RS-enabled EBV User Handbook: for ecologists

V4
Date: June 2020

Contract No.

4000120011/17/I-NB

Submitted by

DOCUMENT RELEASE SHEET

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Approval (internal)	Approved	
Approval (ESA)		
Distribution:	Only for internal distribution	

CHANGE RECORD

Version	***Date***	***Page(s)***	***Change record***	***Release***
0	July .18		Table of Contents	BOC
1	Sept 18		First content (utility analysis from literature studies)	CR
2	Oct 18		Corrected first content (following recommendations made at the MTR)	BOC
3	Sept 19		Updated based on results of UCDs and in response to comments.	SI
3(ii)	Jan 20		Use cases reformatted; some comments addressed and edits made	WS
3(iii)	Apr 20		Incorporated WUR inputs of 200226 (section 3.1 – why measure habitat fragmentation, and revised UCD on La Camargue - Annex1) and inputs of ITC of 200402 (revised UCD on Bavaria – Annex 2)	WS
4	June 20		Incorporated Siberian white crane use case and updated Bavaria and Camargue use cases. For all use cases added a summary into main text, and rearranged material between sections 2-4 and the annexes. Repetition reduced between sections 1 and 5. Final formatting and editing, including	WS

1. Contents

Acronyms and Abbreviations

BIP – Biodiversity Indicators Partnership

CBD – Convention on Biological Diversity

CCC – Canopy Chlorophyll Content

CESBIO - Centre d'Etudes Spatiales de la Biosphère

CMS – Convention on Migratory Species

CITES – Convention on the International Trade of Endangered Species

EBV – Essential Biodiversity Variable

ECV – Essential Climate Variable

EnMAP - Environmental Mapping and Analysis Program

EO – Earth Observations

EOS/EGS – End of Growing Season

ESA – European Space Agency

ESA CCI – European Space Agency Climate Change Initiative

GBO-4 – Global Biodiversity Outlook 4

GCOS - Global Climate Observing System

GEO BON – Group on Earth Observations Biodiversity Observation Network

HERO - Hyperspectral Environment and Resource Observer

HISUI - Hyper-spectral Imager SUIte

IPCC – Intergovernmental Panel on Climate Change

LAI – Leaf Area Index

MEAs – Multilateral Environmental Agreements

MODIS - Moderate Resolution Imaging Spectroradiometer

PFT – Plant functional type

POS/PGS – Peak of the Growing Season

SDG – Sustainable Development Goal

SOS/SGS – Start of Growing Season

UHB – User Handbook

UNCCD – UN Convention to Combat Desertification

UNFCCC – UN Framework Convention on Climate Change

WMO – World Meteorological Organisation

About this User Handbook

This User Handbook is a product of the GlobDiversity project, funded by the European Space Agency. GlobDiversity is endorsed and supported by GEO BON (https://geobon.org/about/projects/) as a project to develop EBVs enabled from satellite remote sensing data as well as to define the processing chains and best practice to do so. GlobDiversity is actively contributing to the discussion on defining the key EBVs retrievable from satellite remote sensing. GlobDiversity is composed of two phases from June 2017 to June 2020.

This handbook is targeted at a technical audience, literate in the science of terrestrial biodiversity, ecology and ecosystem function and structure. Additionally, it is appropriate for those in the remote sensing community who might have less familiarity with the EBV concept as ecologists but for whom satellite remote sensing is a key tool in analyses of biodiversity-related parameters. This interdisciplinary target audience is advantageous in two ways: (i) in pushing the EBV concept forward; and (ii) in advancing Earth Observation by exploring the demand for a new suite of space observations focused on the biosphere and its component parts – particularly the structure and function of terrestrial ecosystems. This User Handbook is accompanied by a shortened, condensed version for policy makers.

This handbook is structured in five sections. The first introductory section outlines the EBV concept, why it is important and how satellite remote sensing is a key observation tool to develop a subset of the EBVs and turn them into operational data products. The next three sections are focused on the three core EBVs enabled by remote sensing (RS-enabled EBVs) of the GlobDiversity project: Land Surface Phenology, Habitat Fragmentation and Canopy Chlorophyll Content. In each case, there is presented a use case of a practical application of the RS-enabled EBV in a real world conservation project, focused on a site of conservation importance, each from a different terrestrial biome.

Section 5, the last section of this handbook, is important for a broad audience with interests beyond the three RS-enabled EBVs documented in sections 2, 3 and 4. It is policy-focused, examining the demand for EBVs, especially those from satellite remote sensing, in evidence-based decision making in the Multilateral Environmental Agreements (MEAs) governing biodiversity conservation. The role of EBVs in biodiversity indicators for thematic, regional and global assessments of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), for the indicators and targets of the Agenda 2030 Sustainable Development Goals (SDG) and the Aichi Biodiversity Targets are explored. Section 5 is summarised in a science traceability matrix, showing the pathway from the core EBVs to their use in biodiversity indicators for answering global questions about biodiversity change.

1. Introduction

1.1. What are the Essential Biodiversity Variables?

According to the Convention on Biological Diversity (CBD) of the United Nations, Article 2, biological diversity means “the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems”[1]. This all-encompassing definition acknowledges the multi-dimensional nature of biodiversity from genes to species to ecosystems.

Yet, biodiversity is in decline as suggested by recent mid-term reviews of progress towards the Aichi Biodiversity Targets (Tittensor *et al.*, 2014). This decline is evident as genetic diversity is decreasing (Miraldo *et al.*, 2016), more species are at risk of extinction than previously thought (Ocampo-Peñuela *et al.*, 2016) and ecosystems are being modified and degraded by human action and climate change faster than ever before.

The need for global, systematic and scientifically meaningful observations of biodiversity in order to monitor these changes, and to implement the appropriate management responses, has been argued by ecologists of the Group on Earth Observations Biodiversity Observation Network (GEO BON). They have called for a unified biodiversity observation system based on interoperable sub-national, national, regional and global monitoring initiatives (GEO BON, 2017).

Yet, as the CBD definition suggests, biodiversity is a complex, multi-faceted concept, including at the macro-level. Ecosystems are composed of multiple biotic and non-biotic components. Earth supports an enormous array of natural ecosystems, inhabited by an overwhelming diversity of living organisms on land and in the waters. Ecosystems can be as extensive as the entire Arctic tundra, or as small as a particle of soil (Department of the Environment Water Heritage and the Arts, 2009). The cross-scale nature of ecosystems includes ecological processes that operate from centimetres and days to hundreds of kilometres and millennia and collectively affect biodiversity (Vold and Buffett, 2008). They are characterized by their composition, function, and structure which depends on the local environment, as well as management approaches.

Terrestrial ecosystems are communities of organisms and their environments that occur on land masses and dependent, for its primary production, on resources from the three media of air, soil and sun (Chapin III, Matson and Vitousek, 2011). Terrestrial ecosystems are intimately linked with human well-being. They have economic, consumptive, recreational, ethical, social, medicinal, aesthetic and spiritual values for human beings, often described in terms of ecosystem services or natures benefits to people. Humans derive a variety of

[1] Convention on Biological Diversity, UNEP/CBD/94/1

direct economic and consumptive benefits from harvesting terrestrial ecosystem products. Natural ecosystems also provide the settings for a wide range of recreational opportunities including camping, boating, sports fishing, hunting, and hiking. Many people derive enjoyment and comfort from experiencing nature or from merely knowing that minimally disturbed natural ecosystems exist and will be available for future generations to enjoy. Despite the benefits from biodiversity, human activities are leading to both biodiversity loss and substantial alterations of biodiversity distribution, composition, and abundance (Pereira, Navarro and Martins, 2012).Yet surprisingly little is known about the spatial and temporal extent of the threats biodiversity faces at the global level (Joppa *et al.*, 2016) or the distribution and abundances of all terrestrial species, ecosystems and genes (Lindenmayer *et al.*, 2011).

One of the responses from the scientific community to fill this knowledge gap has been to improve biodiversity monitoring by the introduction of a minimum set of variables, which collectively captures biodiversity change at multiple spatial scales and within given time intervals. This approach was described in 2013, in a seminal publication by Pereira et al. (2013). They proposed a harmonized biodiversity observation system based on Essential Biodiversity Variables (EBVs) - a concise set of measurements which are required to study, report, and manage biodiversity change. As a reference for the EBV development process, Pereira et al. (2013) cited the successful implementation of the Essential Climate Variables (ECVs) that underpin the operation of the Global Climate Observing System (GCOS). The ECV concept has been widely accepted as the cornerstone of climate observation networks by the United Nations Framework Convention on Climate Change (UNFCCC), World Meteorological Organization (WMO), and space agencies operating Earth observation satellites. ECVs are now a core part of advanced climate monitoring systems across the terrestrial, marine and atmospheric domains and serve as inputs to global climate models to inform Intergovernmental Panel on Climate Change (IPCC) scenarios.

Within the biodiversity observation and managing system, EBVs represent an intermediate layer of abstraction between primary biodiversity observations and biodiversity indicators: statistical measures which help scientists, managers, and politicians to understand the condition of biodiversity and the factors that affect it, whilst measuring progress towards biodiversity conservation targets at different levels (see section 1.3). The Group on Earth Observations - Biodiversity Observation Network (GEO BON) is taking a leading role in the development of the EBV concept and its operationalisation in national, regional and global biodiversity monitoring networks. As part of this process, GEO BON is attempting to define standards for how to measure these variables. An initial candidate reference list of 22 EBVs in six EBV classes has been published by GEO BON (see table 1), as part of a wider framework of monitoring biodiversity change. These classes have been defined according to the different levels of biological organization: genes, species, populations, and ecosystems, as well as some general, synergistic categories: genetics, taxonomy, function, and structure. Progress in the EBV development process is being facilitated by GEO BON through open review of this list by the expert community who are continually adopting and developing EBVs from the reference list. GEO BON has proposed an end-to-end strategy for the EBV development. This entails dialogue with potential EBV developers to submit their ideas on EBV content and standards, as well as to suggest new EBV candidates (GEO BON, 2017). In addition, an online, open platform is being developed to facilitate that development, publish new EBV datasets and communicate progress. A use case and trial for the portal has been developed for the EBV class Ecosystem Structure and is publicly accessible (https://vat.gfbio.org/).

Table 1: EBV classes and EBV candidates, published by the GEO BON Management Committee (2017)

	EBV classes					
	Genetic Composition	**Species populations**	**Species traits**	**Community composition**	**Ecosystem function**	**Ecosystem structure**
EBV Candidates	Co-ancestry	Species distribution	Phenology	Species richness	Net primary productivity	Habitat structure
	Allelic diversity	Population abundance	Natal dispersal distance	Species interactions	Secondary productivity	Ecosystem extent and fragmentation
	Population genetic differentiation	Population structure	Body mass		Nutrient retention	Ecosystem composition by functional type
	Breed and variety diversity		Migratory behaviour		Disturbance regime	
			Demographic traits			
			Physiological traits			

The development of the EBV framework distils the complexity of biodiversity into a manageable list of priority measurements (Brummit et al., 2015) and help globally consistent reporting of changes in the state of biodiversity. Comparison between regions, between different taxonomic groups, and between various aspects of biodiversity becomes straightforward when the complexity of biodiversity is broken down into EBVs. EBVs allow comparison and harmonization of biodiversity measurements, thereby facilitating the evaluation of progress towards global biodiversity targets. Measures of EBVs may also be used to prioritize conservation actions and to assess the return on investment through monitoring changes in those EBVs (Brummit et al., 2015). This fosters the documentation and quantification of global biodiversity change, overcoming challenges due to sparse or biased data and the general lack of agreed international data standards. The EBVs enable to consistently aggregate variables across time, space and taxa. Therefore, the monitoring of a limited number of essential variables on the structural, functional and compositional aspects of biodiversity is seen as the most cost-effective and efficient framework to develop a global understanding of the changing status of biodiversity (Paganini et al., 2016).

1.2. From EBVs to Indicators

Indicators are the primary mechanism developed for monitoring progress towards targets at any level, whether global, regional, national or sub-national. Indicators help to identify whether actions for protecting biodiversity are working and should continue, or if different approaches need to be examined. Indicators are statistical measures which help scientists, managers, and politicians to understand the condition of biodiversity, and the factors that affect it. Indicators are standardized measures that make it easier to monitor, compare and communicate changes.

An indicator can be a simple metric, such as a count of individuals of a species present, or the percentage coverage of forest, in an area. It can equally be a complex, composite index, combining different data to tell a story about a particular issue. An example is the living planet index (LPI), which was first developed by WWF in 1998. The defining feature of an indicator, as opposed to a 'measure' or 'metric' is that the information has been interpreted in relation to a specific issue or question. For example, a measure of 'forest cover' can be used as a number of different indicators, depending on the question it is needed to answer. It could be used as an indicator of progress in forest conservation, of the status of forest-dependent species, or of carbon stocks, among others.

The Biodiversity Indicators Partnership (BID), a global initiative to promote and coordinate the development and delivery of biodiversity indicators for use by the Convention on Biological Diversity (CBD) and other biodiversity-related conventions, defines an indicator as 'a measure, based on verifiable data, that conveys information about more than just itself' (BIP 2010). The BIP has, over the course of years of experience working at site, national and global levels, developed the 'Biodiversity Indicator Development Framework' (BIDF). This framework (see **Figure 1**), consists of ten steps and primarily aims to ensure that appropriate indicators (and, accordingly, data) are selected that respond to the high level management or policy questions being asked. This helps in turn ensure that the indicators are used, and therefore that there is support for their continued production. Whereas often indicators are selected based primarily on available data, and the user then tries to manipulate the indicator to fit the necessary purpose, the overarching message from the BIDF and the experience of the BIP, is that the user should start by determining the purpose of the indicator before considering the data that is required. Indicators are most effective when developed in response to 'key questions', which themselves are identified by key stakeholders, including those who will be using the indicator.

