globdiversity

rs-enabled ebvs

Project Final Report

V3

Date: 22/10/2020

Contract No.

4000120011/17/I-NB

Submitted by

DOCUMENT RELEASE SHEET

Authors: Review:	Claudia Röösli, Vladimir Wingate (UZH) U. Heiden (DLR), R. Van De Kerkove (vito) , W. Simonson (WCMC), R. Darvish (ITC)	
Approval (internal)	Andrew Skidmore, Michael Schaepman	Zurich, November 8, 2020
Approval (ESA)	Marc Paganini	
Distribution:	Public release	

CHANGE RECORD

Version	***Date***	***Page(s)***	***Change record***	***Release***
1	July. 20	9	Version 1, first draft	CR
2	Oct. 20	40	Version 2, including detailed results	CR
3	Nov. 20	39	Version 3 update, including Feedback MP	CR

1 Acronyms and Abbreviations

Acronym	Definition
ABT	Aichi Biodiversity Targets
CCC	Canopy Chlorophyll Content
CEOS	Committee on Earth Observation Satellites
DLR	Deutsches Zentrum für Luft- und Raumfahrt, German Aerospace Agency
EBV	Essential Biodiversity Variable
EO	Earth Observation
EODC	Earth Observation Data Centre for Water Resources Monitoring
EOS/EGS	*End of the Growing Season*
ESA	European Space Agency
GCOS	Global Climate Observation System
GEO-BON	The Group on Earth Observations–Biodiversity Observation Network
GUIDOS	Graphical User Interface for the Description of image Objects and their Shapes (toolbox)
HR	High Resolution
IPBES	Intergovernmental Platform on Biodiversity and Ecosystem Services
ITC	University of Twente Institute for GeoInformation Science and Earth Observation
LAI	Leaf Area Index
LARCH	Landscape ecological Analysis and Rules for the Configuration of Habitat (model)
LiDAR	Light Detection and Ranging
LPV	Land Product Validation (subgroup of CEOS)
LSP	Land Surface Phenology
MAES	Mapping and Assessment of Ecosystems and their Services
MODIS	MODerate-resolution Imaging Spectro-radiometer
MSI	Multi-Spectral Imager (for Sentinel-2)
NASA	National Aeronautics and Space Administration
POS/PGS	*Peak of the Growing Seasons*
PRB	Project Requirement Baseline
RS	Remote Sensing
RS-enabled EBVs	Remote-Sensing enabled Essential Biodiversity Variables
SAR	Synthetic Aperture Radar
SOR	Satellite Observation Requirements
SOS/SGS	*Start of the Growing Season*
TdV	Tour du Valat
TOPC	Terrestrial Observation Panel for Climate
UCD	Use Case Demonstration
UT	University of Twente
UZH	Universität Zürich, University of Zurich
VH	Vegetation Height
VITO	*Vlaamse Instelling Voor Technologisch Onderzoek, Flemish Institute for Technological Research*
WCMC	World Conservation Monitoring Centre

Table of Contents

2 Introduction

The main objective of the European Space Agency (ESA) Data User Element (DUE) funded GlobDiversity project was to conduct a set of engineering activities for the definition, specification, algorithm benchmarking & prototyping, validation, scaling up and utility demonstration of 3 High Resolution (HR) Remote Sensing enabled Essential Biodiversity Variables (RS-enabled EBV) on the structure and function of terrestrial ecosystems.

GlobDiversity is the first large-scale project explicitly designed to develop and engineer RS-enabled EBVs. This project supports the efforts of the Convention on Biological Diversity (CBD) and Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), among others, and is adopted under the umbrella of the Group on Earth Observations Biodiversity Observation Network (GEO BON). The GlobDiversity project's goal is to support the initiative to build a global knowledge of biological diversity of terrestrial ecosystems (= on land) and of relevance for society.

The GlobDiversity project started in June 2017 and ended in September 2020, and was coordinated by the Remote Sensing Laboratories (RSL) of the University of Zurich. The project partners were the German Aerospace Center (DLR), Faculty of Geo-information Science and Earth Observation of University of Twente (ITC), Wageningen Environmental Research (WENR) of the Wageningen University & Research, UN Environment World Conservation Monitoring Centre (UNEP-WCMC), Vito NV (Vito), Earth Observation Data Center for Water Resources Monitoring GmbH (EODC), Tour du Valat (TdV), Tartu Observatory of the University of Tartu (Tartu).

The work was divided into three different parts 1) requirement analysis, 2) algorithm development and implementation and 3) utility analysis. The core outcome of the project are the algorithms of three RS-enabled EBVs that have been engineered within the project for the domains of a) Canopy Chlorophyll Content, b) Habitat Fragmentation, and c) Land Surface Phenology. A fourth topic, Vegetation Structure, was additionally discussed in the requirement analysis but was not implemented due to a lack of (global) satellite data.

The three algorithms are based on high-resolution satellite data from Sentinel-2 (10m resolution), partly on Landsat-8 images (30m resolution) and in case of fragmentation on available land cover maps. The algorithms were selected based on a trade-off analysis to find the most suitable algorithm towards a global application for biodiversity monitoring. The algorithms were then applied to ten different pilot sites of natural conservation areas located in four different biomes (arctic tundra, temperate forest, wetlands, tropical rainforest) and shown in Figure 1.

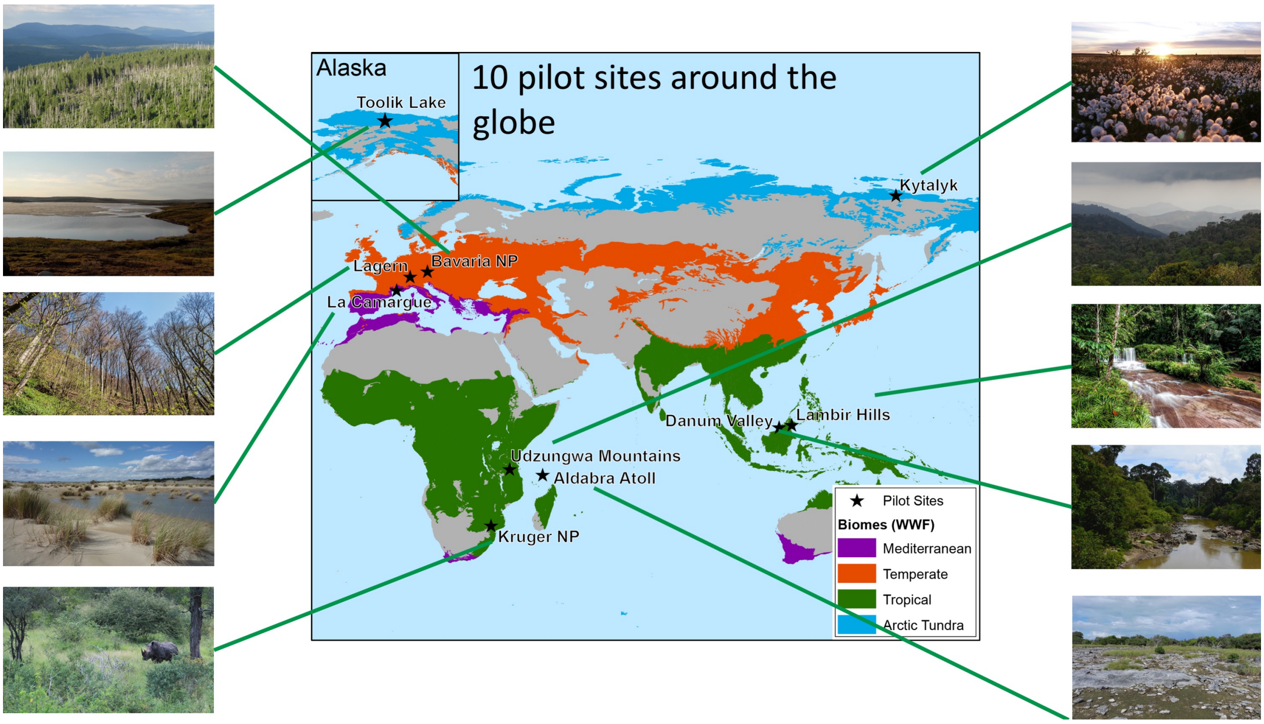


Figure 1: Overview of focus pilot site for the GlobDiversity project. The pilot sites are natural, protected ecosystems (mostly national parks) located in four different biomes and distributed around the globe.

In addition, the algorithms were applied on a cloud computing platform in the frame of a technical upscaling exercise in Finland and Senegal.

In order to demonstrate the utility of the products, the RS-enabled EBV data sets were used in four different use cases developed in collaboration with some of the pilot sites. The project developed one modelling use case using CCC and LSP for ecosystem modelling in the Udzdungwa and Kruger national parks, CCC was used in the Bavarian forest national park (Germany) for an early warning system of bark beetle infestation, fragmentation was investigated on a dragonfly species in the La Camargue (France) wetland, and LSP was used for a use case on the endangered Siberian White Crane breeding in the Kytalyk National Park in the Siberian tundra (Russia).

In addition to the technical engineering work, the project also developed a number of strategic documents, such as the Algorithm Theoretical Basis Document (ATBD, the definition of satellite requirements, the so-called Satellite Observation Requirement (SOR) document, as well as a roadmap to put the RS-enabled EBV development in the context of the larger framework of EBVs and biodiversity stakeholders such as IPBES, GEO BON, as well as in the context of the work done by the Committee on Earth Observation Satellites (CEOS) to facilitate the access, use and uptake of satellite observations by the biodiversity community.

Figure 2 introduces the workflow of the GlobDiversity project with the different tasks performed and the created deliverables of these steps.

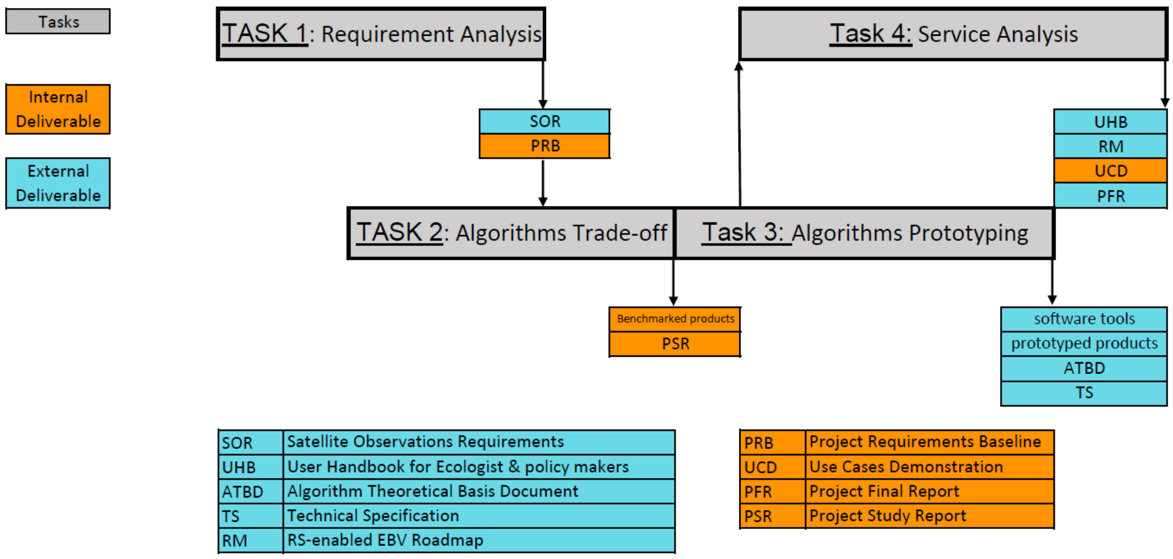


Figure 2: Workflow and deliverables of the GlobDiversity project. Outputs marked in blue are openly available and introduced in detail within this report.

