of biodiversity in fragmented landscapes and are for example involved in the impact assessment of new transport infrastructure on the sustainability of populations and or are involved in finding mitigating solutions for fragmentation such as conservation landscapes or building ecological corridors (Hanski, 2011, Opdam et al., 2003). Improved landscape coherence is increasingly considered a viable management strategy to maintain biodiversity, ecosystem functions, and services (Ziter et al., 2013). For instance, (Ziter et al., 2013) found that carbon stocks can be increased by considering species-specific management, improving habitat coherence, and taking care of functional diversity in forest ecosystems. Additionally, the significant contributions of small forest fragments to regional diversity and service provision emphasize the important role that these fragments can play in conservation efforts (Ziter et al., 2013).

2.3. Spatiotemporal coverage

Both the spatial and temporal resolution to be selected is dependent on the target level (geographical extent), and the habitat under consideration and can vary from a kilometer to meter resolution, and from yearly to every decade. In theory, an ecosystem (and its related fragmentation component) can be as small as a few amphibians living in some small scattered ponds, or as large as the Amazon tropical rainforest stretching across thousands of kilometers.

To be globally measurable, global-scale monitoring of habitat fragmentation will and must, therefore, be related to global land cover monitoring activities. The status of current global land cover products vary in resolution between 20 meters and 300 meters and is being updated at a maximum frequency of once a year. From a species perspective this update frequency at a spatial resolution of 10-30m is applicable for a) a large range of species covering major species groups, b) observable (major) changes in ecosystem patterns at global scale and c) related to minimum temporal shifts in population fragmentation patterns (Opdam et al., 2003).

2.4. Remotely sensed EBV products

The main basic EBV product used as a source to calculate fragmentation of ecosystems is habitat suitability. Recent years have seen a massive increase in the availability of regional- and global scale spatial data sets to support the quantification and extent of habitats; these include detailed global data of elevation at 30-m resolution, land-cover data, and forest cover at 30-m resolution (Brooks et al., 2019, Ocampo-Penuela et al., 2016).

Based on these data, Habitat Suitability Indices (HSI) are a representation of the suitability of habitat for a given species or group of species representing an ecosystem, based on an assessment of habitat attributes; HSI's generally derive a single composite index by combining multiple variables (such as land cover, soil type, and elevation) ((Schamberger et al., 1982, Thuiller and Münkemüller, 2010). Rondinini et al. (2011) show a clear application of the combined use of coarse resolution global land cover data (10x10km) and information on species elevation preferences, to globally assess how land cover change alters the global extent of suitable habitat of species and their risk of extinction. Another global application is the mapping of the extent of suitable habitat as showed by Brooks et al. (2019) for the IUCN Red List of Threatened Species. This Red List assesses the extinction risk of approximately 100000 species, including documentation of a range map, habitat, and elevation data for each species. These range, habitat and elevation data were matched by Brooks et al. (2019) with terrestrial land cover and elevation datasets to map the species' HSI.

Currently, there are many methods to quantify the fragmentation of habitat (Hanski, 2011, Opdam et al., 2003). Habitat coherence, being the antonym of habitat fragmentation, is often measured using simple structural metrics, e.g., Euclidean distances between habitat patches. Functional metrics calculated with more advanced (meta-)population models account for behavioral aspects of species or ecosystems (Hanski, 1994a). While simple structural metrics can be used to investigate local or small-scale effects on species diversity, landscape-scale fragmentation analyses should consider species behavioral aspects by using more complex functional ecological scaled metrics (Vos et al., 2001). Such species' behavioral aspects can be summarized in a so-called 'eco profile' or 'flagship species': a set of species demanding similar dimensions of ecosystem coherence in order to persist at a regional scale. "Similar" is meant herein a relative sense and refers to the similarity in choice of a) required ecosystem type(s), b) area requirements, and c) dispersal capacity of the species, encompassed by a single ecoprofile, relative to the difference between species classified in other ecoprofiles (See figure 2)