The BIDF contains three sections:

- **Red boxes**: Steps necessary to determine the **purpose** of the indicator
- **Purple boxes**: Steps necessary to **produce** the indicator

- **Green boxes**: Steps necessary to ensure the **permanence** of the indicator

Understanding the context in which EBVs have been used in relation to the BIDF helps demonstrate to future potential users of the EBVs their value and appropriateness, and also helps ensure the selection of the optimum indicators and underlying data.

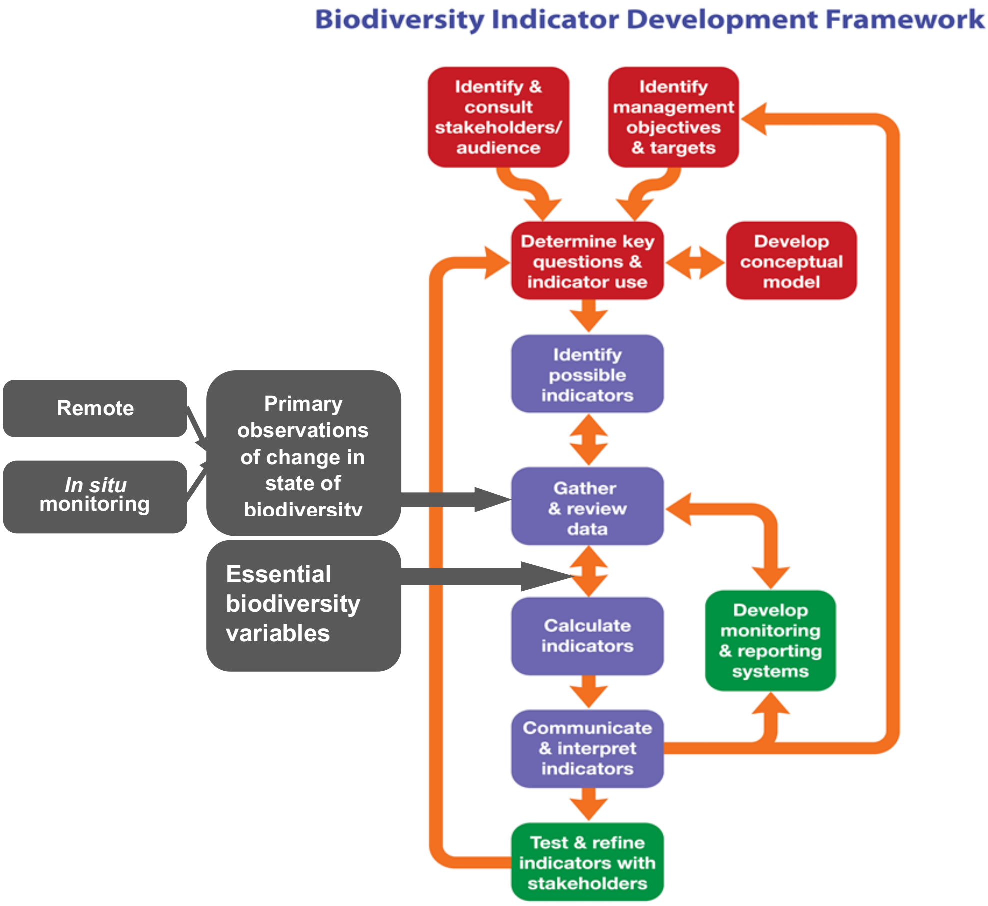

Figure 1: *Biodiversity Indicator Development Framework showing the relevance of EBVs. Adapted from BIP (2010). Red boxes show steps necessary to determine the purpose of the indicator, blue boxes show Steps necessary to produce the indicator, green boxes show steps necessary to ensure the permanence of the indicator.*

Consequently, the development of national, continental and global indicators has received increasing interest in recent years. However, a challenge often lies in the sheer number of indicators that are available (or seen to be needed), making it difficult to select a short list of supporting variables that are both useful and feasible.

To overcome this challenge, clear priorities need to be established to guide the development of observation systems worldwide. Here EBVs can play a crucial role because they focus effort on a finite set of measurements, essential for the characterization of global biodiversity change and, are intended to facilitate the harmonization of existing monitoring schemes to guide the implementation of new ones.

EBVs can be independently used to measure indicators or can be combined with other information for the calculation of indicators. For instance, an observation system that collects data on species abundance for several taxa at multiple locations on our planet can support the derivation of the Living Planet Index, Global Wild Bird Index, measures of species range shifts and many other high-level indicators (COP-CBD, 2012). Some biodiversity indicators require the integration of two or more EBVs, together with other datasets, such as on drivers and pressures (GEO-BON, 2014b, Pereira et al., 2013). For instance, the species extinction risk estimates, that are the basis of the Red List Index, include information on trends in species abundance and occurrence (an EBV); trends in ecosystem extent and distribution (another EBV); complemented with ancillary information about the species, such as the generation time or migratory behavior.

EBVs are viewed as enduring entities insulated from changing technologies at the observation level and from changing approaches and information needs at the indicator level (Pereira et al., 2013). They are an intermediate abstraction layer between primary observations and indicators (

Figure 2). By combining EBV observations with other information, such as on the attributes of biodiversity, or drivers and pressures of biodiversity change, indicators can be developed which are directly useful for policy support Their multiple potential uses include:

- the calculation of indicators, for instance to assess progress towards the CBD 2020 targets;
- exploring the future of biodiversity under different policy and management scenarios (e.g., through modelling);
- helping to guide the development of biodiversity observation systems;
- as a tool to identify existing biases in policy reporting and indicator use, through which comprehensiveness of biodiversity reporting can be enhanced;
- helping to prioritize data mobilization and modelling efforts;
- facilitating data integration over large spatial scales and across a broad taxonomic spectrum and improve availability of information on past and current biodiversity change at all biological levels (genes, populations, species and ecosystems) (Geijzendorffer et al., 2016).

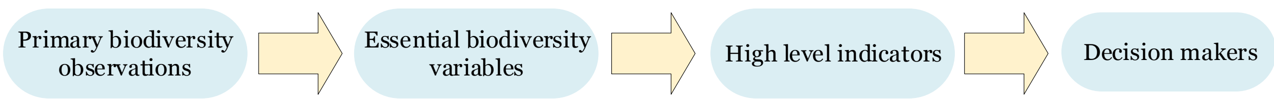

Figure 2: *EBV relationship to high-level indicators (GEO-BON, 2017)*

The introduction of EBVs can transform the shape of monitoring systems from an ever-broadening pyramid to a more focused, streamlined and efficient form (Reyers et al., 2017).

The capacity of EBVs to capture key system dimensions means that one EBV can potentially contribute to multiple indicators, and the same observation can link to more than one EBV, thus potentially enabling a reduction in the numbers of observations needed to deliver those indicators (Reyers et al., 2017; **Figure 3**).

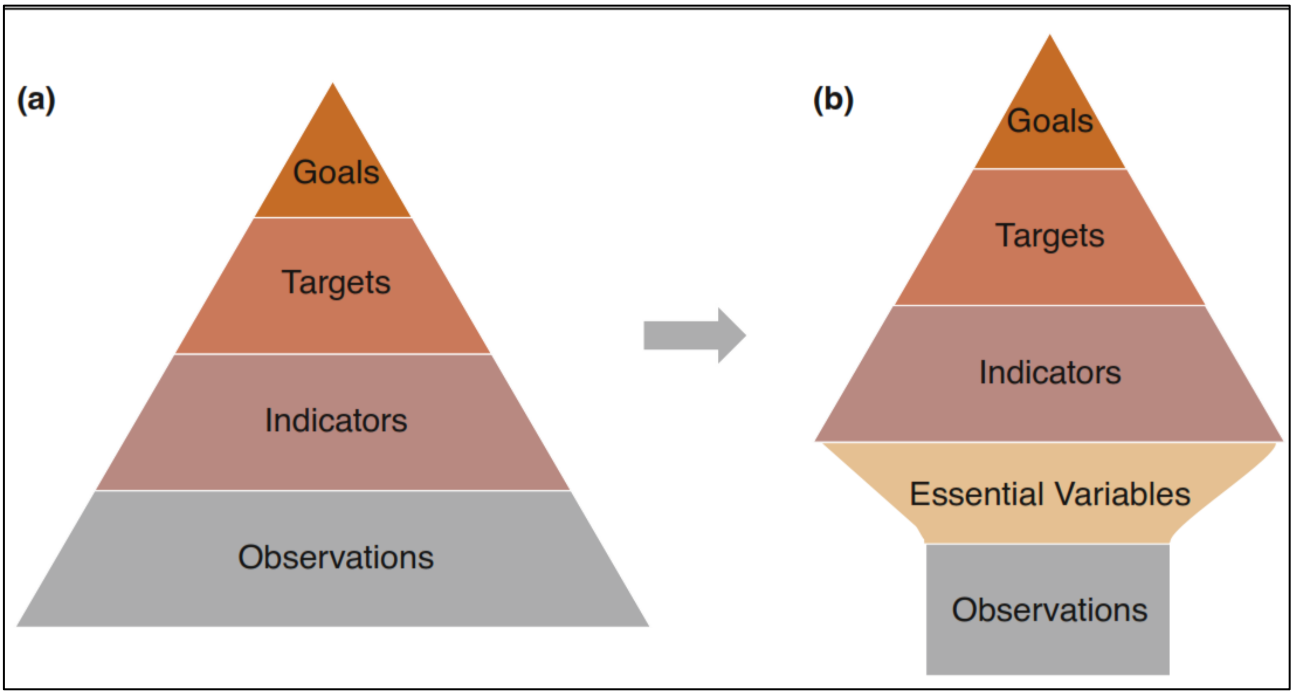

Figure 3: *The significance of EBVs in reducing the required observation data. An ever-broadening pyramid (a) and a more streamlined form (b) due to a limited number of EBVs, directing a targeted set of repeatable and universal observations, underpin a changing superstructure of policy-relevant indicators, targets and goals (Reyers et al., 2017).*

1.3. Using satellite remote sensing as a tool to monitor EBVs

A number of candidate EBVs have been proposed to guide biodiversity observations. Such observations may be obtained *in situ* by direct, field measurements of individuals, populations, species, habitats, etc., or they may be collected at a distance using specialised instruments for *remote sensing*.

There is an enormous potential for satellite remote sensing (or 'Earth Observation', EO) to support the aims of GEO BON in the implementation and progression of Essential Biodiversity Variables (EBVs), supporting biodiversity indicators that facilitate evidence-based decision making. This is owing to the key characteristics of EO (O'Connor *et al.*, 2015):

1. Synoptic view of the Earth's surface – polar-orbiting, sun synchronous EO sensors observe wide swaths of the Earth in one pass, acquiring and storing large amounts of Earth surface imagery under constant conditions of solar illumination;
2. Regular and repeatable observations – polar-orbiting EO satellites orbit the Earth several times per day allowing consistent and systematic surface observations of the entire Earth surface (with the exception of the extreme poles);
3. Multi-annual time series of observations – since the 1970s the average operational lifetime of an EO mission has almost tripled to today's average mission lifetime of 8.6 years (Belward and Skøien, 2014) enabling more stable and continuous observations from the same sensor over several years or more;
4. Cost-effective for monitoring remote and inaccessible areas – EO satellites are designed to observe any location on the Earth's surface at some time in their orbit, albeit with some constraints around polar regions, permitting observation of areas otherwise inaccessible for ground-based surveys.

Regarding cost-effectiveness, a study by Rhodes et al. (2015) on the relative value of field survey and remote sensing for biodiversity assessment indicated that the relative cost of field survey is more than two fold of the remotely sensed methods (228%). Mumby et al. (1999) categorized the costs of mapping from remote sensing as: i) set-up costs (e.g. hardware and software), ii) field survey costs for calibration or validation of the products, iii) the time required for image and field data processing (analysis), and iv) the cost of imagery. The prevalence of a remote sensing facility in a plethora of institutes worldwide and availability of fine resolution remote sensing data at little/free cost tremendously reduces the cost of the approach. The advancement in technology enables remote sensing data to be easily processed and analyzed fast.

Nowadays due to the launch of many Earth Observation satellites, there is more opportunity for applying satellite images to biodiversity assessment and monitoring. More and more processed satellite data are freely available, which minimizes the cost of utilizing remote sensing. Long term availability of free data from satellites such as Sentinel-2 and Landsat series has opened new windows to retrieve biodiversity variables systematically and globally at low cost, and thus becomes highly beneficial by rendering suitable data for efficient real time assessment and monitoring of biodiversity.

With this greater open access to EO data, and more cloud computing power than ever before, EO products and the computational tools to process them can readily help countries use EBVs to support the indicators necessary to track progress towards global biodiversity and related goals, such as the Sustainable Development Goals (SDGs) and the 2020 Aichi Biodiversity Targets. It also becomes possible to use EBVs in large modelling efforts to explore alternative futures for biodiversity, ecosystems and human livelihoods, comparable to the use of ECVs in climate models.

Although Skidmore et al. (2015) proposed a number of EBVs that can be directly measured and monitored using remote sensing, the potential of remote sensing data in the context of EBVs has not been thoroughly investigated until the GobDiversity project described in this handbook.