In the following chapters, the output products of the project are introduced with a short summary of the outcome. The project's deliverables are classified into two types of documents, internal and publicly available documents, whereas mainly the public documents are introduced within this report.

3 Task 1: Requirement Analysis

The Group on Earth Observations–Biodiversity Observation Network (GEO-BON), which represents the biodiversity component of the Global Earth Observation System of Systems (GEOSS), is making a coordinated effort together with decision-makers and the scientific community to address the need for a global biodiversity observation network that contributes to the effective management of the world's biodiversity and ecosystem services. To improve the detection of significant changes in global biodiversity, GEO-BON is currently adopting the concept of Essential Biodiversity Variables (EBVs).

Skidmore et al. (2015) proposed a number of EBVs that can be directly measured and monitored using remote sensing (hereby RS-enabled EBVs). Remote sensing (RS) is anticipated to play a significant role, particularly for the effective monitoring of rapidly changing ecosystems that cover extensive areas. In conjunction with *in situ* data, RS imagery, which can be derived from airborne and space-borne sensors, provides vital input for biodiversity assessments and monitoring at a fine spatial resolution and high temporal frequency. However, the potential of remote sensing data in the context of EBVs has not been thoroughly investigated yet.

This chapter briefly discusses the document outputs of the Task 1 requirement analysis with the Satellite Observations Requirement document (public) and the Project Requirement Baseline (internal).

3.1 Satellite Observation Requirement Documents

The Satellite Observation Requirement Document comprises three parts, including I) general background of the EBV framework for terrestrial ecosystems in relation to the development and implementation of conservation/restoration actions and the reporting to the biodiversity policy agendas (e.g. CBD, SDGs, Ramsar). II) Prioritization and Selection of RS-enabled EBVs on terrestrial ecosystem function and structure III) Satellite Observation Requirement Definition and Analysis for selected RS-enabled EBVs.

For developing Part II) and III), two workshops were organised (Sept. 2017 and Jan. 2018, respectively) within the scope of GlobDiversity. The prioritization and selection task were concluded into a scientific publication (Skidmore et al., 2020 - in review), therefore not discussed in detail here. Part III) proposes a structure for defining the satellite observation requirements for RS-enabled EBVs of terrestrial ecosystems as shown in Figure 3. This structure has been developed by the consortium and reviewed and discussed during the workshop in 2018 followed by an expert review within the GEO BON community. The structure has been applied to the four RS-enabled EBVs selected for the project (Fragmentation, Canopy Chlorophyll Content, Vegetation Structure, Land Surface Phenology). These four chapters (also reviewed within the workshop and the GEO BON community) and the introductory chapter are available, together with the introductory Part I), on the GEO BON website[1]. The aim of this work was to provide a structured approach to the definition of the satellite observation requirements for RS-enabled EBVs, which can be followed by the RS-enabled EBV developers and would enable the space agencies to conduct

[1] https://geobon.org

in-depth satellite data analyses (including gap analyses) with a review of the current mission scenarios and an analysis of the needs for new satellite missions.

1. Definition of the RS-enabled EBV..
2. The role of the RS-enabled EBV in biodiversity assessing and monitoring .....
3. Spatiotemporal coverage..
4. Remotely sensed EBV Products...
5. Spatial extent and temporal frequency requirements.............................
6. Transferability of retrieval approaches ....
7. Calibration and Validation ....
8. Existing data sets and performance ....
9. Feasibility, scientific and technology readiness levels ....
10. Summary and outlook ....

Figure 3: Chapter structure for the definition for a remote sensing enabled EBV, detailed description of these chapters can be found under Appendix 10.1.

3.1.1 Outlook and recommendation for the SOR document

- The structure of the SOR was developed during a workshop followed by an expert review with the biodiversity community. This document could be used as the basis to specify the satellite observation needs of other RS-enabled EBVs or as a document to identify the observation needs for the implementation of EBVs that can be (partly) enabled by RS. Such documents can also be used as the observation baselines towards space agencies and CEOS in order to conduct in-depth reviews of satellite data, including the need for new EO missions.
- The SOR helped the project partners to reflect not only on the observations and on the retrieval algorithms but also on the assessment of the RS-enabled EBVs from a broad scientific and policy perspective. In particular it helped to raise awareness among the (potential) users of the products. While developing the document and the examples, the project partner came into an in-depth discussion with the community and users of different kinds.
- Developing and applying such a framework on the RS-enabled EBVs means, time-intensive discussions with the community. Time effort of such review processes should not be underestimated, and handling of inputs from different perspectives need to be defined transparently. Defining the RS-enabled EBVs requirements for different contexts of use, i.e. by biodiversity scientists, for policy applications and for conservation actions, implies addressing a variety of interest that needs to be considered.

3.2 Definition of workflow: Project Requirement Baseline

The Project Requirement Baseline (PRB) consolidates the technical requirements of the project and defines the guidelines for the following engineering tasks of Task 2 & 3 & 4. The document takes the proposal as the starting point and defines the methodological approaches to be benchmarked for the selected subset of RS-enabled EBVs. Verification and validation approaches in connection with the pilot sites and biomes are included as well as the technical scaling-up and utility demonstration.

This internal document served the project in particular in the first part to structure the tasks and to plan the methodical approaches, including the validation approaches and interactions with the pilot sites. In addition, the documents allowed to reflect on the strategy what users could be addressed by the project and how to include different parties of interest.

3.2.1 *Lessons learnt from PRB*

- In the course of the creation of this document and also products, the consortium had in-depth discussion on "who is the user" and to "whom should the results" be addressed/targeted. This question in general is not that easy to answer depending on the complexity the users, which needs to be considered. In the case of GlobDiversity this question was even more complex as the entire project and its goal defined are a mixture between strategic discussions and definition (mainly Task 1), scientific consideration (Task 2 with algorithm definition and development), engineering tasks (Task 3 with the prototyping of the code) and the application of the code (Task 3, use cases). Including all these different steps into one project means that there is a very broad and complex set of interest and potential users. Identifying and defining these users and their different needs was one of the main challenges within the project.

4 Task 2: Algorithm Trade-Off

Task 2 was dedicated to evaluate, select and benchmark end-to-end algorithmic methods for the selected RS-enabled EBVs by using satellite imagery at high spatial resolution (10-30m) and a free and open data policy, as principle source of input data. The algorithms were first evaluated with an in-depth literature review followed by some selective testing. The RS-enabled EBVs were benchmarked and calculated in four different pilot sites per RS-enabled EBV, located in different biomes. The implemented algorithms, the corresponding data sets and the documentation were used as input for the followed step of algorithm prototyping.

The result of Task 2 was mainly documented in the internal Project Study Report that contains all work and testing that has been performed during Task 2. The final algorithmic implementation and a summary of the results and validation is documented in the public algorithm technical specification document (ATBD) that is the main output from Task 3 and the prototyping task (Chapter 5).

4.1 Documentation of results and work done: Project Study Report

The Project Study Report (PSR) documents a scientifically sound trade-off analysis for future operational use of the three selected RS-enabled EBVs. The PSR is an internal document, however, the most important one for the development of the algorithm, as it documents all scientific and technical work performed within the project, including trade-off analyses. Each RS-enabled EBV is documented as a single document and includes a study of the most widely used and accepted algorithms and the documentation of the experimental analysis (including algorithm trade-off, benchmarking and testing) to justify the design choices made within the project. The PSR is the main scientific and technical document of the GlobDiversity project and it gathers the results of all scientific analyses and technical developments conducted during the duration of the project, from algorithm requirements engineering, to algorithm selection, benchmarking, testing and prototyping, and to product verification and validation. The document describes all algorithmic analyses and inter-comparisons done, all algorithms trade-off and design justifications, and all product benchmarking, testing, prototyping and validation.

The PSR contains 3 main technical components:

- - ***The Algorithm Selection Justification (ASJ)***
    - Scientific algorithmic background for each set of the RS-enabled EBVs
    - Algorithms benchmarked, tested and validated
    - Trade-off, design choice justifications, feasibility analysis, supporting technical assessment
    - Comparison of various algorithmic approaches
- - ***The Product Validation Plan (PVP):*** activities planned to validate the RS-enabled EBVs data products and validation plan
- - ***The Product Validation Report (PVR):*** Results of the data product validation on the selected pilot sites

Based on the criteria published by GEO BON with its definition of EBVs and the statement of work of the GlobDiversity project, the following criteria were taken into account for the testing, selection, implementation and validation of the algorithms:

- Capture major changes in biodiversity
- Ecological meaning
- Policy relevance
- Globally measurable
- Fully automatic procedures with minimum human intervention
- Independent from measurement platforms
- Scale-free (local to global scale)
- Robust, reliable and well-tested retrieval methodologies
- Estimation of accuracies and uncertainties, preferably at the product's spatial unit (pixel, object)
- Global monitoring in space and time should be affordable and cost-effective
- Intermediate abstraction layer between the primary observations and the biodiversity indicators
- key information needed for the generation of biodiversity indicators on the state of and changes of biodiversity
- Possibility of the integration of products into national biodiversity monitoring and assessment activities

4.1.1 Habitat Fragmentation: selected algorithm

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. Habitat loss and fragmentation are and will continue to be one of the major threats to biodiversity (Hanski, 2011; Pereira et al., 2010). Not only will areas of natural habitats be lost, but the remaining habitats will become smaller and more isolated (Fahrig, 2003; Opdam, 1991). 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 society in general and human wellbeing specifically. Monitoring habitat fragmentation can be supported by remote sensing through the collection of information on the spatial distribution of habitats and associated land covers, ultimately helping to reveal what it means for the species occurring in those habitats.

Fragmentation (FRAG) can be calculated based on remotely derived habitat and/or land-cover type maps. From an operational point of view, it is most practical to use satellite-derived habitat or land-cover maps. The spatial resolution will vary by land-cover product, with a targeted temporal resolution of one year. The achievable performance will depend not only on the spatial resolution of the land-cover product but especially on the distinct land cover types which are affiliated with the targeted species/habitats.

FRAG accounts for direct habitat loss, changes in the quality of patches, network density, distance between habitat patches, and changes in matrix permeability. It focuses on the effects of dispersal on the persistence of species across land cover types.

Wageningen University selected an algorithm based on the LARCH-SCAN-Hanski metric which applies a formula simulating the dispersal capacity of species to all habitat types cells within the dispersal distance. FRAG is implemented generically through four steps. Firstly, it selects a land cover product. Secondly, it applies the algorithm to all land cover classes with a standard set of distances, which results in individual maps of spa al cohesion values per class. Thirdly, it selects the ecoprofile (i.e. a species with specific habitat type and fragmentation distance) and combines output cohesion maps by adding up the relevant habitat classes to represent the habitat and species of choice. Finally, it derives size and number of clusters in the study area based on the ecoprofile and select on of relevant classes.