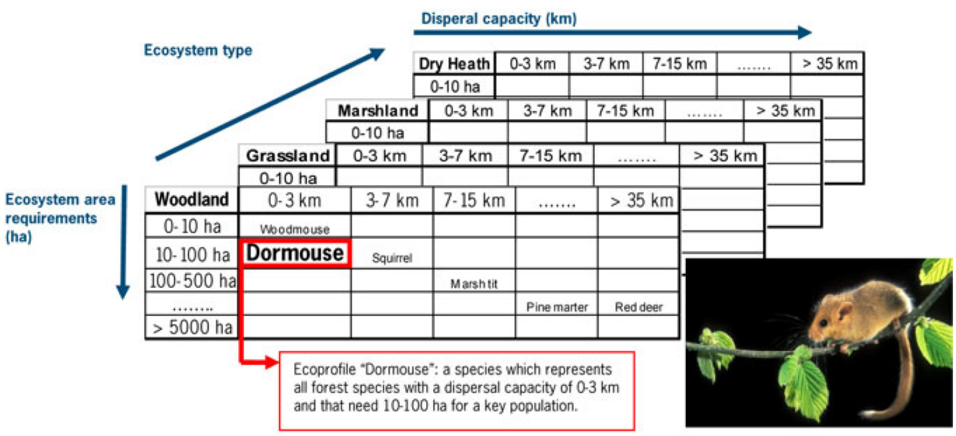

Figure 2: Design of three-dimensional eco profile matrices, one per identified ecosystem type, based on the carrying capacity of regional ecosystems (vertical axis), and the inter-patch distance that can be crossed during dispersal. Species are assigned to cells in the matrix by their habitat preference, individual habitat area requirements, and dispersal capacity. Each cell in the matrices represents one ecological profile (Opdam et al 2008).

In general, maps showing cohesion of habitat areas can be used to derive clusters of connected patches, to construct ecological networks, and thus evaluate fragmentation of the landscape. Patterns of cohesion values can be used for planning corridors between local patches or to improve weaker spots in networks. Depending on the application and species different thresholds for habitat coherence levels can be set to create such clusters forming networks of non-fragmented habitat. In this way, the effects of habitat configuration, isolation, dispersal capacity on the persistence of organisms across habitats types can be evaluated (Hanski, 2015, Opdam et al., 2003).

The main products of the RS-enabled EBV habitat fragmentation are quantitative maps that show the spatial distribution of the level of fragmentation of a specific ecosystem. Since fauna species can require a combination of land cover types in their habitat (See HSI definition above and in table 1), it should be possible to combine individual habitat-class based spatial cohesion maps to one based on a specific composed habitat. Quantitative maps of individual habitat types should be combined as a stack of spatial-temporal datasets based on remotely derived habitat types using multiple dispersal distances (if the metric is sensitive for those distances). In principle, this approach can be applied to many types of connectivity, core and edge metrics (McGarigal et al., 2012), as long as such combinations are considered ecological meaningful. Some metrics, e.g., contagion (McGarigal et al., 2012) need a specific final combination of habitat types before they can be calculated (McGarigal et al., 2012, Soille and Vogt, 2009). For such metrics, a stacked approach is not feasible.

A stacked calculation method on an RS-derived (multi-)habitat-type product gives maximum flexibility. Not only is the spatial cohesion calculated per habitat or land cover type, but also a tailor-made combination of the individual results for multiple specific flagship species, species groups or ecosystems can be assessed. This stack of spatial cohesion metrics (Figure 3) can be created using different land cover/habitat products. Table 10 summarizes typical properties that are used and useful for habitat fragmentation studies.

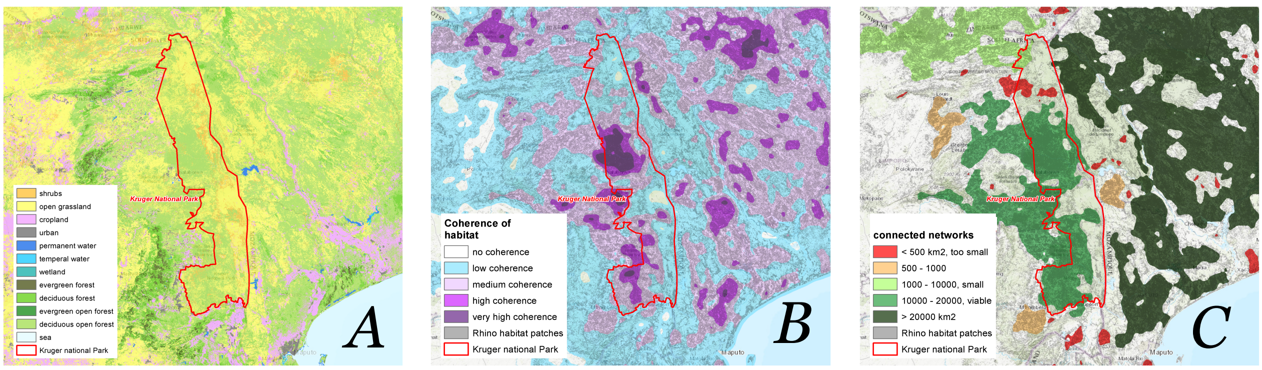

Figure 3: Example of a typical habitat fragmentation analysis (following the method as applied in Bruinderink et al. (2003): tropical / sub-tropical shrubland habitat area extent (A) in Kruger National Park, South Africa. Based on a selection of habitat classes (shrub and open forest) a spatial cohesion output map (B) can be calculated, for a specific fragmentation distance (10000m). Connected clusters based on species-specific thresholds can then be derived (C).