1.4. GlobDiversity: the relevance of RS-enabled EBVs in policy and practice

The EBVs have the potential to support the monitoring and implementation of a range of Multilateral Environmental Agreements (MEAs) and intergovernmental processes. Those of particular relevance to EBVs are the Convention on Biological Diversity (CBD), the Ramsar Convention on Wetlands, the Convention on Migratory Species (CMS), and the UN Convention to Combat Desertification (UNCCD). In addition, EBVs are highly relevant to the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and the Sustainable Development Goals (SDGs). All these different MEAs and processes have their own ways in which progress is monitored, using suites of indicators defined, agreed, and produced in different ways. While the SDG indicator framework takes a 'bottom up' approach, with data collated from the national level, the indicators for the CBD use a mixture of national-level data and global data, collected in a variety of ways (including in-situ data collection, modeling and remote sensing). Other MEAs and processes have more focus on implementation, and collect data using national reports in which countries confirm if they have implemented a particular aspect in response to questions.

Regardless of the way in which indicators are currently produced, the RS-enabled EBVs have clear relevance for tracking progress towards targets, and for monitoring the impact of the individual targets and the broader goals and objectives of the different strategies. The GlobDiversity focused on the development of three RS-enabled EBVs: Land Surface Phenology, Habitat Fragmentation, and Canopy Chlorophyll Content. Table 2 summarizes the relevance of these three RS-Enabled EBVs for the above-mentioned global policy processes. The contribution of these and other RS-enabled EBVs to the implementation and monitoring of MEAs is further discussed in the concluding section 5 of this handbook.

The three selected RS-enabled EBVs were each the subject of a site-based use case demonstration under the GlobDiversity project. These use case demonstration (UCD) studies were primarily intended to highlight the relevance of high spatial resolution Remote Sensing-enabled Essential Biodiversity Variable (RS-enabled EBV) developed within the framework of the GlobDiversity project. The UCDs were on the following:

- Land Surface Phenology: Siberian white crane in Kytalyk National Park, eastern Russia
- Habitat Fragmentation: dragonfly habitat connectivity in the Camargue, France
- Canopy Chlorophyll Content: spruce bark beetle attack in the Bavaria Forest National Park.

These use case demonstrations (UCDs) are summarized in Sections 2-4, including potential applications of the RS-enabled EBV that was developed, and lessons learned from the use case. More detail on each of these UCDs can be found in Annexes 1-3, including highlighting how the RS-enabled EBV product, or the eventual indicator that it supports the measurement of, fits within key areas of the Biodiversity Indicator Development Framework.

A further use case looked at the utility of RS-enabled EBVs in ecological modelling. We conducted a series of explorations on this topic: an expert consultation of their utility for vegetation modelling; a statistical analysis of the relationships between the RS-enabled EBVs (LSP and 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. In Annex 4 are reported the results from the Kruger case study, along with findings from the expert consultation. The results 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 here suggests that this does not translate into significantly improved model performance.

Table 2: *Summary of relevance of RS-enabled EBVs to biodiversity and sustainable development processes*

	CBD	Ramsar	CMS	UNCCD	IPBES	SDGs
Land Surface Phenology	Directly relevant to Aichi Biodiversity Target 15 (resilience and restoration), among others.	Directly relevant to Target 5 (ecological character)	Indirectly relevant to Target 10 (area-based conservation)	Directly relevant to Strategic Objectives 1 (improved ecosystem condition) and 3 (enhance resilience against droughts)	Relevant to the land degradation assessment and to regional/national assessments ("nature")	Directly relevant to Goal 15 (Life on Land), in particular Targets 15.1 (ecosystem conservation), 15.2 (sustainable forest management), 15.3 (desertification), 15.4 (mountain ecosystems), 15.5 (habitat degradation)
Habitat fragmentation	Directly relevant to Aichi Biodiversity Targets 5 (habitat loss) and 11 (protecdted areas) in particular.	Directly relevant to Target 6 (connectivity) and Target 5 (ecological character)	Directly relevant to migratory pathways, and I particular Target 3 (governance of migratory species and migration systems), Target 6 (adverse impacts of fishing and hunting), Target 10 (area-based conservation).	Directly relevant to Strategic Objectives 1 (improved ecosystem condition) and 3 (enhance resilience against droughts)	Relevant to the regional and global assessments ("nature").	Directly relevant to Goal 15 (Life on Land) (Life on Land), in particular Targets 15.1 (ecosystem conservation), 15.2 (sustainable forest management), 15.3 (desertification), 15.4 (mountain ecosystems), 15.5 (habitat degradation)

Canopy Chlorophyll Content	Directly relevant to a number of Aichi Biodiversity Targets, particularly 15 (resilience and restoration).	Directly relevant to Target 11 (wetland functions) and Target 5 (ecological character)	Indirectly relevant to Target 10 (area-based conservation)	CCC indicates primary productivity and ecosystem function, and thus can be used to understand degradation, relevant to Strategic Objectives 1 (improved ecosystem condition) and 3 (enhance resilience against droughts)	Relevant to the land degradation assessment and to regional/national assessments ("nature")	Directly relevant to Goal 15 (Life on Land), in particular Targets 15.1 (ecosystem conservation), 15.2 (sustainable forest management), 15.3 (desertification), 15.4 (mountain ecosystems), 15.5 (habitat degradation)

2. RS-enabled EBVs in practice: Land Surface Phenology

2.1. Why monitor land surface phenology

2.1.1. Expected societal benefits of the RS-enabled EBV

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 strong indication on the health of the vegetation and influences such as diseases or meteorological effects (e.g., drought). Gradual changes in the profile and 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 – using phenological properties such as start and end of the growing season as well as its amplitude – disturbances and changes in the ecosystem can be detected and documented (e.g., Wu *et al.*, 2018).

On a long-term (decadal) basis, trends in LSP can be indicative of changes in biodiversity or health of the ecosystem. Such effects can be related to changes from external influences such as changing land use, climate or invasive species and can serve indicators such as the CBD generic indicators:

- Changes in extent and structure of forest and other natural habitats
- Influences from invasive alien species (distribution and population)

These indicators are closely connected to the Aichi targets, and can be related for instance to Aichi Targets 9, 12, 5 and 11 (see also Science Traceability Matrix, section 5.3).

2.1.2. Strengths and weaknesses of space-based observations

Many studies using low-resolution optical data such as MODIS (e.g., Myneni *et al.*, 1997; Zeng, Jia and Epstein, 2011) have demonstrated the usefulness of LSP in a long-term and large-scale perspective. With satellites orbiting the Earth without the need of commanding or steering, continuous time series covering almost the entire world are available. They continuously image the world and data are freely available with the density of the time series only depending on the satellite's orbit, atmospheric condition and cloud cover. Nevertheless, free high-resolution images were sparsely available until 2016 and time series were not sufficiently dense for phenological observation. Land-surface phenology observations were only feasible with low-resolution (e.g., 500m for MODIS), which implies coverage at ecosystem level only. With the newest generation of satellites from the European Sentinel fleet, in particular the optical satellites Sentinel-2A and Sentinel-2B, denser sampling up to 5-6 days in mid-latitude is possible and a combination with Landsat 8 allows extracting a robust yearly vegetation profile at high spatial resolution (10 m for Sentinel-2). The two satellite families have sufficient similar sensitivity for the spectral bands of interest (i.e. mostly optic and near infrared) to combine observations from the different sensors. However, careful processing and interpretation are required due to the influence of the different spatial resolution for Landsat 8 and Sentinel-2 (30 vm and 10 m respectively) as well as uncertainties introduced due to their projection procedure, coordinate systems and geometric uncertainty (Storey *et al.*, 2016).

The main drawback of these new monitoring techniques is the very high data volume that needs to be processed and thus the need for sufficient computational power. In addition, atmospheric effects need to be corrected carefully. These two parts require technical skills in order to correct the data correctly and then process them in parallel in a cloud environment. Nevertheless, atmospheric-corrected data are already operationally available for Landsat-8 and ESA has started to publish atmospheric corrected Sentinel-2 images since 2018.

In comparison to other remote sensor platforms, such as drones and airborne systems, satellites operate continuously but with lower spatial resolution. Costs and effort for a spatial coverage of phenological observation with drones or aircraft to accomplish sufficient temporal resolution (e.g. ideally multiple observations per week during green-up and senescence season) is high or even impossible for large-scale coverage. On the other hand, overflights can be planned depending on the weather forecast and the required sampling density (more in spring and autumn) – something that is not possible with satellite observations. The processing chain is then the same as for satellite images, except that the atmospheric influence is lower for drone images in particular. Airborne and drone systems do not always have the (calibrated) near infrared channel, which limits the selection of spectral indices that can be used for the analysis.

Phenology at species level has been observed for hundreds of years – although only for certain species and regions. The main draw-back of *in-situ* and visual observations is the limited spatial coverage. Mostly, these observations have to focus on certain (mostly key) species and regions, as time effort is very high. In addition, inter-comparison between regions is very difficult due to a lack of standards for phenological observations. There are efforts on-going to harmonize observation procedures (e.g., Yost *et al.*, 2018), however, local users may have followed certain protocols for decades and will not want to interrupt their time series. Additionally, the observed metrics may represent inherently different phenological processes than captured by a pixel in a satellite image. Remotely sensed data shows variation in the absorption of radiation in different light channels and the translation to leaf expansion or bud burst is not straightforward. These challenges render comparisons between *in-situ* and remotely sensed phenology very difficult or even impossible. Nevertheless, comparison of long-term trends in both types of data series and at appropriate aggregation level is achievable.

In general, if a global coverage needs to be achieved, satellite observations are the only cost-efficient and feasible technique. Even for larger areas, such as national parks, traditional methods quickly reach the limits of timely and costly effort. With today's high-resolution satellite images, the gap with high-resolution *in-situ* or field data is less significant.

2.1.3. RS-enabled EBV product specification

The RS-enabled EBV 'Land Surface Phenology' is composed of a set of parameters which can be retrieved from long (minimum a year) time series imagery and derived products (e.g. vegetation indices). These parameters are often referred to in the literature as 'LSP metrics' or 'phenometrics', but are hereafter referred to as "properties". Common properties are Start of the Growing Season (SOS/SGS), End of the Growing Season (EOS/EGS) and amplitude. Other metrics may include Peak of the Growing Seasons (POS/PGS), Green-up/Senescence Rates, (Partial) Integrals of vegetation indices and number of growing seasons per year. Satellite-based properties can be calibrated, verified and validated using on-the-ground observation networks, ideally with the use of phenological cameras (phenocams) which are fixed position, mounted cameras designed to image the phenological development of an area over time.

A dense time series of observations is crucial for a reliable observation of LSP. So far, most projects focused on the lower spatial resolution MODIS satellite (500 m for bands 3-7) that nevertheless has a revisit time of one day. Before the launch of the Sentinel-2A satellite in 2015, it was almost impossible to construct a reliable time series at high spatial resolution, except for very high latitudes with many overflights. Nowadays and in particular with the availability of Sentinel-2B (mid-2017), there is a dense time series for 2017 and 2018 (see Figure 4). With this availability of images, we concluded that – for most regions – the time series is dense enough to extract phenology and there is no need to use low-resolution images such as MODIS data for the interpolation of potential data gaps.

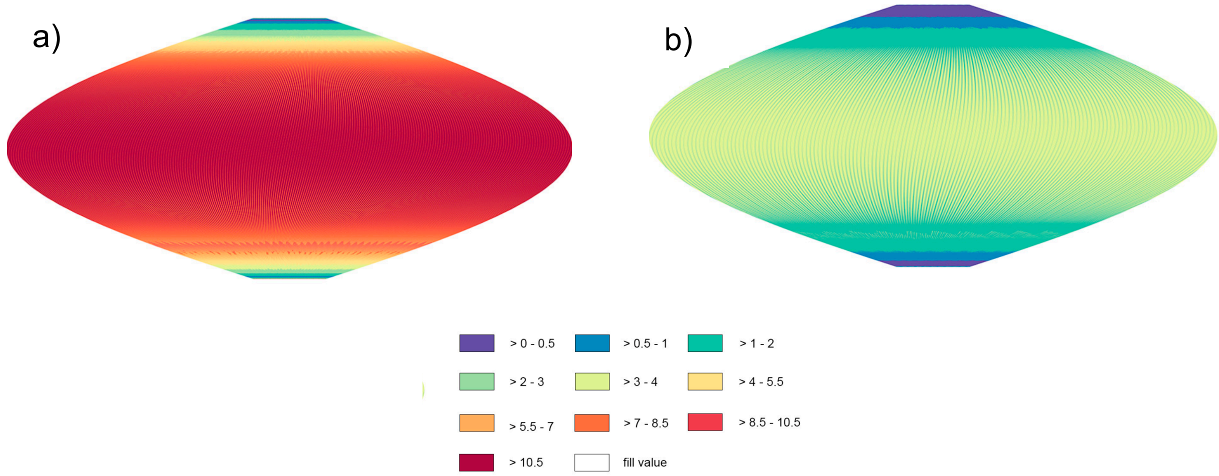

Figure 4: *from* (Li and Roy, 2017) *(figure 5): Averaged revisiting time for a) Landsat 8 and b) Landsat 8, Sentinel-2A and Sentinel-2B during one year (1/1 – 31/12). The revisiting time drops from around 16 days with Landsat 8 only to less than four days with the three satellites. More details in* (Li and Roy, 2017).