4.1.2 Land Surface Phenology: Algorithm Selection

Land surface phenology (LSP) characterizes recurrent events in the annual profile of vegetated land surfaces as observed by remote sensing (RS). Each dominant tree or shrub in a vegetation canopy has a temporal signature of vegetative activity that is indicative of the species type but also varies with temperature, radiation, precipitation, soil properties or other local influences (Schwartz, 2003). Deviation of the yearly profile from the long-term mean gives a strong indication on the health of the vegetation and influences such as diseases or meteorological effects (e.g., drought). Gradual changes in the profile may show adaptation of the vegetation to changing environmental conditions or changes in composition, for instance due to invasive species. Monitoring the changes in the yearly vegetation profiles – within this project the phenological properties start, end and length of the growing season, as well as its amplitude, were defined – disturbances and changes in the ecosystem can be detected and documented (e.g., Wu et al., 2018).

The evaluated and selected algorithm is based on yearly time-series of the Normalized Difference Vegetation Index (NDVI) per pixel that is represented with a double-logistic mathematical model as represented in Figure 4.

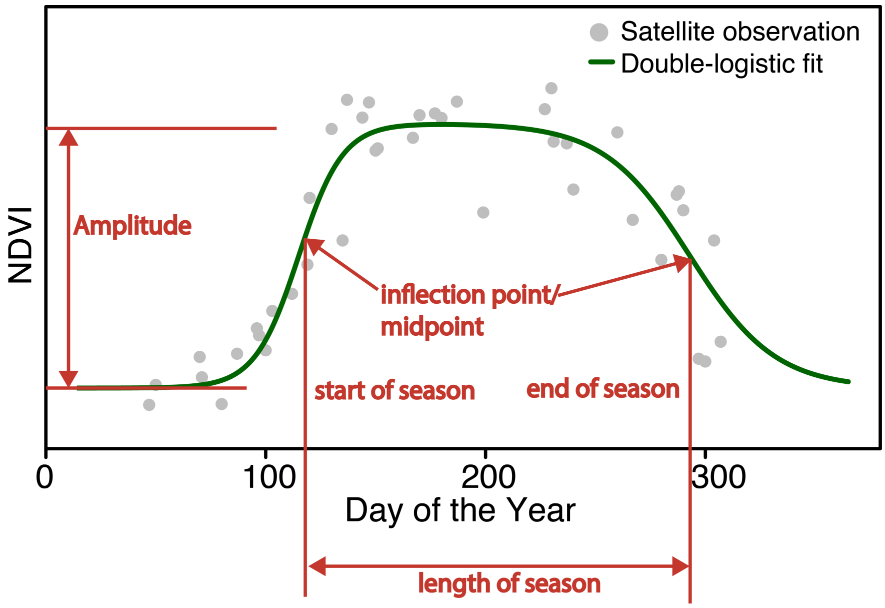


Figure 4: Double logistic model used to fit the yearly changes in vegetation activity per pixel, represented by the NDVI, with the extracted phenological parameters Start of Season, End of Season, Length of season and amplitude.

The model was found to be robust against outliers and irregularly distributed observations, and was therefore selected to characterize LSP across different biomes. Results were quality tested to exclude non-vegetated areas and regions without seasonal vegetation activity.

Validation is based on the same processing procedure using the time series from terrestrial phenocam images as independent input. As the Near infrared-images is often missing for phenocam cameras, the validation procedure uses the phenological curve based on Green Chromatic Coordinates (GCC) for phenocams and satellite images and then compared with the phenology derived from NDVI.

4.1.3 *Canopy Chlorophyll Content: algorithm selection*

Canopy chlorophyll content (CCC) is the product of chlorophyll content of a fresh green leaf per unit leaf area and leaf area index (LAI). It describes chlorophyll pigments distribution within the three-dimensional canopy surface. CCC contributes to the ecosystem function class of Essential Biodiversity Variables and has been long used for a wide range of terrestrial ecological applications. CCC can be used as an important input variable for terrestrial biosphere models to quantify carbon and water fluxes, primary productivity and light use efficiency. In addition, monitoring the dynamics of CCC provides valuable information about plant physiology and ecosystem processes or functions at different scales, thus supporting assessments of the influence of climate change and other anthropogenic and natural factors on plant functions.

A trade-off analysis performed by the University of Twente identified two operational algorithms for measurement of CCC from remote sensing data. These were (1) a simple ratio vegetation index (SRVI) and (2) a Look-Up Table (LUT) inversion of two physically-based models: one for forest ecosystems ("INFORM"), and an alternative one for non-forest/short vegetation ecosystems ("PROSAIL"). The algorithms were used to generate the CCC product from Sentinel-2 reflectance data, and showed good robustness and consistency across space and time.

4.1.4 *Lessons learnt*

- The overarching goal of developing global applications of RS-enabled EBVs at high spatial details is only possible recently, since dense time series of high resolution (10-30m) satellite imagery have been made available (e.g., Sentinel-satellites since a few years) and computational resources are now available to deal with very large datasets of satellite data. The scientists of the GlobDiversity team which developed and selected the algorithms, were confronted with the task to select an algorithm that could be applied globally using high-resolution satellite data streams as principal input data source. Thus, the most sophisticated algorithm is not necessarily the one that has the most potential to be deployed efficiently towards a global application. The handling and processing of large data sets and the need to bring the code on a cloud computing platform mean to address new challenges when selecting the best approach.
- Selecting the core RS-enabled EBV algorithms was the main goal and purpose of the project. Nevertheless, without having the properly prepared and pre-processed data, results might not be of the expected quality. For instance, the atmospherically-corrected Sentinel 2 data (i.e. L2A data sets, bottom of the atmosphere reflectance) was not yet available for all areas and times of interest, even if space agencies and processing platforms work towards the availability of "analysis ready data". Therefore, preparing and making the input satellite images available should not be underestimated as well as data sharing of resulting

prepared input or final products. In particular, when using large time series (e.g. used for LSP), a large amount of data need to be handled.

5 Task 3: Algorithms Prototyping

Within Task 3, the benchmarked algorithms developed in Task 2, have been transferred into a prototype system to produce the data sets for all 10 pilot sites with the entire regions of interest. The codes were translated to an optimised system in python (LSP and parts of the fragmentation algorithm) and C++ (LARCH-SCAN core algorithm, CCC), respectively. These core-algorithms were run in combination with DLR's internal pre-processing procedures to produce the data sets for the pilot sites (see Figure 1) for two years (2017, 2018). The codes are available at the partners and next versions might be available through repository platforms such as github. In addition, the detailed algorithms are described in the Algorithm Theoretical Basis Document (ATBD). The verification and validation of the data sets are documented mainly in the internal PSR, and summarised in the ATBD.

5.1 Technical documentation of the algorithms in the Algorithm Theoretical Basis Document

The Algorithm Theoretical Baseline Documents (ATBD) describe the technical details of implementation resulting from the prototyping of the RS-enabled EBV products. The ATBDs follow the same structure for all three core RS-enabled EBVs and specify the process flow of the prototyped algorithms. They allow a transparent documentation of the processing and the possibility to independently reproduce the algorithms.

The ATBDs include a detailed description of the algorithms and their implementation. They also include a synthesis of the algorithms' development (including trade- off analysis, benchmarking, prototyping and validation) and some recommendations and lessons-learnt. Each algorithm is individually described in a single document. The ATBDs follow the same standardised structure that can be reused for other algorithm development work.

The ATBD structure is composed of different parts, including the algorithm justification and a description of the end-to-end workflow, as shown in Figure 5.

1. → **Introduction**¶
2. → **Scientific·background**¶
3. → **Input·Data**¶
4. → **Algorithm·description**¶
5. → **Product**¶
6. → **Remarks·on·prototyped·algorithm·development·and·processing**¶
7. → **Upscaling·results**¶
8. → **References**¶
9. → **Appendix**¶

Figure 5: Structure of the Algorithm Technical Baseline Documents ATBDs of the GlobDiversity project describing the algorithms and work-flows developed within the project for the three core RS-enabled EBVs.

In the scientific background, the variables and mathematical models are described. The chapter on input data describes the required data and pre-processing steps which can be different depending on the area of interest and processing platform (e.g., availability of atmospherically corrected data, availability of high-resolution land cover map, etc). The input data is then fed into the core algorithms that are meant to be universal independently on the region of interest. The outputs of the main processing steps are described in the product itself. The accuracy analysis and validation method are summarised in the analysis of the output product.

5.1.1 *Technical scaling-up*

Within GlobDiversity, Finland and Senegal were used as demonstration countries for the technical scaling-up. The objective was to verify that the algorithms can be applied on an area of interest larger than the pilot site. The technical scaling-up in Finland and Senegal have been done over geographical areas that correspond to 65 and 40 Sentinel-2 tiles, respectively. The aim of this task was to “demonstrate the capacity to produce automatically the selected RS-enabled EBV data products over large areas”, by executing the prototyped RS-enabled EBV processing chain(s) on Vito’s cloud infrastructure. The objective of the demonstration was to showcase the scaling up and to mainstream potentials of the developed algorithms over the countries of Finland and Senegal. These countries have been selected based on a trade-off among the size of the countries (computational costs), available data sets (in particular land cover data), diversity of vegetation types and available national contacts in biodiversity conservation.

This demonstration included the transfer of the algorithms from DLR’s cloud platform to Vito’s cloud and the implementation of software changes, when needed, in particular regarding the handling of the input data (i.e. pre-processing step). Figure 6 shows the result from the up-scaling exercise for the LSP-algorithm applied on Senegal. The LSP output products, calculated for 2019 with their different metrics, nicely show the gradient in vegetation zones from North (desert) to South (tropical savanna). The result for CCC concentration is represented in Figure 7 with different percentiles from the yearly time series. Finally, the FRAG outputs for the ecoprofiles of the chimpanzees in Senegal is shown in Figure 8. The ecoprofile is based on the spatial cohesion maps at different dispersal distances for the class “shrubs (=habitat of the Chimpanzee). For the Chimpanzee habitat, dispersal distances of 500m, 1000m and 5000m with a minimal spatial cohesion threshold of 0.1m and a minimal cluster size of 6km^2 were selected.