Table 1: Typical definition of fragmentation properties

Fragmentation property	Definition
Input A: Classified land-cover	*Classified land-cover relevant to the ecosystem to be analyzed. Fauna species can require a combination of land cover types in their habitat varying in potential use [Class A, Class B, etc., / Year]*
Input B: Abiotic specification (optional)	*Factors needed to describe the ecosystem to be analyzed. E.g. Water extent/duration of flooding [Class X, Class Y, etc., / Year]*
Input A×B: Habitat Suitability (HSI)	*A single composite index by deriving potential suitability directly from one variable (e.g. 'Input A'), or combining multiple variables (e.g., a combination of 'Input A' × 'Input B.' The result is the potential distribution of suitable habitat for a flagship species, species group or ecosystem. [Unit HSI 0-1].*
Output A: Fragmentation • *Output A1: simple structural metrics* • *Output A2: Functional spatial cohesion metrics*	*Spatial-temporal distribution of the level of fragmentation of a specific ecosystem* • *Connectivity, core and edge metrics aggregating the level of structural fragmentation of a specific ecosystem [Unit is metric dependent]* • *Quantitative maps of Habitat Coherence accounting for behavioral aspects of species or ecosystems. [Unit is related to, e.g. fraction of successful dispersers, and average patch carrying capacity]*
Output B: Habitat Clusters Network Strength	*Networks of non-fragmented habitat showing potential to maintain a sustainable population. Only possible in combination with A2 "Functional spatial cohesion metrics" [Unit e.g. population size]*

2.5. Spatial extent and temporal frequency requirements

Depending on the aims of the user and the level of detail of the available input data, both regional species-specific fragmentation analysis, as well as continental and global-wide generalized assessments of fragmentation are possible (Bruinderink et al., 2003, Opdam et al., 2003). To support this, the preferred method to calculate fragmentation should be generically applicable to cover a wide range of applications, ecosystems and -profiles. A rule of thumb is that the scale of the landscape as perceived/used by the species is decisive for the scale of the needed input data (Opdam et al., 2003). Generally, to be useful at regional/landscape level a spatial resolution of 10-30m is applicable for a broad range of applications and Eco profiles (Opdam et al., 2003, Hanski, 2011, Hanski, 1994b). The analysis uses species-specific lists of suitable habitats available within the scientific community (and the amount of habitat required for one reproductive unit), dispersal characteristics (which means the maximum distance between habitat sites for targeted fauna species), as well as the permeability of the landscape matrix between habitat sites (sensitivity to barriers).

Since the EBV Fragmentation is strongly related to species- and biodiversity monitoring purposes, a yearly (or longer) temporal resolution or time interval of the data is generally sufficient. In specific cases, a shorter (e.g., seasonal) interval can be necessary to capture specific fragmentation effects related to changes in seasonal dependencies within the ecosystem. As stated in the introduction, the effects of habitat fragmentation on populations, communities, and ecosystems can take a long period (Hanski, 2011, Wilson et al., 2016, Krauss et al., 2010). Therefore a shorter time frame than one year seems not relevant for applying the EBV a global scale.

2.6. Transferability of retrieval approaches

a) Transferability across biomes

Human-induced fragmentation is present in all globally defined biomes (Haddad et al., 2015). However, the scale at which fragmentation is observable can vary significantly per biome, ecosystem or habitat type, within and between geographical regions. E.g., forest cover loss can be observed at the global level with reliable measurements using intervals of yearly or fewer datasets, showing national observable deforestation patterns in the tropics, but also high intensive forest management in European Boreal forests, causing local temporal shifts in fragmentation patterns (Hansen et al., 2013). Opposite to such rapid shifts in land cover patterns is, e.g., the climate-induced composition change of vegetation patterns within an ecosystem. The arctic tundra is a much more gradual process that is observable at a more local level over a timeframe of multiple years causing a more gradual shift in (fragmentation of) suitable habitats for species over time.