2.2. Utility of Land Surface Phenology

2.2.1 Siberian white crane in Kytalyk National Park

Accurate mapping and change detection of potential breeding habitat is crucial for identifying protection and management priorities for the critically endangered Siberian white crane (*Grus leucogeranus*) in Kytalyk National Park. Accordingly, this study sought to demonstrate the possible contribution of remote sensing data to the conservation of this species by statistically evaluating the Land Surface Phenology (LSP) RS-enabled EBV, in conjunction with a multi-data source habitat suitability model and high resolution habitat map. 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.

The rapidly changing climate conditions in this biome, with more extreme weather events, are altering not only the habitat available for many species, but is also having important carry-over effects for many migratory species such as the Siberian white cranes. Across this Arctic tundra biome, changing temperature and precipitation regimes are altering the timing of snow melt, and hence associated spring flood and drought events, such as those that occurred during the summers of 2017 and 2019, respectively.

Importantly, these changes affect regional hydrological dynamics, soil permafrost and vegetation community composition, with a major consequence being increased shrubification. Moreover, these change processes are thought to be impacting the availability of nesting habitat of the Siberian white crane in the Kytalyk National Park, in particular around the margins of lakes. Shifts visible in satellite-observed land surface phenology, in response to such change processes, are known to be widespread throughout the Arctic tundra biome. Importantly, they represent a well-documented approach to quantify the ecosystem responses to climate change. High resolution LSP products are further expected to provide new insight into landscape-scale vegetation dynamics.

The first aim of this study was to describe and characterize the regional LSP data product and to provide a qualitative assessment of the data product based on comparisons with auxiliary datasets including habitat maps. Secondly, this study examined the correlation between LSP metrics and habitat nesting potential (NPO) of Siberian cranes (Haverkamp et al., In prep.), in order to demonstrate the effectiveness of these LSP metrics at identifying suitable crane habitat.

We found that the LSP metric Start of Season (SOS) can be used as a spatial predictor of NPO (Figure 5), 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 from cranes for nesting (Figure 6). Moreover, shrubification is a major ecological change process in the artic, and tracking this process using LSP products has potentially much wider application in ecology and conservation.

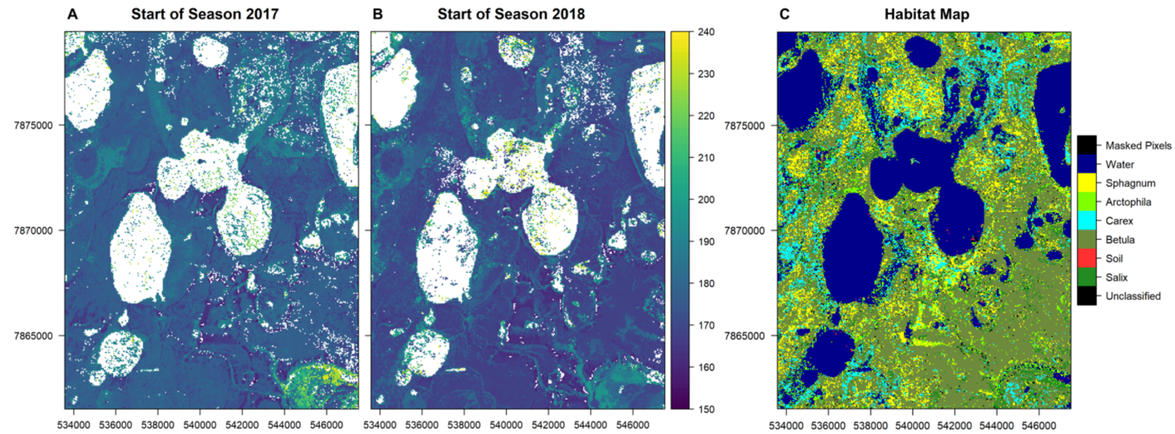

__Figure 5:__ Start of Season metric for the years 2017 (A) and 2018 (B) plotted for a sub-set area of interest; in addition, the corresponding Landsat 8 habitat map (C) is shown.

Finally, as an important outlook of this study, we conclude that the range of LSP metrics can serve as a baseline for monitoring long-term shifts in terrestrial plant community composition. Such detailed information characterizing habitat change is expected to further contribute to a better understanding of the environmental and ecological changes impacting the Park, while facilitating the conservation of the Siberian white crane.

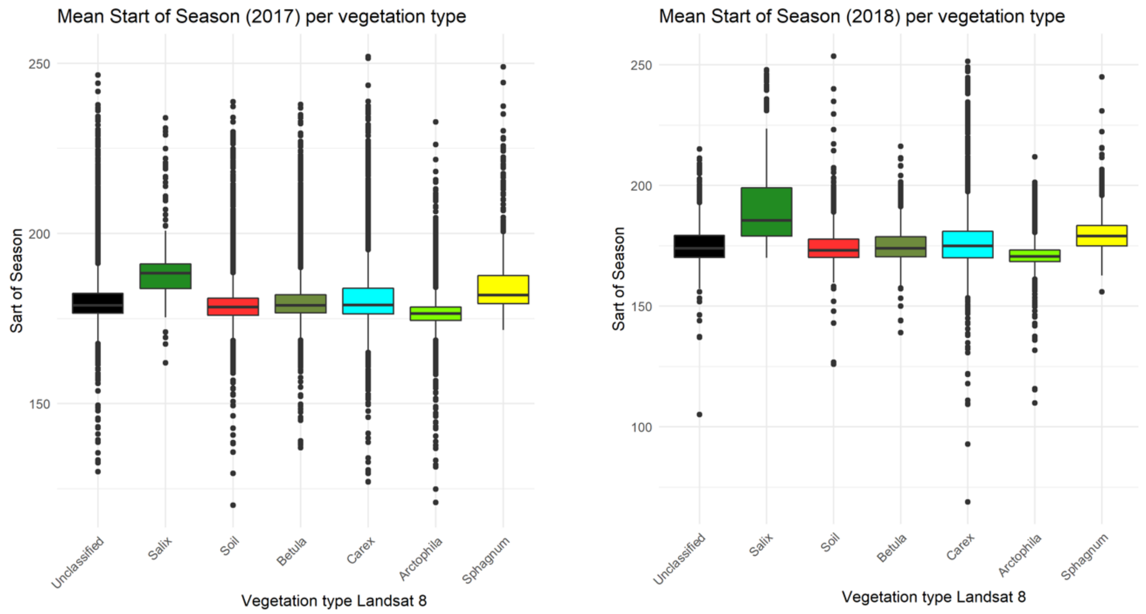

__Figure 6.__ Mean Start of Season metric values extracted for each habitat (vegetation) class of the Budischev et al. 2014 habitat map for 2017 and 2018, for the same region as shown in the previous figures. The LSP metric signature for the vegetation type "Salix" stands out from other vegetation types.

In conclusion, this study establishes and demonstrates the effectiveness of high resolution remotely sensed datasets in providing baseline ecologically-relevant information that is useful to conservation practitioners and researchers for monitoring ecological change.

2.2.2 Potential application of the results

The results were developed, discussed and presented to the Spatial Ecology & Remote Sensing research group, 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. The work performed within this 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.

2.2.3 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, our 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.

3. RS-enabled EBVs in practice: Habitat fragmentation

3.1. Why measure habitat fragmentation

3.1.1. Expected societal benefits of the RS-enabled EBV

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). Construction of transport infrastructure through natural landscapes will also contribute to a further fragmented landscape, especially with a large impact for ground dwelling species (Forman & Alexander, 1998; Jaeger, 2000). 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).

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.

The habitat fragmentation RS-Enabled EBV can be used by stakeholders such as governments, NGOs, research centers, and ecosystem service providers, who are responsible for tackling the decline of biodiversity in fragmented landscapes. For example, these stakeholders may be involved in the assessment of the impact of new transport infrastructure on the sustainability of populations, or 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).

3.1.2. Strengths and weaknesses of the RS-enabled EBV

The main products of the RS-enabled EBV habitat fragmentation are quantitative maps which show the spatial distribution of the level of fragmentation of a specific ecosystem.

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

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 generate from satellite-derived products. The scale of the landscape as used by the species is decisive for the scale of the needed input data. Another strength of the fragmentation EBV is that it can be relatively straightforwardly implemented across different scales, using basic land cover data as a starting point for deriving habitat (suitability) maps. These habitat maps directly derived from global products can serve as an indication of how species perceive and use the landscape. In a second step, existing land cover products can be thematically refined to derive more detailed suitable habitat types to assess species-specific habitat classification. As an example, we can further refine broadleaf forests by separating young and old-growth forests, or ones dominated by particular trees. Since monitoring fragmentation of habitat is strongly related to species- and biodiversity monitoring purposes, is doesn't need a very short (and intensive) repetition frequency. A yearly, or longer, temporal resolution or time interval of the EBV is generally sufficient.

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; Verboom & Pouwel, 2004). 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).

3.1.3. Habitat fragmentation product specification

Fragmentation can be calculated based on remotely derived vegetation, 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.

For fragmentation studies on large mammals and/or birds, one can work with Sentinel-2 (10-20 m) or Landsat (30 m) derived land cover information. For species such as amphibians and/or butterflies one needs more spatial detail, e.g. achievable with 1 m spatial resolution. Compared to using just land cover information, more specific and targeted habitat types can be extracted using additional remote sensing data and derived products.

Sentinel-2 derived land cover products will become increasingly available over time, not only at country and/or regional level but also at the continental level. A good example of a country-wide high-resolution land cover map is the CESBIO land cover map of France based on 20 m resolution Sentinel-2 alone (Inglada et al., 2017). So far at the global level, there are few useful data sources, but these include the ESA CCI land cover products (https://www.esa-landcover-cci.org/) and the methodology of the Global land cover Sentinel-2 (http://seom.esa.int/page_project025.php; http://s2glc.cbk.waw.pl/). At the continental level, newly developed useful products are the Copernicus LC100 2015 produced by VITO (https://land.copernicus.eu/global/content/release-global-100m-land-cover-maps-2015) and the future expected 10 m resolution version of this product.

3.2. Utility of Habitat Fragmentation

3.2.1. Dragonfly habitat connectivity in the Camargue

As just discussed, mapping habitat connectivity and fragmentation is highly important for informing species conservation. Identifying critical pathways for these species can help management bodies to avoid or minimize human impacts in the areas concerned.

The main objective of this use case study on the Camargue was to test innovative approaches for the assessment of habitats 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 Camargue Delta of the Rhône river, southern France, covers 135 000 ha and hosts a richness of species typical of Mediterranean wetlands. It is a complex mosaic of natural and man-made, wet and dry habitats including lagoons, salinas, brackish/freshwater marshes with emergent or aquatic vegetation, as well as halophilous scrubs and steppes and agro-systems such as rice fields.

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 Camargue. For this species, three things were relevant to assess: (1) the location of its habitats; (2) how well these habitats are connected for species movement; and (3) where the opportunities are to strengthen this network. A habitat fragmentation RS-enabled EBV was developed to undertake this assessment.

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. In Mediterranean wetland ecosystems, surface water is typically highly dynamic at intra- and inter-annual timescales and this can be important to the ecology of many species, such as the dark spreadwing. The use of EO-based tools (e.g. high resolution satellite image time series) enables access to data and information that can capture these trends at different time scales.

For the development of the habitat fragmentation RS-enabled EBV, the LARCH-SCAN-Hanski metric was implemented to measure structural ecosystem discontinuity. This metric focuses on the effects of dispersal on the persistence of organisms across land-cover types. The LARCH-SCAN method involves three steps:

Habitat Suitability Index (HSI) generation. Habitat maps where created by combining Sentinel 2 / Landsat-8 derived land cover maps and S2 water-/flooding dynamic data to capture the seasonality of the flood duration.

Calculation of spatial cohesion (LARCH SCAN-Hanski metric). LARCH-SCAN is based on the dispersal capacity of species. The model uses a formula that describes the dispersal curves of birds (Siefke, 1984) and is used for connectivity measures in metapopulation models (Hanski, 1994). Fragmentation for *Lestes macrostigma* was calculated for six distances: 100 m, 500 m, 1 km, 5 km, 10 km and 20 km. The maximum cohesion values of all these distances were chosen to represent the cohesion of *Lestes macrostigma* in the Camargue.

Evaluation of cluster size (sustainability). In the third step cohesion maps were used to derive clusters of connected habitats cells to construct connected (and isolated) habitat areas that can support sustainable populations. Patterns of cohesion values can be used for planning corridors between local patches or to improve weaker spots in networks. Depending on the application, different thresholds can be set to create the clusters. For *Lestes macrostigma* in the Camargue a threshold of 0.1 was used to derive the connected local habitats

The map of connected habitat clusters based on this chosen threshold is given in Figure 7. It shows a large core area of connected habitat to the west of the study area, with small outlying clusters of habitat that could potentially be joined through some targeted habitat management and restoration. Some relatively large, although more isolated, patches and clusters of habitat are spread further to the east, and these would be a priority for preserving and connecting to make a larger network and enhance the resilience of the dragonfly population in the Park. This can potentially be addressed within the elaborate water management plan of the park management authorities (see 3.3.3 below), as water is pumped from the Rhône and distributed through a network of irrigation and drainage channels, including for habitat management purposes. Long-term monitoring of the habitat clusters using the habitat fragmentation RS-enabled EBV, combined with population monitoring data for the dragonfly, would help understand inter-annual variability (as influenced by surface water dynamics) and the resilience of the populations to such changes.