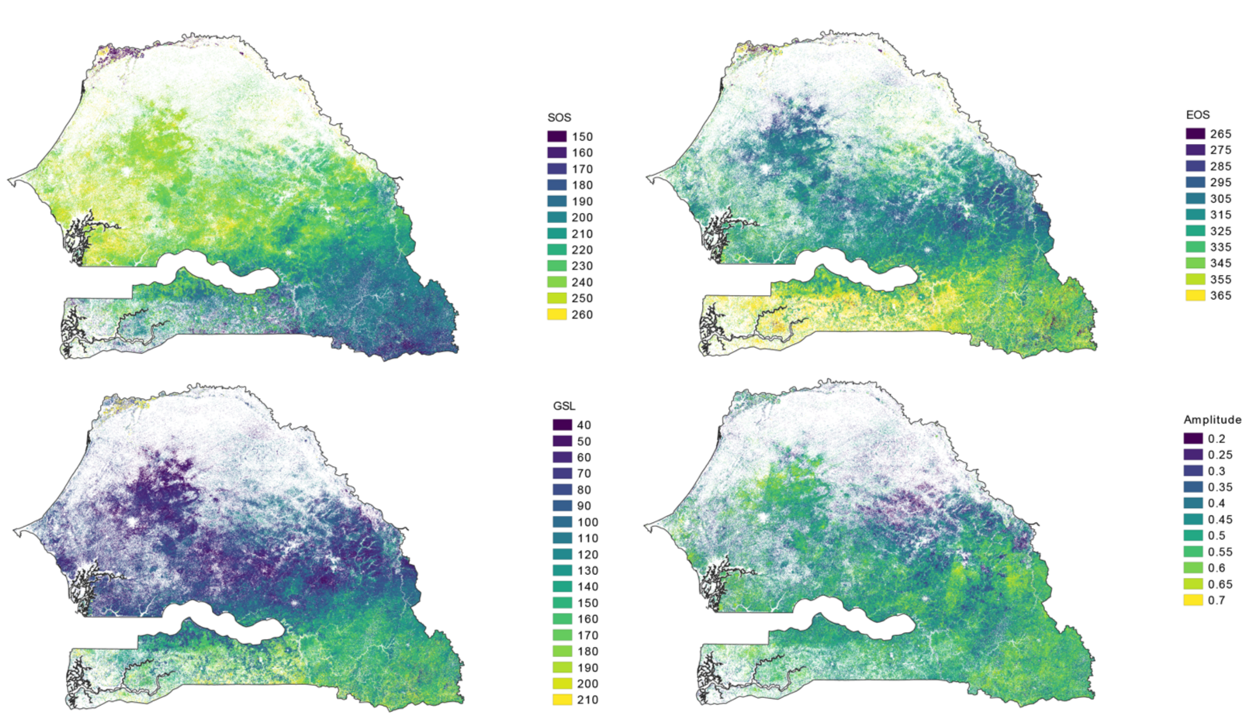


Figure 6: Per pixel LSP metrics over Senegal: Start of Season (SOS, DoY), End of Season (SOS, DoY) dates, Growing Season Length (GSL, DoY) and Amplitude (AMP)

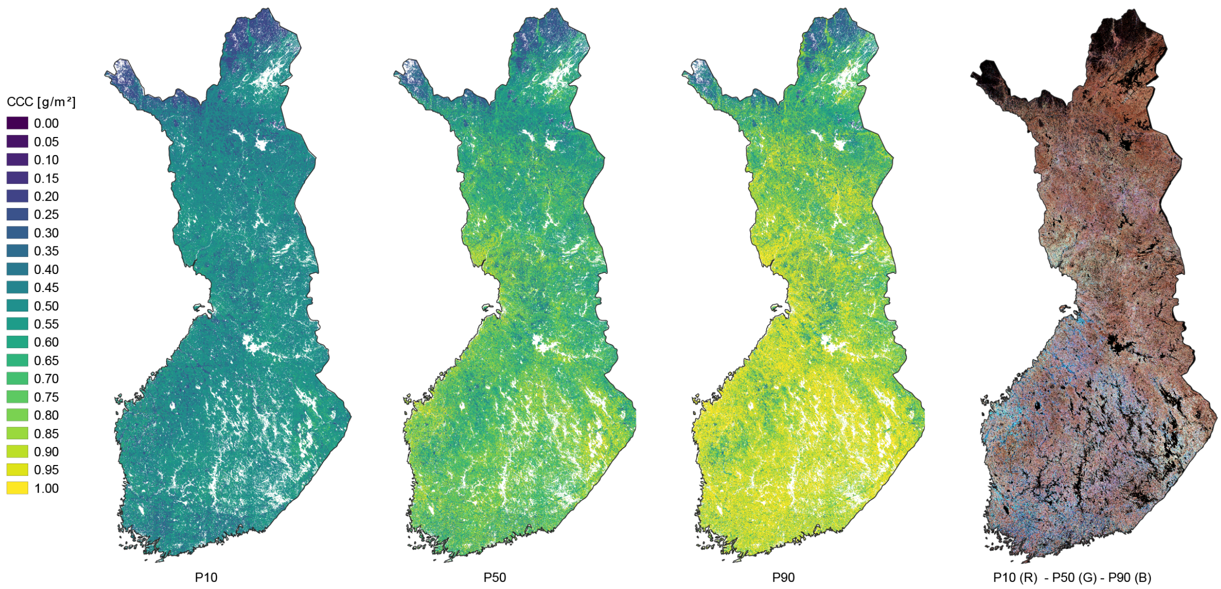


Figure 7: per pixel CCC time series percentiles over Finland: 10th percentile (P10), 50th percentile (P50), 90th percentile (P90) and an RGB composite with R= P10, G= P50 and B=P90)

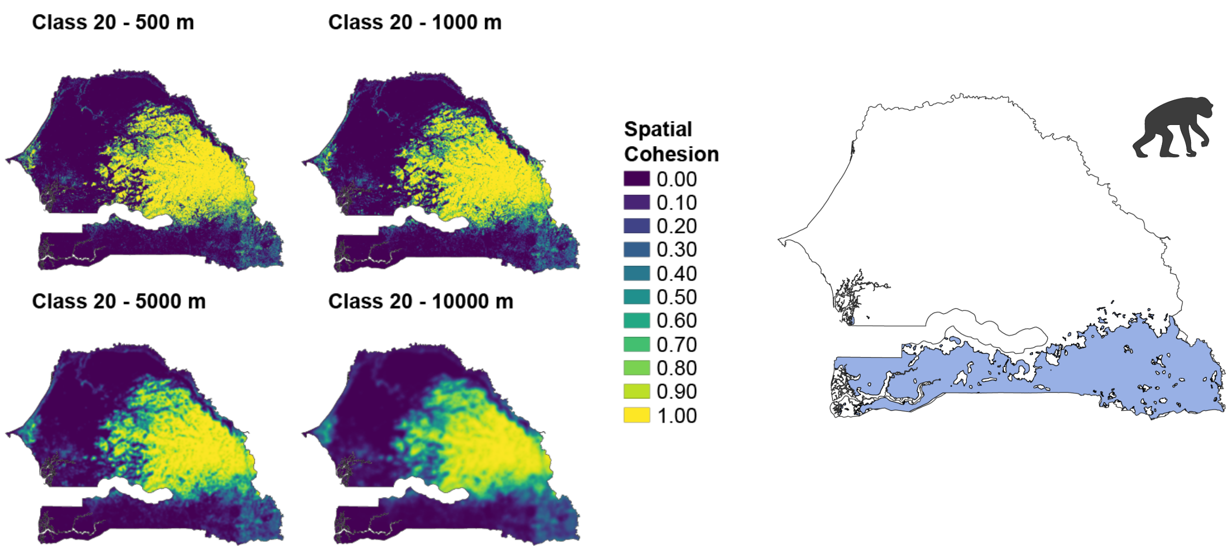


Figure 8: Left: Spatial cohesion maps at different dispersal distances for the class "shrubs". Right: Clusters representing connected habitat with a threshold > 0.1 for Chimpanzee (blue)

The ATBDs also include a chapter highlighting the limitations in the current versions of the algorithms as this is a prototype, not yet ready for an operational use. Nevertheless, the algorithms can be used and applied globally by everyone.

The ATBDs include, as an entire chapter, recommendations and remarks when applying and using the prototyped algorithms. Also, the current limitations and future areas for development are transparently also provided so that a user can apply the algorithms appropriately.

5.1.2 Lessons learnt and recommendation

- The transfer of processing software between one and another system is not straight forward and strongly depends on the underlaid cloud infrastructure, even when using technologies such as docker-containers. It should be noted that in the present project the core activities were focused on the algorithm development and not on a full end-to-end operational processor. The transfer can be challenging as the pre-processing (i.e. preparing the data input for the core processor such as e.g. a NDVI time series) can be different for each platform and needs to be performed before applying the algorithms.
- The core-algorithms were developed and benchmarked, in particular for CCC and LSP, within this project and then prototyped for a larger-scale application. Therefore, these algorithms are not as performant as for instance the Larch-SCAN core algorithm that already underwent a more in-depth development beforehand. The available CCC and LSP algorithms, therefore, have still a high potential for optimisation in particular in terms of performance.

5.2 Technical Specification

The technical specification document (TS) puts the work done within GlobDiversity and in particular the prototyping task into a larger context towards an operational production chain. The TS outlines an operational production system designed to provide continuously updated products as developed during the GlobDiversity project. The TS is based on the specifications of the core RS-enabled EBV algorithms described in the ATBDs. The document is designed in an engineering style with use case analyses (how the system will be used) and scenarios describing the interaction within the components of the production systems. These analyses also define the system requirements. The document introduces possibilities and the context that need to be considered when designing a larger (cloud) technical infrastructure for an operational production of the data sets. Additionally, the TS gives an overview of several potential architectures, including the architecture chosen for the prototype implementation of the GlobDiversity processing chains, and shortly discusses the characteristics of each architecture. It shall enable RS-enabled EBV developers to have an architecture overview and a baseline for further analyses on the system architecture.

6 Task 4: Application and Utility Demonstration

Task 4 was dedicated to the use and utility assessment of the RS-enabled EBV data sets and to the analysis of the RS-enabled EBV development processes. The task resulted in two main outcomes: a) the use cases with the user handbook as a public document and b) the RS-enabled EBV roadmap to put the outputs and findings of GlobDiversity into the larger context of biodiversity monitoring.

6.1 *Product utility demonstration*

The comprehensive User Handbook (UHB) on RS-enabled EBVs for Terrestrial Ecosystems serves as a tutorial for biodiversity scientists, conservation practitioners and policymakers on the concept and widespread use of RS-enabled EBVs for monitoring terrestrial ecosystems. The handbook demonstrates the links between the RS-enabled EBVs and biodiversity and their applications in the conservation context. Four use case studies were conducted to demonstrate the benefits of RS-enabled EBVs in applied biodiversity studies, and their adequacy for conducting ecologically-meaningful biodiversity analyses. The use cases cover different aspects of the biodiversity monitoring, namely, species distribution and ecosystem function modelling, invasive species impact assessment, habitat connectivity, and endangered species management. The following four use cases are presented within the UHB:

Use case #1: Assimilating RS-enabled EBVs in the Madingley model to improve ecosystem modelling of ecosystem functioning

Use case #2: Monitoring invasive species: Spruce bark beetle attack in the Bavaria Forest National Park

Use case #3: Monitoring habitat fragmentation in and around protected wetlands: Dragonfly habitat connectivity in the La Camargue

Use case #4: Management of Siberian White Crane breeding habitat using RS-enabled EBVs.

6.1.1 *Utility of RS-enabled EBVs in ecological modelling*

The project conducted a series of explorations of the usefulness of the RS-enabled EBVs for ecological modelling. This included an expert consultation of their utility for vegetation modelling; a statistical analysis of the relationships between the RS-enabled EBVs (Leaf surface phenology, LSP and canopy chlorophyll content, CCC) and standard environmental variables used in ecological modelling; and two case studies using GlobDiversity remote sensing variables for ecological modelling. The first case study was an analysis of the effect of incorporating LSP and CCC on the modelling of animal abundance patterns across Kruger National Park. The second was an analysis of the effect of incorporating LSP and CCC on the modelling of species occurrences in Udzungwa National Park. The results of these analyses suggest that RS-enabled EBVs have the potential to be useful for ecological modelling. They can bring unique, novel information, although the modelling carried out during the project suggests that this does not translate into significantly improved model performance.