The scope is to produce products with global coverage with transferable retrieval approaches. The most challenging part when upscaling or transferring the EBV fragmentation to other biomes is to relate the suitable species or ecotypes to the observed or expected fragmentation process in an ecosystem and having the correct input data related to the selected (umbrella) species (Opdam et al., 2003, 2008, Haddad et al., 2015). Since the measured fragmentation should be related to the scale of the landscape as used by species, the scale of the needed input data and the used parameters in the analysis should therefore also always be connected to each other (Opdam et al., 2003, Hanski, 2011).

b) Transferability across scales

To date, GeoBON's process of identifying and prioritizing EBVs has largely been based on expert knowledge about globally relevant biodiversity measurements (Navarro et al., 2017), making the global application the starting point to develop also the EBV Fragmentation. However, GeoBON is aiming at a consistent set of globally applicable EBV-metrics with (RS-) data to be quickly mobilized and standardized across scales, transferring these EBV's into local and national organizations and their own monitoring schemes (Navarro et al. 2017). Model accuracy is likely to increase with decreasing raster cell size, so the choices of what data to include in HSI modeling is likely to increase at a regional-local scale where fine resolution (RS-)data is available (Manzoor et al., 2018). As explained by Manzoor (2018), when modeling the potential habitat extent of *Rhododendron ponticum* in Wales, the choice of resolution and the number of variables in an HSI analysis is not just species-dependent. They tested model performance and transferability to a different geographical area by varying the raster cell size (50m, 300m, and 1km). Based on species relevant multiple RS-derived variables (land cover, distance to water, elevation slope, aspect and a series of climate variables), they found that use of the coarser bioclimatic variables could negatively affect the predictive potential of the HSI model since the used biophysical variables are likely to be more important determinants of suitable habitat extent at fine spatial scales. However, successful model transferability to other regions was found to be optimal at medium raster cell size, indicating that the coarser climatic variables may have a greater effect in determining the potential suitability for a species over a larger spatial scale (Manzoor, 2018).

The responses of the fragmentation algorithms on changing raster cell size vary significantly among different landscape metrics and across different landscapes (Uuemaa et al., 2005). Metrics like 'contagion' and 'mean euclidean nearest neighbor distance' (McGarigal et al., 2012) are directly dependent on raster resolution; therefore, they should be used and interpreted carefully in case of changing the resolution of the input data (Uuemaa et al., 2005). Also, most known core and edge indicators based on RS-data are highly sensitive for variations in resolution of the used product (McGarigal et al., 2012, Riitters et al., 1995, Uuemaa et al., 2005), which makes it also more difficult to transfer, calibrate or validate these metrics across a range of scales biomes and RS-products.

Some metrics, especially in the group of (focal) area-based metrics, are much less sensitive for differences in raster resolution as long as the minimum fragmentation area and distances are kept larger than the raster cell-size, and input habitat is comparably defined across different spatial resolutions (are derived in a comparable manner, from similar sources) (Brown et al., 2004). This ensures that the total habitat area share is kept as equal as possible, less effecting the metric results. E.g., the Hanski fragmentation algorithm (Hanski, 1994a) calculates for each raster cell the amount of habitat-area in its surroundings. Habitat further away is accounted for less than habitat close by, using Hanski's negative exponential function for cohesion related to a given (species dispersal) distance. As such this metric is accounting for fragmentation, both related to changes loss of habitat area and the spatial configuration of the landscape, the isolation of habitat. As long the dispersal distance of the species of interest is larger than the used resolution of the raster product this metric enables us to calculate and compare fragmentation in both local as continental /global context (Pouwels et al., 2002). Eupen et al. (2001) conclude for the Mean Proximity Index (a similar focal-area-based metric (McGarigal et al., 2012), that a factor 10 between cell resolution and fragmentation distance is sufficient to eliminate the raster resolution effect completely. For example, based on a remote sensed based input product with a 10x10m resolution, one should focus on an output EBV product with a minimal fragmentation distance of around 100m or a minimum fragmented area of 0.1 hectares.