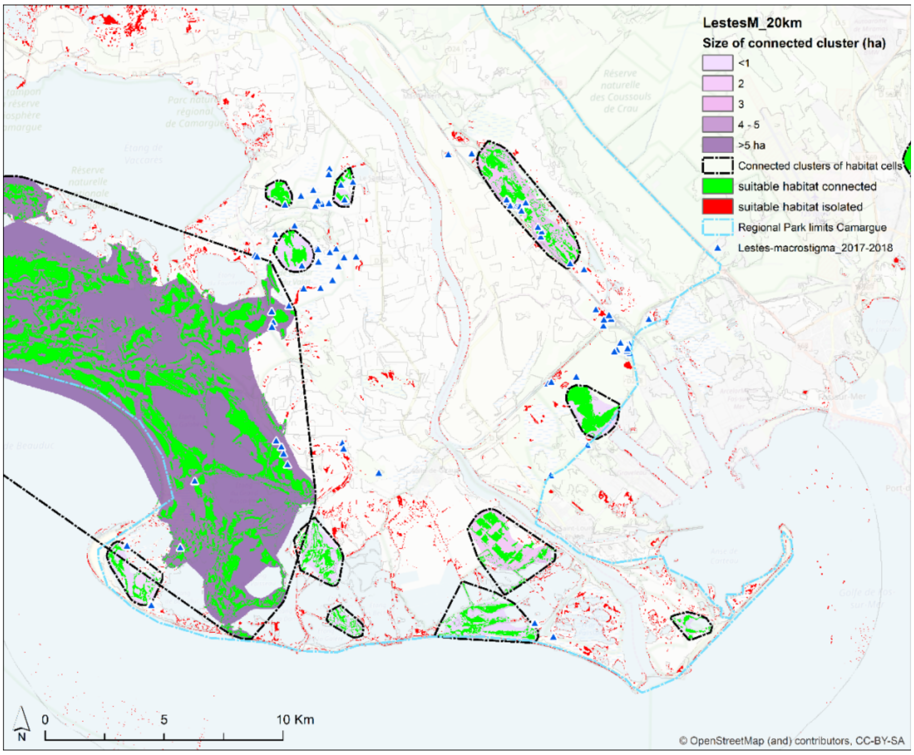

***Figure 7**: Zoom in of output connected habitat clusters for* Lestes macrostigma *in the Camargue and their size in hectares of habitat using a Scan-threshold of 0.1 (10% of Habitat in the defined neighbourhood).*

3.2.2 Potential application of the results

The results are of potential use by the Tour du Valat and the management authorities of the Regional Nature Park of the Camargue and the National Reserve of the 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 Camargue are predominantly influenced by the salinity, and the quantity and the quality of water that is available year round. Large areas naturally dry up during the summer period, but through a complex network of irrigation and drainage channels, 730 millions of 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.

3.2.3 Lessons learnt from the use case

Tour du Valat collected the main input data to create the 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 loaded into standard GIS software for viewing and further processing into printable maps (e.g. QGIS / ArcMAP). The level of technical ability required to produce the EBV is mainly sufficient GIS-knowledge to extract S2/L8-datasets, classify them and combine them into habitat maps. These preprocessing steps are all done using standard GIS/remote-sensing software. The running of the fragmentation algorithm doesn't require specific skills other than basic computer handling knowledge.

One of the most relevant lesson 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).

Finally, the tested habitat connectivity EBV could become even more useful if implemented at broader scales than sites such as the 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.

4. Examples of RS-enabled EBVs in practice: Canopy Chlorophyll Content

4.1. Why measure canopy chlorophyll content

4.1.1. Expected societal benefits of the RS-enabled EBV

Canopy chlorophyll content (CCC) has a crucial role in ecosystem function, from which humans derive benefits, at the interface of social and natural systems, in the form of ecosystem services. This is because chlorophyll is Earth's most important organic molecule that is necessary for photosynthesis (Blackburn, 2007). CCC defines the total photosynthetically active radiation absorbed by the canopy (Gitelson et al., 2015, and 2005), and is a critical input variable of terrestrial biosphere models to quantify carbon and water fluxes (Luo et al., 2018), primary productivity (Houborg et al., 2013, Peng and Gitelson, 2011), and light use efficiency (Wu et al., 2012). Changes in CCC indicate effects of disease, nutritional and environmental stresses (Korus, 2013, Zhao et al., 2011, Inoue et al., 2012). CCC is an essential ecological variable that plays a vital role in the exchange of carbon, water, and energy between the biosphere and the atmosphere. It is a plant pigment that provides valuable information about plant physiology and ecosystem processes (associated with specific functions). It can be measured at different scales according to different needs, e.g. ecologists might be interest in species-specific chlorophyll measurements, farmers in field level chlorophyll for mixed crops, while decision makers might be interested in CCC as an indicator to assess the influence of climate change, and other anthropogenic and natural factors on plant functions. Monitoring the dynamics of CCC helps to understand the adaptation of forest, crop, and other plant canopies to such factors (Féret et al., 2017).

Therefore, from an ecosystem management perspective, chlorophyll may act as a bio-indicator of plant physiological condition, where changes in chlorophyll can be indicative of plant stress, for example, due to limited water availability, disease, pollution, or extremes in temperature. At global and regional scales, an accurate measurement of chlorophyll content across a range of plant functional types (PFTs) and appropriate temporal intervals is one of the overarching variables to improving the accuracy of ecosystem models for forecasting carbon dynamics within the context of a changing climate. Quantification of CCC at multiple scales therefore helps to make management decisions (plan management strategies) objectively and easily, while assessing the impact of decisions on biodiversity.

Thus, CCC is one of the RS-enabled EBVs that can be used to support indicators in use by the Convention on Biological Diversity (CBD) and all its Contracting Parties, biodiversity-related conventions and scientists, conservation agencies, national governments engaged in biodiversity management and policy development to assess progress towards the 2020 Aichi Biodiversity Targets (GEO-BON, 2017). CCC is a vital input to estimate indicators such as trends in carbon stocks and trends in resilience within ecosystems of Aichi target 15, and net primary productivity of Aichi target 3 (Secretariat of CBD, 2010). National Biodiversity Strategies and Action Plans (NBSAP) are the principal instruments for implementing the Convention at the national level. Information on the amount and distribution of CCC could be used in NBSAPs to assess and report biodiversity indicators related to ecosystem processes and functional aspects of biodiversity (e.g., ecosystem health and vegetation physiological status). The CCC RS-enabled EBV supports efficient and timely evaluation of measures taken to implement the convention and the effectiveness of these measures (Secretariat of CBD, 2011) by providing spatially and temporally contiguous information.

4.1.2. Strengths and weaknesses of space-based observations

Remote sensing products such as CCC are a fundamental source of information for assessing and monitoring the functional diversity component of biodiversity, yet they have no market or monetary value. Generally, it is challenging to translate the values of remote sensing products into financial terms. To address this, economists need to work together with remote sensing and ecology scientists to understand the contribution of RS-enabled EBVs in biodiversity assessment and monitoring. Owing to the difficulties in quantifying prices, here we provide generic indicators in valuing the costs and benefits of remote sensing based information.

It is apparent that global Earth observations from space provide a tremendous near real-time data to understand our living planet. Like other remote sensing products, global CCC products have both costs and benefits. However, the benefits are much more difficult to estimate than costs. This is due to the fact that CCC map products (information) can be utilized for a number of purposes ranging from being used as input to biosphere process models to the more specific precision agricultural applications. We can be certain, however, that the benefits from remote sensing derived CCC maps are significant, deriving from better decision-making that is made possible in various sectors of activity.

Traditional approaches to CCC assessment are based on field survey and are typically costly in time, labour and other resources. Such approaches are therefore limited to local scale, and not realistic for monitoring biodiversity over large spatial extents. Remote sensing is the alternative most effective and efficient means to quantify CCC at different scales to capture CCC temporal dynamics in different ecosystems. Earth observations from space make a significant contribution to our ability to analyze regional plant physiological conditions. The large area, and repetitive coverage by space-based satellites provide accurate, near-real-time CCC conditions to understand ecosystem processes and functional aspects of biodiversity for regional and/or global forecasting of carbon dynamics. These make remote sensing approach as the most cost effective and efficient framework to develop a global biodiversity knowledge system including canopy chlorophyll content.

4.1.3. Canopy Chlorophyll Content product specification

Canopy chlorophyll content (CCC) is defined as the product of leaf area index (LAI) and leaf chlorophyll content (Blackburn, 1998, Gitelson et al., 2005). Canopy chlorophyll content, being the sum of chlorophyll pigments distributed within the 3D canopy, defines the capacity of the vegetation canopy to absorb photosynthetically active radiation. At a stand level, canopy chlorophyll is related to functional diversity metrics including light use efficiency, wood growth and net primary production (Ollinger and Smith, 2005). *In situ* measurement of both LAI and leaf chlorophyll content at canopy level is not easy, time demanding and prone to errors (Jonckheere et al., 2004, Parry et al., 2014). In contrast, estimations based on remotely sensed spectral reflectance are non-destructive, rapid, and can be obtained for spatially distributed vegetation covers.

CCC requires a timely acquisition of high spatial and spectral resolution remote sensing data. Hyperspectral sensors are the ideal platforms for this, although they are currently only available only available airborne and not satellite platforms. Airborne sensors are too expensive to acquire at a regional and global level, and so are envisaged mainly for global CCC products verification/validation purpose.

The alternative for regional global mapping of CCC is utilizing hyperspectral and/or multispectral satellite data. Therefore, the benchmarking and prototyping of the CCC RS-enabled EBV products generation developed within this project relies mainly on the freely available European wide-swath, high-resolution, multi-spectral imaging twin satellite mission Sentinel-2. For historical and systematic analysis to monitor changes over a long time frame, imagery from the Landsat satellite series has also been considered. Other past and future satellite missions that offer high spectral data include EO-1 Hyperion, the Hyper-spectral Imager SUIte (HISUI), RapidEye sensor as well as the upcoming Environmental Mapping and Analysis Program (EnMAP) of Germany, HyspIRI of NASA and PRISMA of the Italian Space Agency. Also, the Hyperspectral Environment and Resource Observer (HERO) could be potentially used for historical change studies of CCC.

4.2. Utility of Canopy Chlorophyll Content

4.2.1. Spruce bark beetle attack in the Bavaria Forest National Park

The use case demonstration was conducted in the Bavarian Forest National Park in Germany (BFNP). The Park is a mixed mountain forest with an approximate area of 240 km^2. Alluvial spruce forests are dominant in the valleys, mixed mountain forests on the hillsides and mountain spruce forests in the high areas. The European beech (*Fagus sylvatica*), Norway spruce (*Picea abies*) and Fir (*Abies alba*) are the three dominant tree species (Heurich and Neufanger 2005).

The main questions addressed by the use case 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?

Remotely sensing of plant traits that are indicative of vegetation stress can play a key role in providing timely, accurate and cost-effective information to mitigate and control bark beetle outbreaks. This is because the infestation causes changes in the biochemical and biophysical characteristics of the entire tree. Bark beetle attack causes a significant reduction in leaf foliage chlorophyll content during the infestation time (Abdullah et al., 2018). Hence, CCC, which can be accurately retrieved from remote sensing, can be used as a better proxy to discern healthy and bark beetle infested spruce trees than conventional ground surveys when there are no apparent visual symptoms in needles.

A radiative transfer model inversion was implemented to generate CCC products from time series images of Sentinel 2 and RapidEye. The CCC products were then used for stress mapping caused by bark beetle infestation. For this purpose, field measurements of leaf chlorophyll as well as leaf area index collected during June/July 2016 in infested and healthy spruce stands were used to produce *in situ* derived values of CCC and also determine threshold values in classifying the CCC products into healthy and moderately/severely stressed areas. Maps obtained from interpretation of aerial colour photographs by the park management staff were used to validate the accuracy of the stress (infestation) maps.

The generated CCC products showed a significant variation in CCC products in space and time (Figure 8). CCC was high in mixed stands where spruces and beech grow together. The bark beetle-infested trees are expected to exhibit relatively lower CCC values compared to healthy trees. However, it is worth noting that the high CCC of beech trees compared to coniferous trees (even when the latter are not affected by bark beetle) in mixed stands substantially raised the CCC of pixels in these stands irrespective of the infestation, and that may compromise the overall accuracy of the classification in those stands in our next step.

The stress mapping based on CCC products showed different stress levels over time (Figure 9), which confirm the significance of the canopy level variable for successful classification of stressed and healthy vegetation. The spatial distribution exhibited consistency over time. Specific sites with stress status in 2011 appeared stressed throughout the six-year study period (2011-2018) although there were shifts between severely and moderately stressed status. Temporal trends show positive slopes for CCC that are significant ($p < 0.05$) over time (Figure 10).