6.1.2 Spruce bark beetle attack in the Bavaria Forest National Park

The main questions addressed by the use case in the Bavarian forest were

- How can the Canopy Chlorophyll Content (CCC) RS-enabled EBV be used to detect stress and change to ecosystem structure and function caused by European spruce bark beetle?
- What is the potential contribution of CCC products derived from remote sensing datasets to understand the dynamics of the bark beetle infestation and improve the management of bark beetle outbreaks in forest ecosystems over time?

To answer these questions, a stress map based on the CCC products has been created based on a six-year study period (2011-2018) and a time series of images from Sentinel-2 and RapidEye images. The threshold for separating healthy and moderately/severely stressed areas was derived based on field measurements of leaf chlorophyll and leaf area index collected during June/July 2016 in infested and healthy spruce stands.

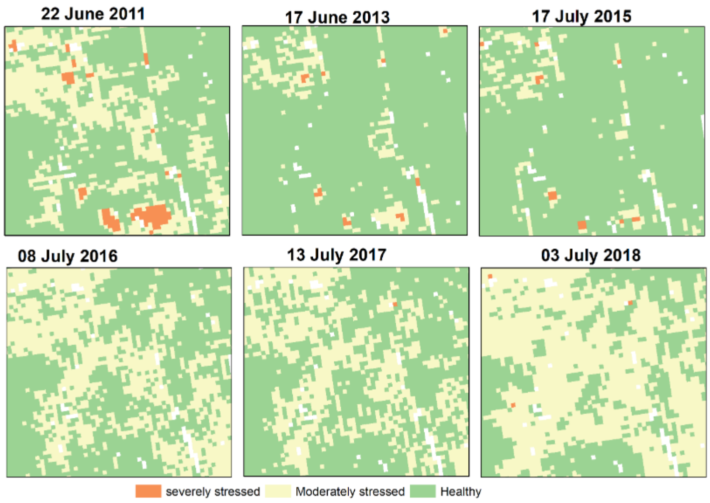


Figure 9: Spatio-temporal distribution of vegetation stress in the Bavarian national park as predicted by CCC during the study period 2011-2018.

The findings in this use case show that the stress maps derived from the CCC products can be used to support foresters, natural resource and protected area managers in taking informed intervention actions. Bark beetle outbreaks can be controlled and mitigated if timely, accurate and cost-effective information is available. Thus, stress maps play a tremendous role to guide natural resource and protected area managers in identifying areas infested by beetles, as well as to define the timing of bark beetle control activities. This simple stress mapping technique reduces the time and cost compared to expensive conventional surveys required at the early stage of bark beetle infestation. An infested but still physiologically green tree exhibits stress that can be detected by remote sensing. The CCC RS-enabled EBV provides valuable information about plant physiology and ecosystem processes (functions), which can be used to assess the influence of natural factors (e.g., beetle infestation), climate change, and other anthropogenic factors on plant functions and plants adaptation. Thus, the spatio-temporal dynamic products of the RS-enabled EBV acquired from remote sensing can be used to measure the impact of conservation activities on improving ecosystem functioning.

Lessons learnt from the use case

The results in this use case showed that CCC products generated from remote sensing data offer a simple and robust means to detect bark beetle infestation at an early stage.

- The detection of the bark beetle infestation is based on the assumption that infestation causes stress which in turn resulted in lower CCC. However, other natural and anthropogenic factors such as drought, climate change, and other diseases may also cause stress.
- Once the algorithm is implemented, RS-enabled EBV products do not demand professional image processing skills and the processing chain is automatic.
- The validation provides a proof of concept that early bark beetle infestation can be accurately detected based on CCC stress level.
- Data on plant traits such as nitrogen, dry matter and water contents together with CCC may boost the accurate and timely detection of bark beetle infestation.
- Communication and interpretation of the CCC products require simple technical skill to visualize and interpret the results.

6.1.3 Dragonfly habitat connectivity in the La Camargue

The main objective of this use case study on the La Camargue was to test innovative approaches for the assessment of habitat connectivity and fragmentation for a specific species of conservation concern, and to see whether conservation and water management measures at the local scale have impacted its dispersal over the last years.

The species targeted in this study is the dragonfly *Lestes macrostigma* (dark spreadwing), a very localised species, with a fragmented distribution in Europe and associated with the brackish temporal water ecosystem in the La Camargue. For the development of the habitat fragmentation RS-enabled EBV, the LARCH-SCAN-Hanski metric was implemented to measure structural ecosystem discontinuity. The assessment of habitat connectivity required detailed maps of the Land Use/Land Cover (LULC) and the surface water dynamics at the scale of the whole site. The use of EO-based tools (e.g. high-resolution satellite image time series) enabled access to data and information that can capture these trends at different time scales. A resulting product in the form of a map displaying connected clusters of habitat cells is shown in Figure 10.

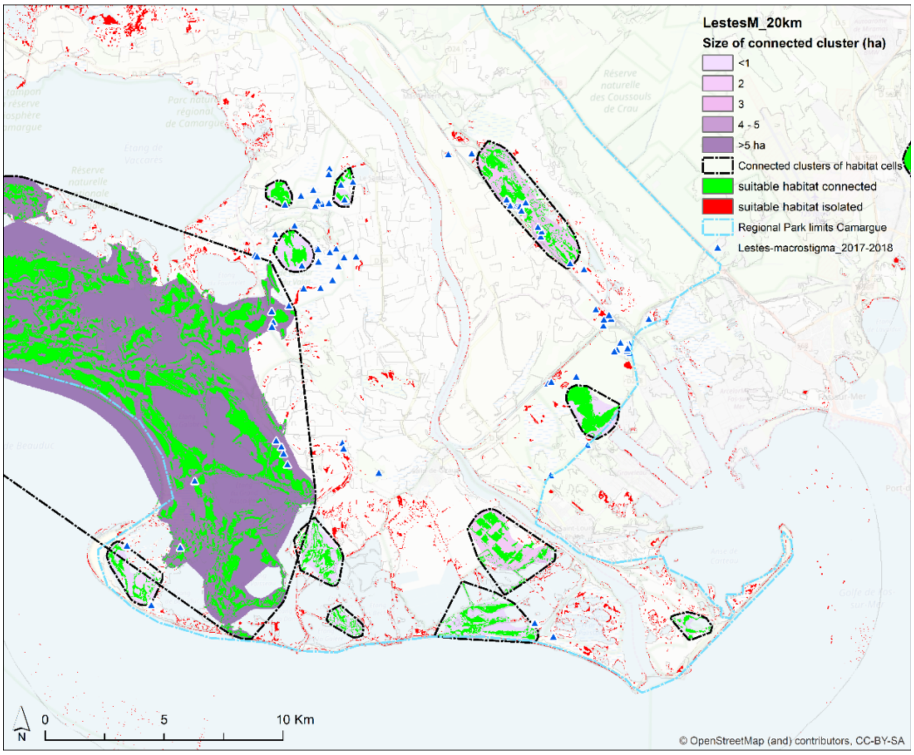


Figure 10: Map of connected habitat clusters for Lestes macrostigma in the La Camargue and their size in hectares of habitat using a Scan-threshold of 0.1 (10% of Habitat in the defined neighborhood) estimated in collaboration with the local research institute for conservation Tour de Valat.

The results of the use case were performed in collaboration with Tour du Valat and shared with the management authorities of the Regional Nature Park of the La Camargue and the National Reserve of the La Camargue to assess the impacts of some management, conservation and habitat restoration measures for the dispersal of the targeted species. The functional biodiversity and habitats of the La Camargue are predominantly influenced by the salinity, and the quantity and the quality of water that is available through the year. Large areas naturally dry up during the summer period, but through a complex network of irrigation and drainage channels, 730 million cubic meters of water are pumped from the Rhône on average each year to compensate for river embankment, and to avoid soil salinization, enhance primary production (overcome summer drought) and create suitable habitat for species of conservation interest. The map of habitat clusters for the dragonfly *Lestes macrostigma* is one piece of evidence that park managers can use to inform water management to increase the connectivity and dispersal of this, among other, important species.

Lessons learnt from the use case

- Tour du Valat collected the main input data to create the La Camargue habitat maps. Then there was an intermediate step needed to combine the Sentinel-2/Landsat 8 derived land cover maps and Sentinel-2 water-/flooding dynamic maps before running the fragmentation algorithm, in order to match the habitat data with species habitat preferences (*Lestes macrostigma*) and local fragmentation issues of interest. The combination of input data to create habitat maps was straightforward, although was reliant on detailed expert input on the habitat preferences of *Lestes macrostigma*. In other cases, a more general habitat profile and habitat input data set can be sufficient. In such cases simple literature can be used if available to define the habitat preferences and to select input habitat data from available sources.

- The creation of the output indicator fragmentation maps was also a very straightforward step performed with a standalone version of the GitHub script. The resulting datasets can be analysed by a GIS software (e.g. QGIS / ArcMAP) and these preprocessing steps are all done using standard GIS/remote-sensing software. The running of the fragmentation algorithm thus requires only basic computer handling knowledge. One of the most relevant lessons learned through this use case is the fact that in order to better assess habitat connectivity and fragmentation, it is important to take into account the natural dynamics of the environment (e.g. flooding regimes).
- The tested habitat connectivity RS-enabled EBV could become even more useful if implemented at broader scales than sites such as the La Camargue Delta, for example, across the Mediterranean Basin. The information would then be more relevant to be linked with national policies that could have impacts on biodiversity corridors and species dispersal at wider scales.

6.1.4 Siberian white crane in Kytalyk National Park

This study sought to demonstrate the possible contribution of remote sensing data to the conservation of the Siberian white crane by statistically evaluating the Land Surface Phenology (LSP) RS-enabled EBV, in conjunction with a multi-data source habitat suitability model represented by the habitat nesting potential (NPO, Haverkamp et al., in prep.) and high resolution habitat map. In Figure 11, an example for the LSP metric start of the season (SOS) for the years of investigation 2017 and 2018 is shown in comparison with a derived habitat map based on a Landsat 8 satellite image classification. The high spatial resolution information characterizing suitable breeding habitat and its seasonal dynamics and changes over time is expected to allow local conservation practitioners and authorities to improve their ability to conserve this species.

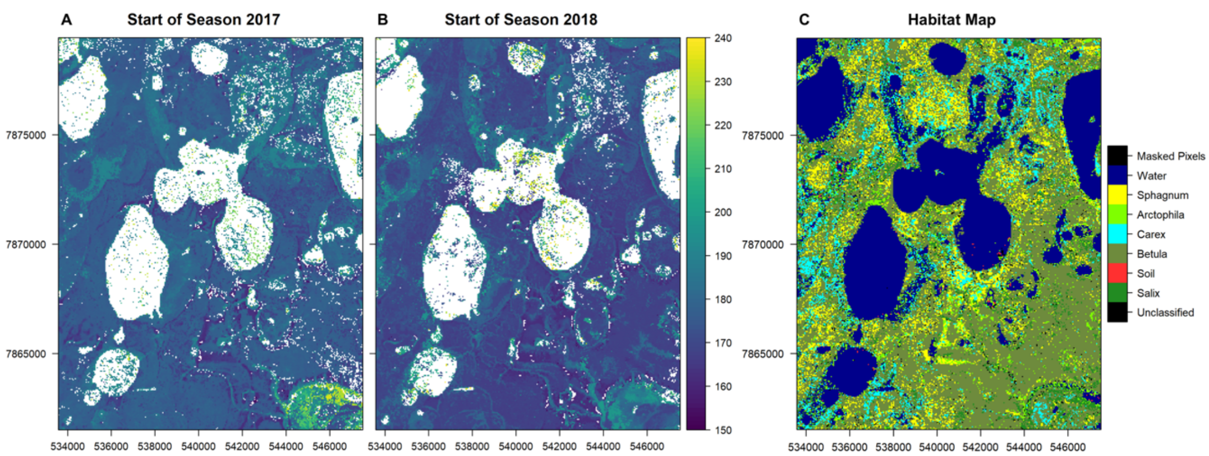


Figure 11: Start of Season metric for the years 2017 (A) and 2018 (B) plotted for a sub-set area of interest in Kytalyk (Siberia); in addition, the corresponding Landsat 8 habitat map (C) is shown.