2.7. Calibration and validation

The total amount of habitat and the degree of fragmentation are typically closely correlated; which makes it hard to tease apart their effects with observational data (Fahrig, 2003, Hanski, 2015, Wilson et al., 2016), however, several approaches have been tested in the past to come with robust parameters to (correlatively) link structural ecosystem discontinuity to biodiversity values. Most of these approaches are based on empirical studies validating the size, configuration defining the isolation of habitat patches for specific species (Hanski, 1994a). For example, Pouwels (2016) validated a fragmentation metric for bird and mammal species showing a high correlation between the fragmentation metric and the species persistence in the landscape over space and time. From a data point of view, creating HSI models with predictor variables at very small raster cell size leads to very specific species-habitat relationships, and thus needs to be verified with accurate presence records (Manzoor et al. 2018).

Approaches like described in Pouwels (2016), Manzoor et al. (2018), and Opdam et al., (2003) clearly showed that to define robust fragmentation parameters, clearly defined and derived habitats types are needed to monitor fragmentation. Concluding, the focus of a validation process should be on an assessment of (an) EBV-fragmentation metric(s) based on comparing independent local species distribution maps or GPS tracking / -movement data in defined pilot areas. This ancillary information can be used to calibrate and validate the EBV-fragmentation results and judge the transferability across regions.

Secondly, an analysis using different RS land cover products can be carried out to check the reliability of the metric(s) used. Such an assessment can be done using and comparing at least three different scaled land use products. This step can be used to calibrate the metric over different scales and RS-products and show its uncertainties using different classifications.

2.8. Existing data sets and performance

In global applications, habitats and their spatial configuration are normally a refinement of RS derived land cover products See, e.g. section 2.3.4 for examples from Rondinini et al. (2011) and Brooks et al. (2019). Global land cover classifications derived from high and medium resolution satellite imagery are already available, such as ESA's GLOBCOVER product and Global Land Cover at 30m spatial resolution (www.globallandcover.com). Habitat can be selected from land cover products, directly, or by combining them with other products through geo-processing. To serve a variety of potential species ranges, the fragmentation EBV can be calculated for each habitat-class from a chosen product. Individual output maps can then be combined to represent the habitat and species of choice. At the regional level, habitat or land cover data can be derived from products like Landsat 8, Sentinel-2, depending on the level of detail in the habitat classification (e.g. forest, shrubs, grasslands). However, at continental or global level such detailed land cover products are often not available (except for some major land cover types, e.g. Hansen et al. (2013) for global forest and the Copernicus high-resolution layers (https://land.copernicus.eu/pan-european/high-resolution-layers)), and still, depend in most cases on coarser-resolution products such as MODIS and PROBA-V at 100-300 meter resolution.

An analysis testing existing datasets should be based on a variety of input data (local habitat data, EU-wide ecosystem types maps, classified Sentinel/Landsat data. A typical analysis focusing on using different RS land cover products could look like this:

- Local land cover data as provided by pilot areas with a spatial resolution varying from less than 20m to +/- 30m. Such pilot areas should preferably also have ancillary information about species distribution to calibrate and validate and calibrate the EBV-fragmentation metrics.
- 20m classified Sentinel-2 land cover data for a wider region, with a limited number of classes (e.g., the "Land Cover Classification System" (LCCS) as developed by FAO (FAO.org))

- 100m classified land cover data (e.g., PROBA-V with LCCS legend) for a complete continent.

2.9. Feasibility, scientific and technological Readiness Levels

There are many scientifically described methods to quantify the fragmentation of landscapes (Wilson et al., 2016; Opdam et al., 2003). Most of this work is dating back to the basic work on landscape metrics development from the 1980s onwards. Many of these studies describing methods using generic landscape-level metrics derived from GIS-based tools (e.g., Fragstats (Neel et al., 2004, Riitters et al., 1995)). Other more specific fragmentation focused toolboxes exist, like the LARCH-SCAN (Landscape Analysis and Rules for Configuration of Habitat) toolbox which calculate a relative measure for spatial cohesion based on dispersal characteristics of species (Bruinderink et al., 2003), or the GUIDOS-toolbox creating fragmentation metrics based on morphological shapes of land cover (Soille and Vogt, 2009). Stand-alone versions of the most interesting metrics are up-and-running or not difficult to be implemented.

The feasibility to calculate such metrics is mainly depending on the availability of classified input ecosystem data. Regarding the available RS data, a wide range of such data is globally and regionally available. Habitat types can be selected from remoted sense based land cover products, directly or by combining them through pre-processing (Mücher, 2009, Mücher et al., 2015).

2.10. Summary and outlook

Depending on the aims of the user and the level of detail of the available input data, both regional species-specific network analysis as well as European wide generalized assessments of fragmentation are possible to derive from satellite-derived products. The scale of the landscape, as used by the species, is decisive for the scale of the needed input data.