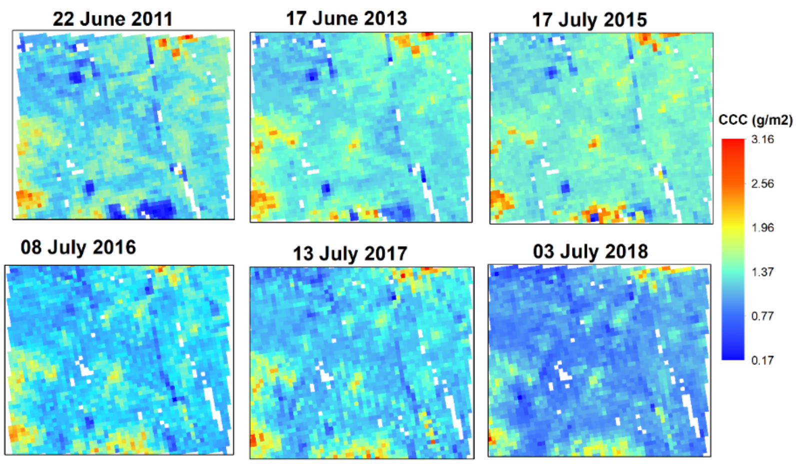

Figure 8: *Canopy chlorophyll content (CCC) distribution variability in space and time (2011 -2016) within a sample mixed stand of Bavarian Forest National Park.*

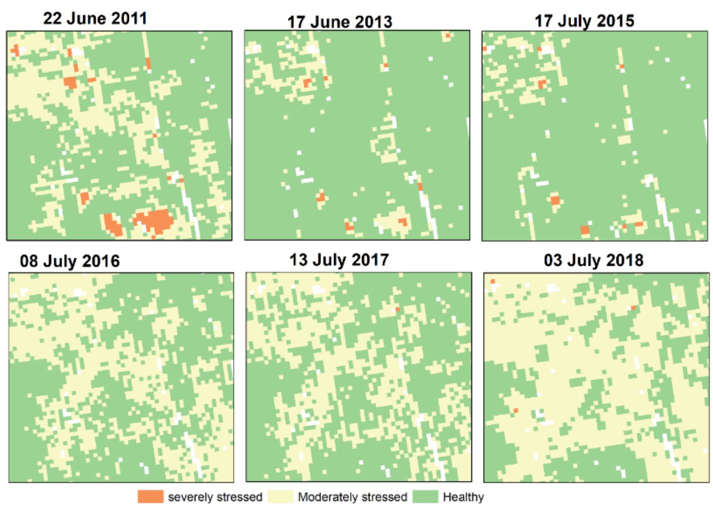

Figure 9: *Spatio-temporal distribution of vegetation stress in the Bavarian national park as predicted by CCC during the study period (2011-2018).*

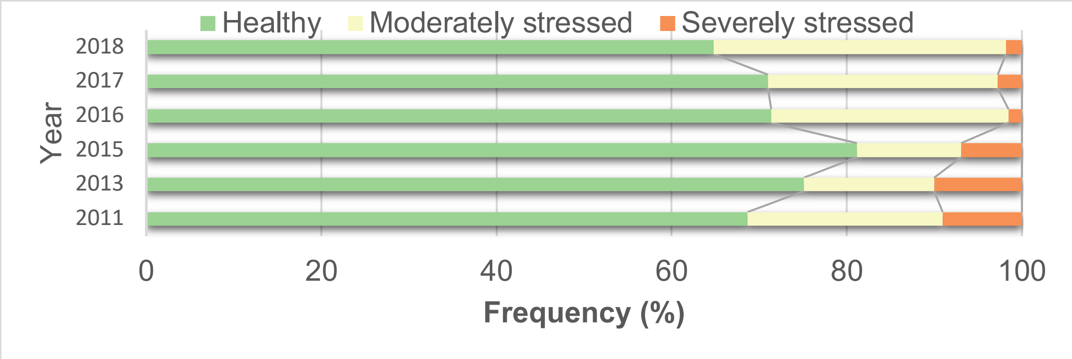

Figure 10: *Proportion of pixels classified as stressed and healthy vegetation in the Bavarian Forest National Park when CCC is used as the predictor.*

The accuracy assessment results demonstrated that most of the bark beetle infested trees (>70%) identified through the high-resolution aerial photographs were classified either severely or moderately stressed category. However, it is worth noting that other plant traits other than CCC may play a significant complementary role in detecting bark beetle infestation. Thus, using additional plant traits such as dry matter content and Nitrogen content (which can be reliably estimated from RS data) as predictors may considerably improve the accuracy of early detection of bark beetle infestation using remote sensing. Nevertheless, trees which were classified as healthy in our products while identified as infested in the colour aerial photograph are not necessarily considered to be an accuracy error. Some trees may be healthy during the acquisition of the remote sensing data in June/July and are infested later before the colour aerial photographs acquired in June/July one year later.

4.2.2 Potential application of the results

The findings in this use case demonstration 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 reduced otherwise the time and cost expensive conventional surveys required at the early stage of bark beetle infestation when the infested tree is still physiologically green but exhibiting 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 spatiotemporal 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.

4.2.3 Lessons learnt from the use case

The results in this UCD showed that CCC products generated from remote sensing data offer a simple and robust means to detect bark beetle infestation at the 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, 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.

5. RS-Enabled EBVs monitoring for the Contracting Parties of Multilateral Environmental Agreements

5.1. Introduction

The Group on Earth Observations–Biodiversity Observation Network (GEO-BON), which represents the biodiversity component of GEOSS (the Global Earth Observation System of Systems), is making a coordinated effort with other actors, in order to address the need for an observation system for global biodiversity assessment. This will help to compute indicators for assessing progress towards the post-2020 biodiversity agenda, as called for by the UN CBD, and contribute to initiatives such as the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) regional and global assessments (GEO-BON, 2017). To improve the detection of significant changes in global biodiversity, GEO-BON is currently adopting the concept of essential variables.

As described in section 1, Essential Biodiversity Variables (EBVs) are key variables that help to coordinate worldwide biodiversity monitoring by enabling consistent reporting of changes in the state of biodiversity, and monitoring progress towards international and regional goals and targets, e.g. as stated by the UN 2030 Agenda on Sustainable Development. In the last few years, several studies dedicated to the prioritization and specification of EBVs have been undertaken (e.g., Pereira et al., 2013, Skidmore et al., 2015, Pettorelli et al., 2016b). Pereira et al. (2013) introduced 22 EBVs under six classes of EBVs that include genetic composition, species populations, species traits, community composition, ecosystem structure and ecosystem function.

This user handbook supports the efforts of the Convention on Biological Diversity (CBD) (Secretariat of CBD, 1992), IPBES (Cardinale et al., 2012) and GEO-BON (Scholes et al., 2008), among others, in order to generate global knowledge about the status and changes to terrestrial ecosystem structure and function by using remote sensing data. Users of these data at the global level include the scientific and technical bodies of the three major global Conventions governing sustainable development. These legally binding agreements are the so-called Rio Conventions as they were opened for signature at the Earth Summit in Rio de Janeiro in 1992:

- Convention on Biological Diversity (CBD)
- Framework Convention on Climate Change (UNFCCC)
- United Nations Convention to Combat Desertification (UNCCD)

To support monitoring efforts towards the attainment of the targets set by these conventions, various progress indicators have been conceived, on which countries are expected to measure and report. These are further described in the sections that follow.

5.2. Global Biodiversity and Sustainable Development Processes

5.2.1. The Aichi Biodiversity Targets

At the 10th meeting of the Conference of the Parties to the Convention on Biological Diversity (CBD COP 10) Parties, through decision X/2, adopted a Strategic Plan for Biodiversity 2011-2020, including a vision for 2050 and twenty Aichi Biodiversity Targets, organised under five Strategic Goals. Parties committed to using these as a framework for setting national targets and to report on progress using indicators. The Strategic Plan has been endorsed or supported by other conventions and the United Nations General Assembly, and accordingly provides a universal framework for action on biodiversity.

At COP 11 in 2012, Parties took note of a new Indicator Framework for the Strategic Plan for Biodiversity 2011-2020 (Decision XI/3). It contains an indicative list of 98 indicators providing a flexible basis for Parties to assess progress towards the Aichi Biodiversity Targets. For each Target, one or more 'generic' indicators were identified. One or more specific indicators are then provided for most of the generic indicators; however, a number of gaps still remain for which no indicators have yet been identified.

In Decision XI/3, Parties decided that the indicator framework should be kept under continual review, although updates have not been published. Nonetheless, the Biodiversity Indicators Partnership (BIP), the primary initiative mandated by the CBD for the coordination and delivery of indicators, has identified a number of additional relevant indicators that could fill gaps in the indicative list, and others that could support and enhance the existing indicators for certain Targets. Nonetheless, not all elements of all targets have an associated indicator, and many indicators are poorly aligned with the wording of the Target and thus do not give a full picture of progress.

The fourth edition of the Global Biodiversity Outlook (GBO-4), published in 2014, reviewed progress towards the Aichi Targets and, using extrapolations of some indicators to 2020, aimed to determine if the global community is on track to achieve the Targets by their deadline. The results were not positive, and showed that, despite progress in many areas, the rate of progress would not allow the targets to be met by 2020 (SCBD, 2014).

There are clear opportunities for the RS-enabled EBVs to support the monitoring of progress towards the Aichi Targets, both through contributing to or even improving existing indicators, or by serving as the basis for new indicators (see **Error! Reference source not found.** above) – Targets for which no indicators are available for either individual elements, or for the Target as a whole, should be a focus for the EBV community.

5.2.2. The post-2020 global biodiversity framework

With the Strategic Plan for Biodiversity 2011-2020 soon to expire, Parties are currently discussing on the post-2020 framework which will replace it. The 2050 Vision of the Strategic Plan remains relevant for the post-2020 plan, although a number of Parties are calling for a different approach to a framework for achieving it over the next decade.

In 2018, the Secretariat of the CBD issued an invitation for input from experts on the development of a post-2020 global biodiversity framework (https://www.cbd.int/doc/notifications/2018/ntf-2018-063-post2020-en.pdf).

At COP 14, held in Egypt in 2018, Parties discussed the submissions received by the Secretariat, as well as the process for developing the new framework. An Open-Ended Working Group (OEWG) was established, with chairs elected from Uganda and Canada, which met for the first time in August 2019 in Nairobi. The meeting was an opportunity to hear reports from the ongoing consultative processes, to discuss potential elements of the structure and scope of the post-2020 global biodiversity framework, and to agree future meetings in the run up to COP 15, at which the new framework will be agreed. As well as soliciting written submissions from Parties and observers, regional and thematic consultations have been held, and specific dialogues have been supported by certain Parties and observers. Two further meetings of the OEWG are anticipated in 2020, prior to COP 15.

An important element of the development of the new framework, is, of course, the identification of a monitoring framework. A number of calls have been heard for indicators to be developed in parallel with the targets, which will not only help ensure that each indicator is well aligned to the target in question, but also that targets themselves are measurable – two issues that are apparent in the current indicator list. Currently, no conclusions have been drawn or decisions made regarding the indicator framework, but contributions are calling for the new indicator framework to build upon the existing list of CBD indicators. The importance of remote sensing and the EBVs is clearly acknowledged in terms of having indicators that can be regularly updated and cover the implementation period of the post-2020 framework[2].

The new framework will also be closely aligned to the Sustainable Development Goals (see section 2.4), given the links with Goals 14 and 15 (life below sea and life on land, respectively). Calls have been made for a similar structure to be used, and for the new framework to be consistent with the SDGs, albeit potentially more ambitious. As such, there is likely to be alignment in the monitoring frameworks used.

Although there is still much uncertainty about the format and content post-2020 framework, it will require evidence-based decision-making and a solid scientific basis on matters related to multi-scale biodiversity change. The RS-enabled EBVs and downstream services (such as the prototype GEO BON data portal on ecosystem structure) will provide this,

[2] https://www.cbd.int/doc/c/58f8/6926/dc3d8d9f16c9307e91e650e5/post2020-prep-01-inf-02-en.pdf

through the use of innovative Earth Observation technologies. GlobDiversty is the first project to explore how RS-enabled EBVs can be used to measure and characterise changes in terrestrial ecosystem structure and function across the globe. Such science-based data is a priority for the post-2020 agenda, as it can be used to inform the production of and progress towards ambitious, measurable, realistic, and time bound targets (SBI recommendation 2/19) and provide data to inform scenarios and models (SBSTTA recommendation XXI/1).There have also been a number of calls for streamlining the number of indicators, so the list is not so extensive as the current list of indicators, but is potentially more informative as indicators are more carefully selected to respond to the targets. The RS-enabled EBVs could potentially support such efforts.

Indicator computation should be a major element of the RS-enabled EBV downstream services and should be specifically designed for multi-purpose use across different reporting requirements related to biodiversity and ecosystem services. This supports a post-2020 global biodiversity framework which is aligned with major global frameworks such as the 2030 Agenda for Sustainable Development, and that is built on existing indicators, including those for meeting targets under the Sustainable Development Goals (SBI recommendation 2/19).

5.2.3. Other relevant Conventions

5.2.3.1. The Ramsar Convention on Wetlands

The Ramsar Convention on Wetlands, adopted in 1971, provides the framework for the conservation and wise use of wetlands and their resources. The current Ramsar Strategic Plan runs from 2016-2024, containing 19 specific targets and four overall goals. While the Ramsar Convention does not have a dedicated suite of indicators, monitoring implementation of the Convention is important and there are clearly a number of Targets for which RS-enabled EBVs could provide important information on progress.

5.2.3.2. UN Convention to Combat Desertification

In 2017, Parties to the UNCCD adopted a Strategic Framework for 2018-2030. This framework contains 15 Expected Impacts, organized under five Strategic Objectives. The same Decision as adopted the Strategic Plan also adopted a list of 11 indicators to be produced, in addition to six indicators identified in Decision 22/COP 11 and three in Decision 15/COP 12. Many of these are still under development, providing a prime opportunity for RS-enabled EBVs to feed in and provide support.

5.2.3.3. Convention on Migratory Species

Parties to the CMS adopted the Strategic Plan 2015-2023 at its Tenth COP in 2011. It consists of 16 Targets organsied under five Goals. An indicative list of indicators was adopted with the Strategic Plan, but this list is largely speculative, and few (if any) of the indicators are currently operational. While many of the targets, being species-based, do not naturally align with RS-enabled EBVs, there are clear opportunities around habitat fragmentation and connectivity along migration routes.