The output showed that the LSP metric Start of Season (SOS) can be used as a spatial predictor of NPO, and that LSP metrics are also useful for accurately identifying vegetation and habitat types, in particular areas of high shrub density, which are known to be avoided by cranes for nesting. The work performed within the study is a first step towards a yearly breeding success estimate, though ground validation of nesting sites is required to develop a more reliable model. Nevertheless, together with the nesting potential map, the LSP SOS product is certainly a valuable input for further refining the nesting potential model as well as assessing the breeding habitat on an annual basis.

The results were developed, discussed and presented to the Spatial Ecology & Remote Sensing research group at University of Zurich, which is doing intensive research in this area. They are currently the main users of the data. If the outcome and findings of this study can be further refined, extended and validated, their incorporation into this ongoing research could become a powerful tool for informing conservation management of the National Park by the local conservation authorities.

Lessons learnt from the use case

- The main challenge in this use case was to gain sufficient knowledge on the crane habitats. The cranes are highly endangered and protected, and thus only sparse information on breeding habitats can be shared in papers or reports. In addition, the region is very remote and only very few data have been collected on observed nest locations or breeding success. For future studies, additional data sets for validation would be highly useful; currently only remote data sets from satellite observations for the entire area are available.
- The main advantage when using satellite data is the homogenous coverage of the entire area. Nevertheless, it shouldn't be neglected that the processing of such large areas at high resolution of 10-30 m is highly computationally expensive.
- In conclusion, the use case study has shed light on potential uses and applications of the RS-enabled EBV LSP in applied conservation studies. We have demonstrated a potential application of LSP for the identification of: i) different habitat types, in particular *Salix* shrubland; and ii) of a major ecosystem change process, namely, shrubification. In particular, we have shown that the use of LSP metrics from our algorithm can be very powerful when used in conjunction with other ancillary datasets, especially for this large and very remote region where ground data are lacking.

6.1.5 Outlook: Science Traceability Matrix

It is important to link science-focused space missions with a wider societal objective by stating the clear scientific aims and goals that are to be achieved (Weiss, Smythe and Lu, 2005). The science traceability matrix (STM) provides this overview of what a satellite mission will accomplish given a set of high-level objectives as suggested through expert opinion and reviews of user needs.

Although a tool for use in designing space missions, the STM concept was adapted for the GlobDiversity project as a 'mission' with defined objectives, shown in Figure 12. As a starting point the IPBES assessments (thematic, global, regional and sub-regional) questions were used as high-level guiding instruments from which biodiversity questions were deduced which were then linked to the corresponding biodiversity indicators proposed by the CBD to answer them (columns 1-3). However, the IPBES assessments can adopt new indicators in addition to those (generic) indicators suggested by the CBD Parties (column 3). The approaches that could be used to satisfy the observational needs of these indicators were then linked to general information needs, our focal RS-enabled EBVs and finally the data products flowing from the EBVs (columns 4-6).

This analysis has been done at a strategic level and is not intended to be exhaustive nor finished, but as a starting point that is representative of the GlobDiversity project goals and its high-level objectives (columns 4-6). The STM approach here could be adopted and used for all RS-enabled EBVs in future, not just the three studied in GlobDiversity. It is also important to emphasise that biodiversity cannot be assessed using a few RS-enabled EBVs alone, but that all the information listed (column 4) needs to be considered to answer the questions (column 2), which may include other sources of geospatial information as well as non-space data on biodiversity. The STM is therefore a tool that defines the boundary between what we can and cannot do, in relation to the stated questions, using a remote sensing approach alone. The remaining knowledge (i.e. the observation gaps) could be used to justify investment in other space-based observations for other RS-enabled EBVs.

Finally, the STM is a communication tool that allows bridging between policymakers, ecologists, remote sensing experts and space engineers to communicate and clearly demonstrate which science questions are addressed with the satellite observation requirements. Assuming it is successful, policy decisions could be supported by the new generated knowledge, if an appropriate channel of communication can be found, e.g. through the IPBES knowledge and data task force.

1	2	3	4	5	6
IPBES questions relevant to decision makers *(extracted from several IPBES assessment reports)*	**Biodiversity questions** *(Formulated to connect column 2&4, with focus on the GlobDiversity's RS-enabled EBVs; non-exhaustive)*	**CBD generic indicators** *(Generic indicators identify types of issues that could be monitored; extracted and matched from CBD conference Dec. 2016* https://www.cbd.int/doc/decisions/cop-13/cop-13-dec-28-en.pdf ; *With the connection to the Aichi biodiversity targets ABT)*	**Information/ data sets needed to assess biodiversity** *(extracted from CBD generic indicators, GlobDiversity's SOR, and others., with focus on the GlobDiversity's RS-enabled EBVs; non-exhaustive)*	**RS-enabled EBV and their contribution to biodiversity monitoring** *(selected RS-enabled EBVs mapped onto the biodiversity questions, col.2)*	**Data product and user requirements** *(specified as defined within the GlobDiversity project)*
IPBES thematic assessment of invasive alien species and their control What methods are available for prioritizing invasive alien species threats? What are the impacts, risks and benefits of invasive alien species for biodiversity and ecosystem services, sustainable development and human well-being?	1 What are adaptation or dispersal strategies of species functional groups to changes in their environment? (How are niches filled?) 2 What are dominant species and what environmental conditions determine species habitats? 3 How do ecosystem disturbances , e.g. IAS, affect biodiversitya 4 How does shrub encroachment affect grassy biomes?	**ABT 9:** - Trends in the distribution and populations of invasive alien species - Trends in impacts of IAS on ecosystems - Trends in the number of IAS introduction events **ABT 12:** - Trends in extinction risk and populations of species **ABT 5:** - Trends in degradation of forest and other natural habitats	> Ecosystem/ species mapping > Environmental conditions > Climate > Health condition > Diseases > Plant growth > Ecosystem primary productivity (GPP & NPP) > Stress level > Heavy metal pollution of the plants > Migration potential for species > Available habitat extent for species > Biomass volume > Diversity of species > Tree cover > (Natural) habitat and wetland extent > Biodiversity Habitat index > Forest carbon stock > Global Ecosystem Restoration index	**LSP** Seasonal profile of vegetation activity 1 2 3 4 11 12	Time series of optical images, seasonal changes per pixel is represented by a profile Extraction and characterization of the temporal profile of VI (e.g. amplitude, slope, integral and events) that can be monitored between years on a spatial scale (per pixel)
IPBES thematic assessment on sustainable use of wild species What methods and tools exist for assessing, measuring and managing the sustainable use of wild species?	5 Which plant traits are indicative for mapping of dominant species? 6 How do changing environmental conditions affect plant stress? 7 Do different species have enough space to live?	**ABT 13** - Trends in genetic diversity of cultivated plants - Trends in extinction risk and populations of wild relatives - Trends in protected area coverage of wild relatives **ABT 8:** - Trends in ecosystems affected by pollution - Trends in extinction risk and populations driven by pollution **ABT 7:** - Trends in proportion of area of agriculture under sustainable practices - Trends in proportion of area of forest production under sustainable practices		**CCC** Photosynthetic activity of the canopy 6 5 12 11 1 3 10 8	Top of canopy chlorophyll content per unit vegetated area from optical images Representation of the absorption of radiation in the canopy
IPBES global assessment of biodiversity and ecosystem services. How do nature and its benefits to people contribute to the implementation of the Sustainable Development Goals? What is the evidence base that can be used for assessing progress towards the achievement of the Aichi Biodiversity Targets? What are the plausible futures for nature, nature's benefits to people and their contribution to a good quality of life between now and 2050?	8 What is the relationship between biodiversity and productivity? 9 How are habitats and migration routes changing with changing environmental conditions? 10 What is the relationship between forest structure, biomass and biodiversity?	**ABT 11:** - Trends in areas of particular importance for biodiversity conserved - Trends in areas of particular importance for ecosystem services conserved - Trends in ecological representativeness of areas conserved **ABT 14:** - Trends in restoration of ecosystems that provide essential services **ABT 15:** - Trends in carbon stocks within ecosystems - Trends in ecosystem resilience		**Fragmentation** Characterization of species habitats geometry 3 7 13 9 **Vegetation Height** Characterization of the 3D structure of vegetation 1 4 11 5 10	Fragmentation and changes are assessed depending on species size and migration need and behavior Landcover as input for size and connectivity of habitats 3D structure is assessed with LiDAR technique to get a 3D point cloud Above ground height and vegetation height profiles from LiDAR measurements
IPBES regional and subregional assessments What are the pressures driving the change in the status and trends of biodiversity, ecosystem functions, ecosystem services and good quality of life in the regions?	11 What are the deforestation and reforestation rates? 12 How do growing season changes affect available niches in ecosystems? 13 What are recent changes in ecosystem extent and connectivity?	**ABT 5:** -Trends in extent of forest - Trends in extent of natural habitats other than forest - Trends in fragmentation of forests and other natural habitats - Trends in degradation of forests and other natural habitats **ABT 11:** - Trends in connectivity and integration of conserved areas			
	[Other biodiversity questions]	**[other indicators]**		**[Other RS-enabled EBVs]**	

Figure 12: Science Traceability Matrix drafted within the GlobDiversity project. The matrix starts from left with IPBES biodiversity questions towards producing products to answer these questions (to the right). Note that columns 1-3 and columns 5+6 have a horizontal connection regarding the topic, otherwise, color code (between columns 2 + 5) needs to be considered.

6.2 RS-enabled EBV Road Map

Within the GlobDiversity project, we drafted a roadmap for the development and integration of Earth observation products into the EBV framework. It is aimed to establish a process for making Earth observation products more useful for biodiversity decision making. We principally focus on EBVs that can be (partly) enabled with remote sensing, the so-called RS-enabled EBVs, and put them in the context of the broader development of EBVs including in-situ approaches, RS-based approaches and the combination of both. The roadmap draws on the experiences gained during the GlobDiversity project.

The roadmap has three main objectives:

1. Help to ensure remotely sensed products become more useful for biodiversity decision making, and that an iterative process for increasing their usefulness continues into the future.
2. Guide future projects that aim to generate operational RS-enabled EBVs to maximise the usefulness and ultimately the impact of the data that they generate, by discussing the project's experiences and positioning GlobDiversity's strategic documents (i.e., SOR, ATBD, UHB).
3. Strengthen the case for why more effort in generating remote sensing information about biodiversity can be impactful and outline the steps needed to achieve that impact.