Habitat types can be selected from remoted sense based land cover products directly or by combining them through pre-processing, although the EBV fragmentation can be relatively straightforwardly implemented across different scales using basic land cover data. However, habitat maps directly derived from global products are often a rough indication of how species perceive and use the landscape. It is therefore often difficult to relate species-specific habitat classifications to global land cover products, indicating that existing land cover products should be thematically refined to derive the suitable habitat types (e.g., instead of broadleaf forests we need to know were old broadleaved forest are located or where they are dominated by specific tree species that characterize the specific forest habitat type).

Depending on the metric to be chosen, a variety of potential species ranges can be served. Habitat fragmentation can be measured for each habitat-class from a chosen product. Individual output cohesion maps can then be combined to represent the habitat and species of choice.

2.11. Specific measurement requirements summary

The satellite measurement specifications and delivery format for the RS-enabled EBV are tabulated in Table 2. This table summarizes key requirements parameters under the following headings: spatial and temporal extent, spatial, spectral and temporal resolution, thematic and geometrical accuracy, spectral domain, existing RS data sources, product delivery mode, format and reference system.

Table 2: Specific measurement requirements of the four RS-enabled EBVs.

Requirement	EEF
Spatial extent	All terrestrial ecosystems
Temporal extent	5 – 10 years
Spatial Resolution	10 – 30 m
Spectral Resolution	Broad band
Temporal Resolution	yearly
Thematic Accuracy	≥ 80 %
Geometrical Accuracy	1 pixel
Spectral domain	400-2500 nm
Existing RS data	S2 and Landsat
Product format	GeoTiff, ESRI Grids, others on request
Reference system	UTM

Reference

Assessment, M. E. 2005. Environmental degradation and human well-being: Report of the millennium ecosystem assessment. *Population and Development Review,* 31, 389-398.

Basu, M. & Xavier, S. 2016. *Fundamentals of Environmental Studies,* India, Cambridge University press.

Brooks, T. M., Pimm, S. L., Akçakaya, H. R., Buchanan, G. M., Butchart, S. H. M., Foden, W., . . . Rondinini, C. 2019. Measuring Terrestrial Area of Habitat (AOH) and Its Utility for the IUCN Red List. *Trends in Ecology & Evolution*.

Brown, D. G., Addink, E. A., Duh, J. D. & Bowersox, M. A. 2004. Assessing uncertainty in spatial landscape metrics derived from remote sensing data. *Remote Sensing and Gis Accuracy Assessment*, 221-232.

Bruinderink, G. G., Van Der Sluis, T., Lammertsma, D., Opdam, P. & Pouwels, R. 2003. Designing a Coherent Ecological Network for Large Mammals in Northwestern Europe

Diseño de una Red Ecológica Coherente para Mamíferos en el Noroeste de Europa. *Conservation Biology,* 17, 549-557.

Caspers, H. 1984. Mark Williamson: Island Populations. — 286 pp. Oxford University Press 1981. ISBN 0-19-854134-1. £ 19.00. *Internationale Revue der gesamten Hydrobiologie und Hydrographie,* 69, 143-143.

Chapin, F. S., Matson, P. A. & Vitousek, P. M. 2002. *Principles of terrestrial ecosystem ecology*.

COP-CBD 2010. The Strategic Plan for Biodiversity 2011-2020 and the Aichi Biodiversity Targets, COP-10 Decision X/2, 29 October 2010, UNEP/CBD/COP/DEC/X/2

DAVIS, M. A. 2006. *The Shrinking World: Ecological Consequences of Habitat Loss,* SPIE.

Diamond, A. W. 1982. Island Populations, by Mark Williamson. Oxford UP, £19.00. *Oryx,* 16, 283-284.

Didham, R. K., Kapos, V. & Ewers, R. M. 2012. Rethinking the conceptual foundations of habitat fragmentation research. *Oikos,* 121, 161-170.

Eupen, M. v., Gaast, J. W. J. v. d. & Knaapen, J. P. 2001. Ecologische landschapsindex (ELI); een nadere uitwerking van de: graadmeter ruimtelijke samenhang & graadmeter hydrologische relaties. Wageningen : Alterra (Alterra-rapport 432) – 88p.

Fahrig, L. 2003. Effects of habitat fragmentation on biodiversity. *Annual Review of Ecology Evolution and Systematics,* 34**,** 487-515.