5.2.4. The Intergovernmental Science-Policy Platform (IPBES)

IPBES is the intergovernmental body which assesses the state of biodiversity and of the ecosystem services it provides to society, in response to requests from decision makers. Established in 2012, it is now reaching the end of its first Work Programme, with the second Work Programme due to be adopted at the Plenary meeting in March 2019. Under the first Work Programme, a number of assessments were carried out, including:

- Global assessment
- Regional Assessments (Africa, Americas, Asia-Pacific and Europe and Central Asia)
- Pollination assessment
- Land degradation assessment
- Invasive alien species assessment
- Sustainable use assessment

These assessments all required a solid evidence base. For the global and regional assessments, a list of indicators was identified in order to ensure a minimum use of evidence in each assessment, and points of comparability across the different assessments. However, uptake of these indicators was limited for a range of reasons.

The broad scope of the assessments under the first Work Programme demonstrates a clear opportunity for the RS-enabled EBVs to provide a comprehensive evidence base. In particular, the RS-enabled EBVs would have allowed the point of comparison between assessments, upon which the platform placed great emphasis, but which is largely absent due to the lack of uptake of indicators into the Regional Assessments.

Under the 2030 Rolling Work Programme, a number of further assessments are planned:

- Assessment of the interlinkages among biodiversity, water, food and health (nexus assessment)
- Assessment of the underlying causes of biodiversity loss, determinants of transformative change and options for achieving the 2050 vision for biodiversity
- Measuring business impact and dependence on biodiversity and nature's contributions to people

Again, there are clear opportunities within these assessments for RS-enabled EBVs to play a key role in providing up-to-date and objective information on status and trends in biodiversity and ecosystem services. As the scope of the assessments is further developed and the timelines better elaborated, opportunities for input will become clearer.

The IPBES assessments ask some overarching and fundamental questions, for which data is required to understand the answers. These are further explored in the Science Traceability matrix, in Section 5.2.

5.2.5. Agenda 2030 and the UN Sustainable Development Goals (SDGs)

The UN Conference on Sustainable Development in Rio 2012 agreed an outcome document *The Future We Want, a* statement renewing commitment to sustainable development and to ensuring the promotion of an economically, socially and environmentally sustainable future for our planet and for present and future generations. Out of this consensus arose the 2030 Agenda for Sustainable Development, agreed at the United Nations (UN) General Assembly in September 2015 (United Nations, 2015). Heads of States and Governments agreed on 17 Sustainable Development Goals (SDGs) as a framework for the 2030 Agenda. The SDGs integrate three dimensions of sustainable development (biosphere, society and economy, as illustrated in Figure 12) and aim to foster action for people, planet, prosperity, peace and partnership. They also emphasize integration, coherence, indivisibility– and an underpinning philosophy of "*we will leave no one behind*".

Figure 12: *Illustration of the 17 Sustainable Development Goals across the three spheres of sustainable development: biosphere, society and economy. Source: (Carl Folke, Stockholm Resilience Centre)*

The UN Agenda 2030 is the world's most ambitious plan for sustainable development and, for the first time, weaves together human development and environmental sustainability to achieve a global ambition for humanity and the planet. The 17 Goals and 169 targets which were announced demonstrate the scale and ambition of this new universal Agenda. Further details on the individual SDGs and targets can be found at https://sustainabledevelopment.un.org/sdgs.

In 2015, as part of the development of the 2030 Agenda for Sustainable Development, an Inter-Agency and Expert Group on SDG Indicators (IAEG-SDGs) was established by the UN Statistical Commission to develop the observation system necessary for monitoring progress towards the 2030 Agenda. The IAEG-SDGs is comprised of Member States plus regional and international agencies as observers. In order to measure progress towards the 169 targets, the IAEG-SDGs developed an indicator framework, consisting of 232 indicators, agreed upon at the 48th session of the United Nations Statistical Commission held in March 2017, and adopted by the UN General Assembly on 6 July 2017. Each indicator has a ‘custodian agency’ – a UN agency, responsible for its production and delivery. In addition, each indicator should be built from national data, or data should be verified by National Statistical Offices. This presents a significant monitoring burden for the UN Member States. Indicators are classified into three tiers, depending on their status:

- Tier 1: Indicator is conceptually clear, has an internationally established methodology and standards are available, and data are regularly produced by countries for at least 50 per cent of countries and of the population in every region where the indicator is relevant.
- Tier 2: Indicator is conceptually clear, has an internationally established methodology and standards are available, but data are not regularly produced by countries.
- Tier 3: No internationally established methodology or standards are yet available for the indicator, but methodology/standards are being (or will be) developed or tested.

In 2020 a comprehensive review of the global indicator framework was organised by the IAEG-SDGs, being completed in March at the annual meeting of the UN Statistical Commission. The review resulted in a framework of 231 indicators (one indicator less than before) with 115 indicators classified as Tier and 95 indicators classified as Tier II. (There are no longer any Tier 3 indicators.) In addition there are 2 indicators that have multiple tiers (different components of the indicator classified in tier levels I or II) and 19 indicators with a tier status between 1 and 2 pending a data availability review.

The onerous demands on national governments and custodian agencies alike, raises the possibility of satellite remote sensing observations as an additional means of information for national statistics and, indeed, maybe the only way for some indicators to be monitored routinely and robustly. RS-enabled EBVs, as a coherent and standardized set of observations of the biosphere, can therefore become integrated into the monitoring framework of countries for appropriate indicators where the biosphere plays a strong role.

Three key entry points exist for RS-enabled EBVs within the SDG monitoring framework: the first is with those indicators currently classed as Tier 3, for which data (or a methodology) may be lacking – there may be opportunities to feed RS-enabled EBVs into relevant indicators that are still under development. Secondly, there may be opportunities to further strengthen the methodologies of Tier 2 indicators. A third entry point is the 2025 major review, which will begin in 2023; countries will be able to put forwards new indicators for inclusion, which could draw on the RS-enabled EBVs.

5.3. Outlook: the 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 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. 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, but as a starting point that is representative of the GlobDiversity project mission 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 we cannot assess biodiversity using our RS-enabled EBVs alone but that we will need to cover all the informational needs listed (column 4) to answer the questions (column 2), which may include other sources of geospatial information as well as non-spatial data on biodiversity. The STM is therefore a tool that defines the boundary between what we can and can't do answer t, in relation to the stated questions, using a remote sensing approach alone. The remaining knowledge where gaps could be used to justify investment in other space based observations for other RS-EBVs. As the project progresses, e.g. into phase 2, it is foreseen that the levels of technological maturity will increase and that matrix will be iteratively improved over time.

Finally, the STM is a communication tool that allows remote sensing experts to communicate and clearly demonstrate what science questions the project is trying to address to policy makers. Assuming it is successful, policy decisions could be supported by the new knowledge generated by the project, provided an appropriate channel of communication can be found, e.g. through the IPBES knowledge and data task force, on which a member of the secretariat of the Biodiversity Indicators Partnership, hosted by UNEP-WCMC, is a resource person.

globdiversity
rs-ebvs for terrestrial ecosystems

esa

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]	

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Annex 1: Use case Demonstration – Siberian white crane in Kytalyk National Park

Abstract

Climate warming is strongly impacting the tundra biome, while simultaneously altering the habitat available for critically endangered species, including the Siberian white crane. As such, there is an urgent need for accurate mapping of breeding habitat, in order to prioritize conservation efforts for this species. Developed within the framework of the European Space Agency's GlobDiversity project, this use case study aims to both characterize and evaluate the effectiveness of the Land Surface Phenology (LSP) RS-enabled EBV, in applied biodiversity studies. Here, we assess the LSP product in relation to a multi-data source habitat suitability model, and high resolution habitat map, with the goal of identifying important crane breeding areas. We find that the LSP metric Start of Season shows a correlation with habitat nesting probability, and is therefore effective in supporting and evaluating crane nesting potential, and in addition, that LSP metrics are useful for identifying specific vegetation types. In particular, areas of high shrub density can be identified and excluded from maps of crane breeding habitat. Moreover, as shrubification is a major ecological change process in the Arctic tundra biome, mapping and tracking this process using LSP metrics is a key application. Importantly, the results of this study provide both a local-scale characterization of land surface phenology, and the establishment of a baseline LSP product relevant for monitoring ecological change, thereby enabling a broad range of novel ecosystem research.

1. Introduction

This study intended to evaluate the relevance of the RS-enabled EBV Land Surface Phenology (LSP) at monitoring biodiversity changes and informing biodiversity conservation and management programs. Satellite-observed LSP metrics, including Start of Season (SOS), End of Season (EOS) and Growing Season Length (GSL), along with related satellite-derived metrics such as the duration and onset of snow, ice cover and melt, are known to be shifting in response to changing climate conditions across the Arctic tundra biome. The observed shifts in LSP metrics are thought to be related not only to the timing of vegetation phenological events, but also modifications in vegetation species community composition, in both cases with relevance to habitat availability and biodiversity (Myers-Smith et al. 2020).

For example, a major land surface change process occurring in the Arctic tundra biome is greening or shrubification. Here, herbaceous graminoid or lichen tundra plant species are replaced by woody species, such as birch (*Betula*), willow (*Salix*) and alder (*Alnus*) species, ultimately resulting in significant changes in plant species richness, community composition and biological diversity (Forbes, Fauria, and Zetterberg 2010; Myers-Smith et al. 2015).

The process of shrubification is thought to be driven by several factors, including rising high-latitude air temperatures, changes in seasonal snow cover and natural or anthropogenic disturbance regimes, including tundra fires and modified herbivory intensity, as well as numerous environmental changes resulting from widespread permafrost thaw. Thus, greening and associated changes in vegetation community composition and associated shifts in the timing of land surface phenology events are modifying the structure and function of tundra ecosystems. More specifically, they are changing the ecological interactions not only between species, but also between species and their environment. Physical processes are also altered, for instance, soil–atmosphere exchanges of water, carbon and nutrients, including energy and water fluxes, while mean surface albedo is reduced. Collectively, Arctic tundra greening and associated processes often comprise positive feedbacks to the climate system, further amplifying warming or altering regional climate (Juszak et al. 2017; Blok et al. 2011; Beringer et al. 2005; Thompson et al. 2004).

Such widespread environmental changes observed across the Arctic tundra biome are also affecting individual species. For example, shifts in land surface phenology resulting from changes in vegetation community composition, variation in the timing of snow melt and associated flood intensities, and anomalous temperature and precipitation patterns, are thought to be impacting the availability of habitat for the Siberian white crane (*Grus leucogeranus*). This species is critically endangered and much of its breeding ground is found within Kytalyk National Park, Siberia, Russia (**Figure 5**). Crane population data collected by researchers using aircraft and ground surveys since the 1960s reveal significant variation in nesting sites and population size. Indeed, the Siberian white crane population has been the focus of numerous conservation and monitoring efforts, which eventually led to the establishment of the park (Germogenov 1998). The species is culturally important and considered as an image of purity by indigenous Sakha people.

The changing structure and function of the Arctic tundra biome is thought to be strongly impacting the breeding habitat available for the Siberian white cranes. Specifically, the species nests and breeds in sedge habitat bordering lake thaw depressions in summer; thus, variability in snow quantities, timing of melt onset and annual flooding events of rivers and lakes, is known to strongly influence the amount and suitability of breeding and nesting sites. Furthermore, an increased shrub density of the surrounding area negatively impacts the birds' ability to spot predators.

The different factors influencing the amount and suitability of breeding and nesting sites for Siberian white cranes are presumed to be linked to LSP and derived metrics, which in turn are strongly related to ecosystem functioning. In effect, LSP metrics can characterize not only numerous vegetated land surface processes, such as the start and length of the growing season, but also various physical processes, including the length of snow cover and the onset of snow melt. For instance, the phenology of snow cover is thought to be relevant to identifying snow-free areas where cranes may nest at the start of the breeding season. Importantly, LSP metrics are also correlated to vegetation species community composition, such as habitat and biodiversity metrics, which can be an important determinant of habitat suitability.

Accordingly, the ability to identify the extent of these process, and quantify their rate in response to climate, contributes not only to our knowledge of ecosystem functioning and associated species communities, but also to an understanding of the factors controlling the breeding success of Siberian white crane. Indeed, such an understanding is expected to facilitate the prioritization of conservation and management actions required for the preservation of habitat required for this species.

Against this background, this use case study aimed to describe a novel LSP product, and show the potential of using LSP metrics for habitat characterization, with subsequent evaluation of the relationship between LSP and a nesting habitat suitability model for the Siberian white crane.

The nesting potential (NPO) map (Haverkamp et al. submitted) was evaluated for statistical correlations with all LSP metrics, in order to demonstrate the effectiveness of LSP metrics at identifying suitable crane nesting habitat. We then extended the focus of our study to evaluate the suitability of LSP metrics for accurately mapping vegetation types known to strongly influence nesting and breeding sites, for instance dense shrubs, which make nesting site unsuitable, and sedge habitat, which is a preferred breeding habitat for the cranes.

2. Location and spatial coverage of use case

Kytalyk National Park, Siberia (**Figure 5**), covers 18,855 km^2 and at its core hosts the Kytalyk field station (red point in Figure 1), known for its research on carbon and energy budget, shrub encroachment as well as feedbacks between climate change and biodiversity. The National Park was established for the protection of the critically endangered Siberian white crane (*Grus leucogeranus*) (IUCN 3.1, 2018). A second crane species, the lesser sandhill crane (*Grus Canadensis*), a species of least concern (IUCN, 2016), is also present in the area and, whilst having similar habitat needs, is not within the focus of this study. The sandhill crane has a population that has increased more than 20-fold in recent decades (Vladimirtseva, Bysykatova, and Sleptsov 2009) (Vladimirtseva et al. 2009).The study area encompasses breeding areas for Siberian cranes near the field station within the National Park, and for which several environmental and ecological datasets exist.