The roadmap is organised as an iteration around, and between, 6 key steps (Figure 13: The proposed cycle for an RS-enabled EBV roadmap in order to integrate and foster the use of remote sensing in the entire EBV-framework.). Steps 1, 2 and 6 are generic to all EBVs, whilst steps 3 - 5 are specific to individual RS-enabled EBV projects or products, and so multiple steps can be running in parallel. The steps are:

1. *Identifying the user community and collecting needs*. This step describes how users can be identified and discuss interaction with them to collect and document their biodiversity monitoring needs and requirements for EBVs.
2. *Selecting EBVs*. Having identified potential users and collected information about their needs, this step describes the process of defining EBVs and prioritizing them for development.
3. *Developing RS-enabled EBVs*. In this step, algorithms are defined by the core remote sensing community in consultation with biodiversity experts.
4. *Demonstrating use and developing guidelines*. This section aims to develop prototypes for the RS-enabled EBVs that can be shared wider with the biodiversity and Earth observation community to gain understanding about how useful, acceptable and efficient they are.
5. *Operationalising*. The translation of developed and demonstrated RS-enabled EBVs into operational products.
6. *Applications, synthesis and developing indicators*. The last section discusses how the RS-enabled EBVs can be brought back into the broader EBV framework and to

end-users. Furthermore, it discusses what is needed for these products to be used in decision-making.

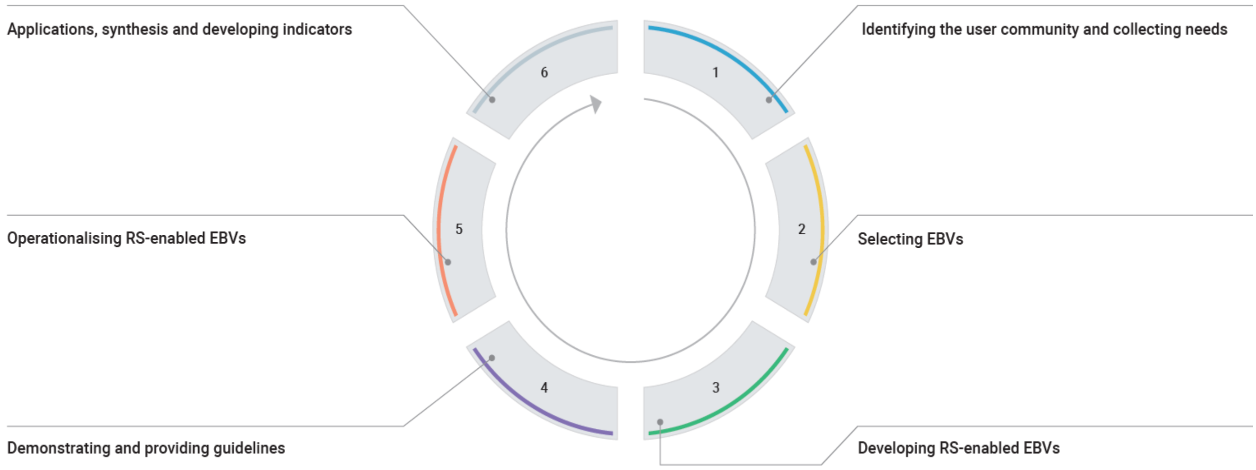


Figure 13: The proposed cycle for an RS-enabled EBV roadmap in order to integrate and foster the use of remote sensing in the entire EBV-framework.

6.2.1 <u>*Into the future: What is needed for the continuation of this roadmap?*</u>

In order to ensure remotely sensed products continue to become more useful for biodiversity decision making, we suggest that there are requirements for progress, both on the supply side of the RS data and on the demand side.

On the supply side, we argue that there is a need for greater engagement in biodiversity monitoring from space agencies and from CEOS. This could make better use of the data we have already, and provide new data from which we can increase our impact on decision making. For this to happen, CEOS and the space agencies require a list of the EBV needs that they try to address. There is a critical need for a list of key EBV data gaps that the EO community could address. In Steps 1 and 2, we discussed actions that can make this happen, including constructing a conceptual map to allow more effective communication of needs and capabilities. GEO BON is the organisation that is best placed to conduct this, having a mandate from the CBD and GEO. Fully demonstrated, tested and documented products resulting from steps 3 - 5 will help to build confidence and acceptance of the products with users.

On the demand side, the important question is: what conditions are needed for RS-enabled EBVs to be widely used in decision making? We argue that there are at least two critical needs here. First, the datasets must be specifically addressed to the needs of users. For example, if RS-enabled EBVs can directly be integrated to address indicators that may be used to monitor progress towards the goals and targets of the post-2020 biodiversity framework, then this would generate widespread interest and acceptance. However, this would be contingent on the second requirement, which is for standards and processes to ensure that products are robust, transparent and validated. In this roadmap we discuss when and how RS-enabled EBV project teams should engage with users of the products they aim to generate. This process should be ongoing and if done well, will lead to continual improvements in the usefulness of these products for understanding biodiversity status and trends. This will stimulate increased demand.

GEO BON is the key organisation to ensure continuation of the process for generating remote sensing products that are useful for biodiversity decision making. It is therefore vital to empower GEO BON to provide progress on the demand and supply sides. Making GEO BON more formally responsible for providing these services to the CBD and its Parties will support the status of GEO BON. Making formal connections between CBD, GEO BON and CEOS would bridge the supply and demand aspects described above. More formal connections might facilitate the scaling up of resources needed to expand the coordination of Earth observation capabilities and EBVs needs. If this coordination can be achieved then RS-enabled EBVs can continually provide more useful information to decision-makers.

7 Conclusion and Outlook

7.1 Achievements of the project

Within the GlobDiversity project, we were able to demonstrate the usefulness and potential that (satellite) remote sensing data have for observing and monitoring biodiversity at a global scale. The project successfully produced three prototypes to derive RS-enabled EBV data sets, contributing to the development of a global biodiversity monitoring system based on Essential Biodiversity Variables. The project partners were able to develop and demonstrate three different algorithms for Land Surface Phenology, Canopy Chlorophyll Content and Fragmentation, and apply the algorithms in a variety of biomes distributed around the globe. The algorithms and products are available for use outside of the project, as well as the documentation produced on the algorithm specification (ATBD) and on their usage and utility (User Handbook). The ATBD and the User Handbook have the potential to serve as baseline documents for future biodiversity-related projects in order to assure a transparent documentation of algorithms (ATBD) and a user-oriented documentation of the applicability of the data sets and algorithms for conservation and policy-relevant users (User Handbook).

In parallel to the technical development of the algorithms, the consortium was highly involved in strategic and conceptual discussions on the development of EBV data sets, based on remote sensing. Some of the key documents produced by the project (e.g., SOR and RS-enabled EBV roadmap) were discussed at length with the GEO BON experts, as well as within the general biodiversity community.

7.2 Outlook and recommendations

This chapter describes the outlook and recommended future steps for building on the development and findings of the project. The recommendations comprise technical recommendations on the development of the algorithms and data products, and recommendations regarding the strategic documents produced by the consortium.

Transition between tasks/knowledge transfer

One of the main challenges within the GlobDiversity project was the knowledge transfer from the scientists doing the trade-off analysis and the benchmarking tasks in Task 1 to the prototyping Tasks 2. From the project's structure, the transition from the selection and development of the algorithms to the prototyping task and the translation into a high-performance algorithm was identified as challenging. It indeed turned out to be one of the most challenging tasks that also resulted in major delays in the project. In a future project, this transition might need even more attention and dedicated transition meetings might be useful.

Nevertheless, the transition between Task 3 and Task 4 (utility analysis) worked again quite well and the output of the algorithms were translated successfully into the utility demonstration with target audience of policy makers and non-specialists.

Maturity of the algorithms towards operationalisation

The FRAG algorithm is the most mature algorithm as it already underwent a long development history at the university of Wageningen. CCC and LSP need more development and optimisation in order to provide an efficient algorithm ready for being operationalised towards large-scale application on the high-resolution data of Sentinel-2 and Landsat 8. A general and future discussion will certainly include what type of organisation can and would be willing to produce such biodiversity products on an operational basis and at global scale.

Pre-processing and input data

One main challenge of the project was the preparation of the input data. Surface reflectance data is required as input data for both the CCC and LSP algorithms. However, this was not available for the years 2017 and 2018 for the regions of interests. Therefore, an evaluation of the L2A software provided by ESA (sen2cor) and other software packages available for atmospheric corrections and cloud screening was needed. Due to a large amount of data (the complete yearly time series from Sentinel-2 and Landsat 8 is required), this was a computationally intensive task that was initially not enough considered in the project processing chain. Nevertheless, this issue is solved for newer Sentinel 2 data as ESA is now providing surface reflectance data operationally starting from the end of 2018 for the entire globe.

In addition to the preparation of the input satellite data, the images also need pre-processing to reliable eliminate pixels without vegetation signature. This step includes the detection of pixels that are contaminated by clouds or cloud shadow, snow covered, non-vegetated (e.g. urban or water areas). In the case of CCC, the separation between long and short vegetation is needed as well, before the input data can be fed into the core algorithm. These pre-processing steps need to be defined and fulfilled to get a reasonable output that can be scientifically interpreted. Within the GlobDiversity statement of work, an end-to-end processor (chain) was not required, nevertheless, it still needs to be defined when useful output results should be produced. For the processing of the pilot sites, this step was solved with processing scripts from DLR (responsible for the prototyping), however, as the upscaling was performed within the Vito cloud, another pre-processing scheme was used. These efforts were not foreseen in the initial workplan, were only partly considered by the developers of the algorithms and needed to be redefined when further developing the algorithms. Most of these pre-processing steps are addressed by many projects, which will largely facilitate the development of RS-enabled operational production systems. Pre-processed and clean data such as Analysis Ready data and fit-for-purposes products are gradually made available on different platforms (e.g. NDVI time series instead of the individual bands).

Land cover input data

For FRAG in particular and also as auxiliary data for CCC (separation between long and short vegetation) and LSP (exclusion of non-vegetated areas), a good and reliable land cover data set is crucial. Nevertheless, a global high-quality land cover data set at high spatial resolution (e.g. based on Sentinel-2 data) is not yet available. Several initiatives have started to work towards the production of such global data sets. The availability of global land cover maps at high spatial resolution will be certainly useful for many RS-enabled algorithms (in particular for fragmentation) and their use in large scale mapping. All the RS-enabled EBV algorithms developed by the project have been designed to replace and adjust the input land cover data sets depending on the algorithm input data needs.

Validation and Verification

For each RS-enabled EBV, the project team developed a validation plan for the ten pilot sites. Nevertheless, the project did not have the available resources for collecting validation data, and thus, was entirely depending on already existing data available in the pilot sites. Therefore, a detailed analysis and validation (and even calibration) were possible for few pilot sites only.

Utility of the data sets and collaboration with pilot sites

The project's statement of work required not only the technical development, but also some regular interactions with the user community (e.g., pilot site managers, GEO BON, biodiversity experts). A close dialogue with the user community is needed in order to develop RS-enabled EBV products useful to the community and demonstrate the usability of the products for biodiversity assessment and monitoring. This approach helps to make the outcome of the project more visible and accepted, and enables the use of such data sets by a large community. For the project consortium, this meant an intense exchange with the pilot sites and with the biodiversity community. Regarding the biodiversity community, this was possible through the organisation of three workshops as well as with the reviews of the strategic documents (e.g., SOR and Roadmap). In particular, the reviews were more time consuming than foreseen and the development of strategic documents with peer reviews required a high level of effort.