Fletcher, R. J., Ries, L., Battin, J. & Chalfoun, A. D. 2007. The role of habitat area and edge in fragmented landscapes: definitively distinct or inevitably intertwined? *Canadian Journal of Zoology,* 85**,** 1017-1030.

Haddad, N. M., Brudvig, L. A., Clobert, J., Davies, K. F., Gonzalez, A., Holt, R. D., . . . Townshend, J. R. 2015. Habitat fragmentation and its lasting impact on Earth's ecosystems. *Science Advances,* 1.

Hansen, M. C., Potapov, P. V., Moore, R., Hancher, M., Turubanova, S. A., Tyukavina, A., . . . Townshend, J. R. G. 2013. High-Resolution Global Maps of 21st-Century Forest Cover Change. *Science,* 342**,** 850-853.

Hanski, I. 1994a. A Practical Model of Metapopulation Dynamics. *Journal of Animal Ecology,* 63**,** 151-162.

Hanski, I. 1994b. Spatial Scale, Patchiness and Population-Dynamics on Land. *Philosophical Transactions of the Royal Society of London Series B-Biological Sciences,* 343**,** 19-25.

Hanski, I. 2011. Habitat Loss, the Dynamics of Biodiversity, and a Perspective on Conservation. *Ambio,* 40**,** 248-255.

Hanski, I. 2015. Habitat fragmentation and species richness. *Journal of Biogeography,* 42**,** 989-993.

IAEG-SDGs 2016. Report of the Inter-agency and Expert Group on Sustainable Development Goal Indicators (E/CN.3/2016/2/Rev.1). United Nations.

Krauss, J., Bommarco, R., Guardiola, M., Heikkinen, R. K., Helm, A., Kuussaari, M., . . . Steffan-Dewenter, I. 2010. Habitat fragmentation causes immediate and time-delayed biodiversity loss at different trophic levels. *Ecology Letters,* 13**,** 597-605.

Liu, J. J., Wilson, M., Hu, G., Liu, J. L., Wu, J. G. & Yu, M. J. 2018. How does habitat fragmentation affect the biodiversity and ecosystem functioning relationship? *Landscape Ecology,* 33**,** 341-352.

Macarthur, R. H. & Wilson, E. O. 1967. *The Theory of Island Biogeography*, Princeton University Press.

Manzoor, S. A., Griffiths, G. & Lukac, M. 2018. Species distribution model transferability and model grain size – finer may not always be better. *Scientific Reports,* 8**,** 7168.

McGarigal, K., Cushman, S., Neel, M. & Ene, E. 2012. *FRAGSTATS v4: Spatial Pattern Analysis Program for Categorical Maps. Computer software program produced by the authors at the University of Massachusetts, Amherst. Available at: www.umass.edu/landeco/research/fragstats/fragstats.html*.

Mücher, C. A. 2009. *Geo-spatial modelling and monitoring of European landscapes and habitats using remote sensing and field surveys.*

Mücher, C. A., Hennekens, S. M., Schaminee, J. H. J., Halada, L. & Halabuk, A. 2015. Modelling the spatial distribution of EUNIS forest habitats based on vegetation relevés and Copernicus HRL : Using habitat suitability maps based on vegetation relevés and and amongst others the Copernicus high resolution layer forest, this report describes in detail the method used to produce the probability maps for the EUNIS forest habitat types at level 3. An assessment of these maps has been done for the whole of Slovakia. All the maps are presented in Annex I. Paris: European Topic Centre Biological Diversity.

Myster, R. W. 2001. What is Ecosystem Structure?
Navarro, L. M., Fernandez, N., Guerra, C., Guralnick, R., Kissling, W. D., Londono, M. C., . . . Pereira, H. M. 2017. Monitoring biodiversity change through effective global coordination. *Current Opinion in Environmental Sustainability,* 29**,** 158-169.
Neel, M. C., McGarigal, K. & Cushman, S. A. 2004. Behavior of class-level landscape metrics across gradients of class aggregation and area. *Landscape Ecology,* 19**,** 435-455.
Ocampo-Penuela, N., Jenkins, C. N., Vijay, V., Li, B. V. & Pimm, S. L. 2016. Incorporating explicit geospatial data shows more species at risk of extinction than the current Red List. *Science Advances,* 2.
Opdam, P., Verboom, J. & Pouwels, R. 2003. Landscape cohesion: an index for the conservation potential of landscapes for biodiversity. *Landscape Ecology,* 18**,** 113-126.
Opdam, P., Pouwels, R., van Rooij, S., Steingrover, E. & Vos, C. C. 2008. Setting Biodiversity Targets in Participatory Regional Planning: Introducing Ecoprofiles. *Ecology and Society,* 13.
Pimm, S. L., Jenkins, C. N., Abell, R., Brooks, T. M., Gittleman, J. L., Joppa, L. N., . . . Sexton, J. O. 2014. The biodiversity of species and their rates of extinction, distribution, and protection. *Science,* 344**,** 987-+.
Pouwels, R., R. Jochem, M.J.S.M. Reijnen, S.R. Hensen & Greft, J. G. M. v. d. 2002. LARCH voor ruimtelijk ecologische beoordelingen van landschappen. Alterra-rapport 492. Alterra, Research Instituut voor de Groene Ruimte, Wageningen. [In Dutch].
Pouwels, R. 2016. LARCH-SCAN status A. WOt-internal document. WOT Natuur & Milieu, Wageningen UR Wageningen, December 2016.
Riitters, K. H., Oneill, R. V., Hunsaker, C. T., Wickham, J. D., Yankee, D. H., Timmins, S. P., . . . Jackson, B. L. 1995. A Factor-Analysis of Landscape Pattern and Structure Metrics. *Landscape Ecology,* 10**,** 23-39.
Rondinini, C., Di Marco, M., Chiozza, F., Santulli, G., Baisero, D., Visconti, P., . . . Boitani, L. 2011. Global habitat suitability models of terrestrial mammals. *Philosophical Transactions of the Royal Society B-Biological Sciences,* 366**,** 2633-2641.
Schamberger, M. L., Farmer, A. H. & Terrell, J. W. 1982. Habitat Suitability Index models: introduction. *FWS/OBS.* - ed.
Schneider, D. C. 2001. The Rise of the Concept of Scale in EcologyThe concept of scale is evolving from verbal expression to quantitative expression. *BioScience,* 51**,** 545-553.
Schoener, T. W. & Spiller, D. A. 1987. High Population Persistence in a System with High Turnover. *Nature,* 330**,** 474-477.
Skidmore, A. K., Pettorelli, N., ,, Coops, N. C., Geller, G. N., Hansen, H., Richard Lucas, . . . Wegmann, M. 2015. Agree on biodiversity metrics to track from space. *Nature,* 523**,** 403-405.
Soille, P. & Vogt, P. 2009. Morphological segmentation of binary patterns. *Pattern Recognition Letters,* 30**,** 456-459.
Thuiller, W. & Münkemüller, T. 2010. Habitat suitability modeling. *Effects of climate change on birds. Oxford University Press, New York***,** 77-85.
Tscharntke, T., Tylianakis, J. M., Rand, T. A., Didham, R. K., Fahrig, L., Batary, P., . . . Westphal, C. 2012. Landscape moderation of biodiversity patterns and processes - eight hypotheses. *Biological Reviews,* 87**,** 661-685.

Uuemaa, E., Roosaare, J. & Mander, U. 2005. Scale dependence of landscape metrics and their indicatory value for nutrient and organic matter losses from catchments. *Ecological Indicators,* 5, 350-369.

Verboom, J. & Pouwels, R. 2004. Ecological functioning of eco-logical networks: a species perspective. In R. H. G. Jongman, &G. Pungetti (Eds.), Ecological networks and greenways: concept, design, implementation (pp. 65–72). Cambridge: Cambridge University Press.

Vos, C. C., Verboom, J., Opdam, P. F. M. & Ter Braak, C. J. F. 2001. Toward ecologically scaled landscape indices. *American Naturalist,* 157, 24-41.

Wilson, M. C., Chen, X. Y., Corlett, R. T., Didham, R. K., Ding, P., Holt, R. D., . . . Yu, M. J. 2016. Habitat fragmentation and biodiversity conservation: key findings and future challenges (vol 31, pg 219, 2016). *Landscape Ecology,* 31, 229-230.

Wu, H. & Li, Z.-L. 2009. Scale Issues in Remote Sensing: A Review on Analysis, Processing and Modeling. *Sensors (Basel, Switzerland),* 9, 1768-1793.

Wu, J., Jones, K. B., Li, H. & Loucks, O. L. 2006. *Scaling and uncertainty analysis in ecology: Methods and applications.*

Ziter, C., Bennett, E. M. & Gonzalez, A. 2013. Functional diversity and management mediate aboveground carbon stocks in small forest fragments. *Ecosphere,* 4.