The project included 10 pilot sites for developing and demonstrating the algorithms. These 10 pilot sites were chosen based on their connection to the consortium members. The interaction with the focal points of the pilot sites was challenging, because their role became mainly important towards the end of the project, since during the first phase most the project's focus laid in the algorithm development. Therefore, for future projects, it is recommended to early define the role and time schedule for interactions with end-users not being part of a project consortium. Within GlobDiversity, in particular with the pilot sites where the use case demonstrations were performed, the interaction was close and fruitful.

Publication and usability of the project's output

The project was not meant to produce the products globally. Nevertheless, the algorithms will be available for download and use through GEO BONs portals and therefore can be applied and used for other areas as well, as long as the input data is available (i.e. land cover data (FRAG) and satellite data (CCC and LSP).

The GlobDiversity project was funded within ESA's "EO science for society" programmatic framework and thus had a very strong focus on developing outputs which can serve as standard for future projects. Therefore, a focus was also to define document structures suitable for other RS-enabled EBVs. All the strategic documents produced by the project (i.e., SOR, ATBD, UHB and Roadmap) will be available through the GEO BON portals and ideally, the work will be taken up and used by the different GEO BON working groups/task forces, and further developed for defining standards for the entire biodiversity community.

The RS-enabled EBV roadmap provides recommendation on how to proceed further with the development of RS-enabled EBVs in the context of the general EBV framework. The elaboration of the Roadmap included a consultation of the biodiversity community. The roadmap gives many recommendations on how to proceed and foster further development towards a global biodiversity monitoring system.

8 Outreach

8.1 Outreach Material produced by the project

Documents available under https://eo4society.esa.int/projects/globdiversity-development-of-high-resolution-rs-enabled-ebvs-on-the-structure-and-function-of-terrestrial-ecosystems/

- Project description brochure GlobDiversity: *With RS-enabled EBVs key characteristics of biodiversity can be observed and monitored with satellites on a global scale*
- Product description:
  - Fragmentation
  - Canopy Chlorophyll Content
  - Land Surface Phenology
- 5x Newsletter
- Webinars recording
- Workshops:
  - 1st GlobDiversity workshop, Sept. 2017, ITC Enschede, the Netherlands. Workshop for Prioritizing Essential Biodiversity Variables derived from EO
  - 2nd GlobDiversity workshop, Feb. 2018, UZH Zurich, Switzerland. Informing Species Distribution Models and Essential Biodiversity Variables using Remote Sensing
  - 3rd GlobDiversity workshop, Feb 2020, WBF Davos, Switzerland. RS-enabled EBV Roadmap

8.2 Scientific Publications

- **Standardizing Ecosystem Morphological Traits from 3D Information Sources**. Valbuena, R., O'Connor, B., Zellweger, F., Simonson, W., Vihervaara, P., Maltamo, M., ... & Chirici, G. (2020). *Trends in Ecology & Evolution.*
- **Evaluating Prediction Models for Mapping Canopy Chlorophyll Content Across Biomes.** Ali, A. M., Darvishzadeh, R., Skidmore, A., Heurich, M., Paganini, M., Heiden, U., & Mücher, S. (2020). *Remote Sensing, 12(11), 1788.*
- **Comparing methods for mapping canopy chlorophyll content in a mixed mountain forest using Sentinel-2 data**. Ali, A. M., Darvishzadeh, R., Skidmore, A., Gara, T. W., O'Connor, B., Roeoesli, C., ... & Paganini, M. (2020). *International Journal of Applied Earth Observation and Geoinformation, 87,* 102037.
- **Monitoring global changes in biodiversity and climate essential as ecological crisis intensifies.** O'Connor, B., Bojinski, S., Roeoesli, C., & Schaepman, M. E. (2020). Monitoring global changes in biodiversity and climate essential as ecological crisis intensifies. *Ecological Informatics*, *55*, 101033.
- **Canopy Chlorophyll Content Retrieved from time series Remote Sensing Data as a Proxy for Detecting Bark Beetle Infestation.** Abebe Mohammed Ali, Haid Abdullaha, Roshanak Darvishzadeha, Andrew Skidmore, Claudia Roeoesli, Marco Heurich, Marc Paganinig, and Uta Heiden (submitted)

- **Book Chapter in Prep:** Remote Sensing Variables Essential for Biodiversity - Assessment of phenology and biodiversity across different biomes from tundra to tropics. in "Earth Observation for Terrestrial Ecosystems (Elsevier)

8.3 Conference contributions

- GEO BON All Hands Meeting 2018: A. K. Skidmore et al., GlobDiversity - informing terrestrial Essential Biodiversity Variables (EBVs) using remote sensing
- EuroGEOSS Workshop 2018: C. Roeoesli et al., GlobDiversity - informing terrestrial Essential Biodiversity Variables (EBVs) using remote sensing
- Swiss Geoscience Meeting 2018: C. Roeoesli et al., From Space to Earth: Observing Land Surface Phenology Processes using Dense Time-Series of Landsat 8, Sentinel-2 and Phenocams
- AGU Fall Meeting 2018, C. Roeoesli et al., Towards a Global Monitoring of Land-Surface Phenology Processes using Dense Time-Series of Landsat 8 and Sentinel-2 Images
- Living Planet Symposium 2019:
    - C. Roeoesli, V. Wingate et al., EO for Terrestrial Biodiversity
    - C. Roeoesli, I. Helfenstein et al., Advances in Monitoring Land Surface Phenology
- Swiss Geoscience Meeting 2019: V. Wingate et al., GlobDiversity: Remote Sensing-enabled Essential Biodiversity Variables to monitor key biodiversity characteristics at a global scale
- World Biodiversity Forum 2020:
    - Session "Remote Sensing for Biodiversity Monitoring" (Chairs: C. Roeoesli, M. Paganini, G. N. Geller, M. E. Schaepman)
    - R. Darvishzadeh et al., Detecting Bark Beetle Infestation Using Plants Canopy Chlorophyll Content Retrieved from Remote Sensing Data
    - C. Roeoesli et al., Land Surface Phenology observed using dense time-series of Sentinel-2 and Landsat 8
    - Workshop RS-enabled EBV Roadmap (Chair: C. Roeoesli, M. Paganini, M. E. Schaepman, M. Harfoot)
- GEO BON Open Science Conference and All Hands Meeting 2020:
    - B. Smets et al., Copernicus new 10m Vegetation Phenology to monitor ecosystems
    - M. van Eupen et al., Essential Biodiversity Variable Fragmentation
    - M. Harfoot et al., RS-enabled EBV Road Map
    - Project Meeting. GlobDiversity – the development and engineering of remote sensing enabled Essential Biodiversity Variables

9 References

Fahrig, L. (2003) Effects of habitat fragmentation on biodiversity. Annual review of ecology, evolution, and systematics, 487-515.

Hanski, I. (2011) Habitat loss, the dynamics of biodiversity, and a perspective on conservation. AMBIO: A Journal of the Human Environment, 40, 248-255.

Haverkamp, P.J., Bysykatova, I., Germogenov, S., and Schaepman-Strub, G. (submitted) Extreme flooding in the Arctic tundra threatens nesting habitat of critically endangered Siberian crane. Global Change Biology.

Opdam, P. (1991) Metapopulation theory and habitat fragmentation - a review of holarctic breeding bird studies. Landscape Ecology, 5, 93-106.

Pereira, H.M., Leadley, P.W., Proença, V., Alkemade, R., Scharlemann, J.P., Fernandez-Manjarrés, J.F., Araújo, M.B., Balvanera, P., Biggs, R. & Cheung, W.W. (2010) Scenarios for global biodiversity in the 21st century. Science, 330, 1496-1501.

Schwartz, M. D. (2003) Phenology: An Integrative Environmental Science (Tasks for Vegetation Science). doi: 10.1007/978-94-007-0632-3.

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.

Skidmore A.K., Coops N.C., et al. 2020 (in review). Priority list of biodiversity metrics to observe from space. *Nature Ecology and Evolution."*

Wu, M., C. Yang, X. Song, W.C. Hoffmann, W. Huang, Z. Niu, C. Wang, W. Li, and B. Yu. 2018. “Monitoring Cotton Root Rot by Synthetic Sentinel-2 NDVI Time Series Using Improved Spatial and Temporal Data Fusion.” Scientific Reports 8 (1): 1–12. https://doi.org/10.1038/s41598-018-20156-z.

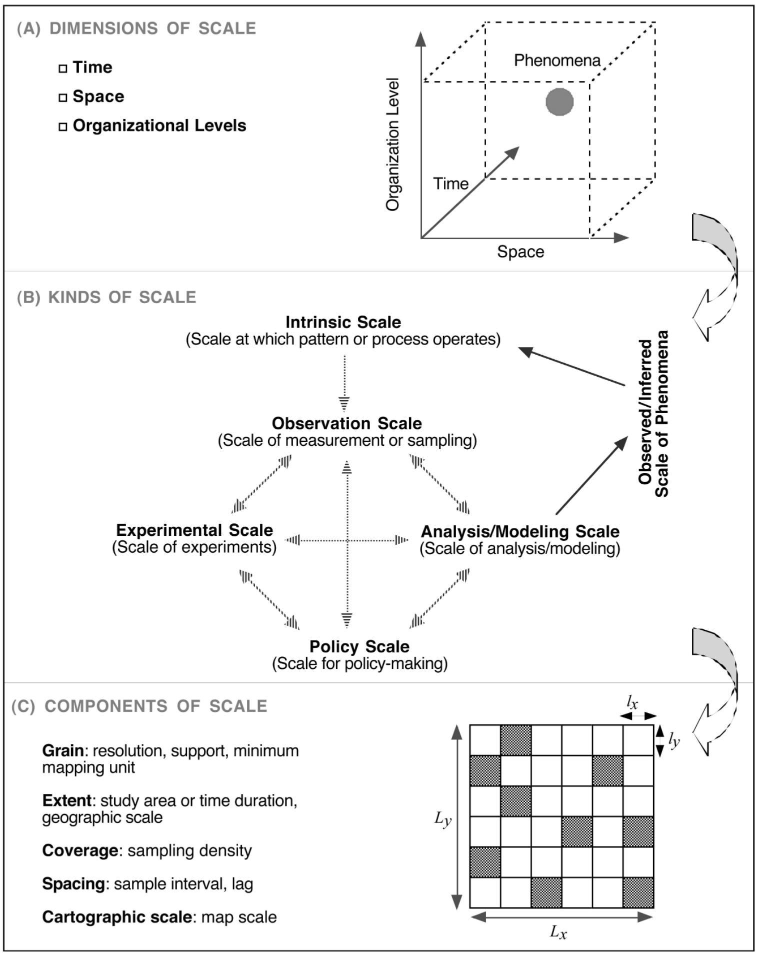
10 Appendix

10.1 Description of Chapters of the Satellite Observation Requirement document SOR

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

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.



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

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.

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.

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]**
…	…

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.

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.

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.

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.

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.

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.