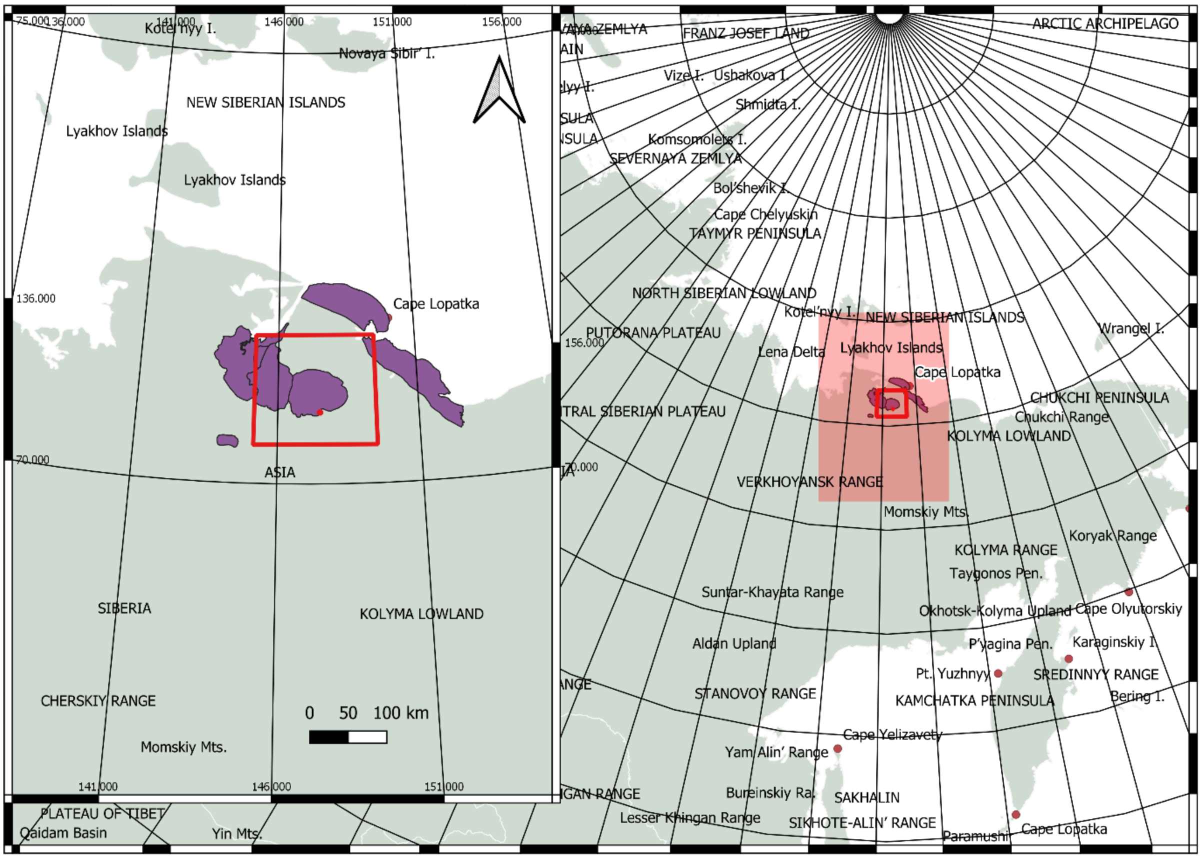

Figure 5. *Kytalyk Protected area, Siberia, Russia (purple area), and the area of interest (AOI) marked as a red square and core arear of interest (red point).*

3. Aims/objectives of the use case

In order to facilitate the development of operational high spatial resolution LSP products, the first aim of the this study was to describe and characterize the regional RS-enabled EBV LSP data product (**Figure 7**). Specifically, we showcase initial results of LSP retrievals from local to landscape-scales across Kytalyk, as our area of interest. Further, we provide several examples highlighting the detail and quality of LSP metrics in relation to important vegetation types and landscape features.

The second aim of this use case study was to use a previously developed nesting habitat suitability model to demonstrate the effectiveness of LSP metrics at narrowing down suitable crane habitat. Here, the map of potential nesting habitat was evaluated for statistical correlations with all LSP metrics.

In addition, we point to the potential future use of LSP metrics to assess the breeding success of the white Siberian cranes and monitor the long-term changes in their habitats.

A final aim of this study was to evaluate the suitability of LSP metrics for mapping vegetation types that influence suitability of areas for nesting habitat.

A key added outcome of this study is that the range of LSP metrics can serve as a baseline for monitoring long-term shifts in terrestrial plant community composition. Such high resolution information characterizing habitat change is expected to contribute a better understanding of the environmental and ecological changes impacting the Park, while simultaneously facilitating the conservation of the Siberian white crane.

Within this use case, we contribute to answer the question: *What LSP conditions are related to suitable nesting habitat for the Siberian white crane, and how are changes in climate and habitat influencing these areas across Kytalyk National Park?*

4. Why RS-enabled EBVs were used

The overarching aim of the use case study was to demonstrate the effectiveness of the RS-enabled EBV LSP at providing consistent, ecologically meaningful land surface phenology information from a high spatial and temporal resolution merged Sentinel-2 and Landsat 8 time series. At the same time, a description and characterization of this novel product is undertaken.

In the context of this particular use case demonstration, the RS-enabled EBV was used in conjunction with a habitat suitability model of potential nesting habitat for the critically endangered Siberian white crane (Haverkamp et al., In prep.), with the aim of i) demonstrating the effectiveness of LSP metrics at narrowing down suitable crane habitat, and ii) evaluating the suitability of LSP metrics to accurately identify vegetation and habitat types that influence suitability of areas for nesting and breeding habitat.

Kytalyk National Park is vast and difficult to access, so *in-situ* monitoring of a species and the condition of its habitat is time consuming, costly and challenging. As such, developing a baseline measure with help of LSP metrics may also provide a tool for evaluating the annual condition of crane breeding habitat and help to better prioritize conservation actions and estimate breeding success of the species.

In providing ecologically relevant baseline data, this study demonstrates how the RS-enabled EBV LSP can i) be used for regular monitoring, ii) complement existing datasets, and iii) contribute towards answering pressing conservation and management questions, including the annual condition for crane breeding habitat.

5. Methodology

The datasets used in this study are listed in Table 3.

Table 3: *Datasets used in this study include the RS-enabled EBV LSP, output from a habitat suitability model, high resolution vegetation and in-situ field observations of crane nesting sites and vegetation type.*

Data	Spatial resolution	Time period	No. of time steps
RS-enabled EBV LSP metrics	10 m	2017/2018	Annual
High resolution vegetation map (Budischev et al. 2014)	10 cm	2017	Annual

Habitat Suitability Model Haverkamp et al., submitted	30 m	2001-2018	Temporal composite (2001-2018)
Vegetation map classified on Landsat 8 based on Budischev et al. (2014)	30 m	2014	Seasonal composite

Characterization of the LSP product

The first aim of this study was to describe and characterize the regional LSP data product that was expected to be made available to the EBV community. The RS-enabled EBV LSP comprises a regional-scale land surface phenology algorithm and data product calculated from Sentinel-2 and Landsat 8 NDVI time-series based on Level-2 Bottom of Atmosphere (BOA) scenes. The NDVI time series is then used to retrieve estimates of land surface phenophase transition dates as LSP metrics at 10 m spatial resolution. The computed LSP metrics included Start of Season (SOS), End of Season (EOS), Growing Season Length (GSL) and Amplitude (AMP) for the years 2017 and 2018. Finally, these metrics were visually evaluated and characterized in relation to major landscape features, habitat types and latitudinal transects.

Statistical correlations between LSP metrics and nesting potential

To demonstrate the effectiveness of LSP metrics at identifying suitable crane habitat, a model of nesting potential (NPO) was evaluated for statistical correlations with all LSP metrics spanning the years 2017 and 2018. The NPO map by Haverkamp *et al*. (in prep.) was developed using maximum entropy (MaxEnt) species distribution modelling, with known nest site locations, a habitat classification map, distance to lakes and rivers, slope, land surface temperature, and mean June surface water extent as input. MaxEnt modelling is based on the maximum-entropy method for predicting occurrences of species distributions. The method used environmental datasets - raster datasets in combination with georeferenced point location observations - with the model expressing a probability distribution function, where each raster cell has a modelled habitat suitability index for the species studied (Phillips, Dudík, and Schapire 2017). The NPO values represent the following:

- 0.00-0.50 no potential nesting
- 0.50-0.66 low potential
- 0.66-0.75 medium potential
- 0.75-1.00 high potential.

LSP metrics for habitat characterization

The LSP metrics were evaluated to identify vegetation and habitat types known to be good or poor as nesting sites. Here, the particular focus was on water sedge vegetation found on the periphery of lakes, which is good nesting habitat, and shrubland, which is poor habitat. A high resolution habitat map described in Budischev et al. (2014) was used to extract mean and standard deviation statistics from the multi-temporal output of the LSP algorithm (**Figure 6**A). However, the area covered by Budischev et al. (2014) only covers a small area of the Kytalyk National Park and does not contain areas of high nesting potential for the cranes. Therefore, the Budischev et al. (2014) habitat map was used to train a Landsat-8 satellite image classification of the entire area Kytalyk National Park (Figure 2B).

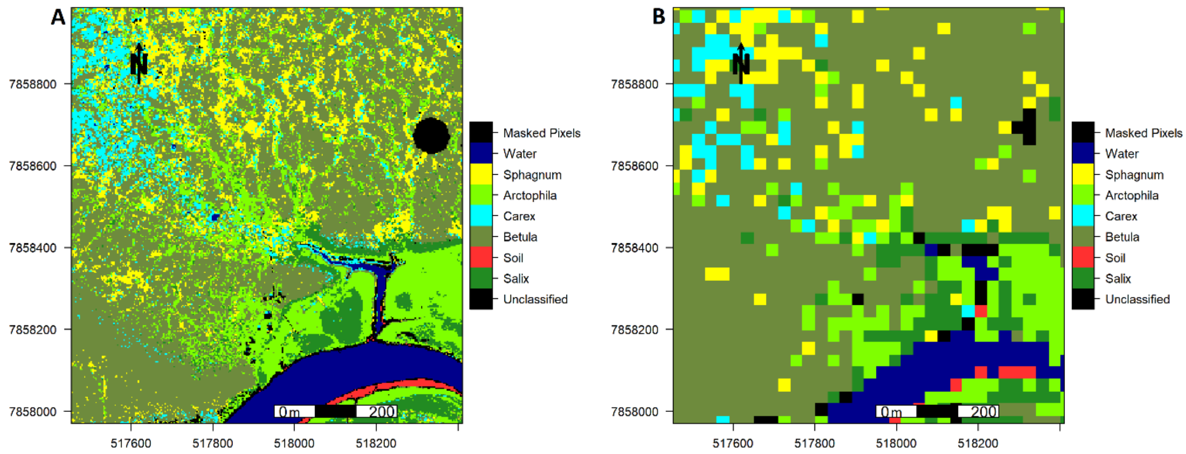

Figure 6 : *Habitat map by Budischev et al. (2014) (A) and a sample of the Landsat 8 based vegetation type classification map.*

This image classification training process was based on a composite Landsat 8 image from 2014, which includes bands 'B2', 'B3', 'B4', 'B5', 'B6', 'B7' and normalized difference vegetation index (NDVI) and Normalized Difference Water Index (NDWI) indices. All pixels falling within the spatial extent of each habitat class polygon were used as training points. The resulting training points dataset was used to train a random forest classifier, which was subsequently used to classify the Landsat 8 multiband image.

To validate the output classification, we first sampled the input habitat map from Budischev et al. (2014) with a different random pixel subset than used for classification to get a validation dataset. This validation dataset was then used to classify the same random forest classifier, and generate a confusion matrix based on the input habitat map and the output classified map, providing estimates of expected accuracy. Validation overall accuracy was 64%. Such moderate accuracy can be expected as a result of the large difference in spatial resolution between in the Budischev et al. (2014) map at 2 m spatial resolution, and the 30 m spatial resolution Landsat input. We used the classified Landsat 8 data set to compute the mean and standard deviation, using all the pixel values of all LSP metrics, from each habitat type. **Figure 6**B (30 m resolution) shows the result of this classification with the same area of interest as **Figure 6**A for comparison.

6. Results and Discussion

Characterization of the LSP product

The results of the LSP product presented in this study, clearly highlight the benefits of deriving high spatial resolution (10 m) land surface phenology metrics compared to previous coarse resolution products such as those derived from AVHRR and MODIS. Importantly, the major innovation of the LSP metric data product generated as part of the GlobDiversity project is its potential to characterize local- to landscape-scale land surface phenology.

Specifically, the merging of Sentinel-2 and Landsat 8 into dense time-series is proven to be effective for extracting LSP metrics. This is especially true for biomes across high latitudes where there is a greater density of over-flights, despite these biomes also being strongly affected by day length and seasonality (i.e. no light during the winter months), as well as frequent and dense cloud cover during the growing season.

The regional map of the main LSP metrics across Kytalyk National Park shows remarkable consistency and spatial detail across both the local- and regional-scale land surface phenology. For instance, regional patterns of Start of Season and End of Season are clearly related to different landscape features, such as flood plains, hills and topographic relief, depressions and river and lake beds. Figure 7 shows the derived LSP metrics for the Kytalyk core area with Start of Season (SOS), End of Season (EOS), Growing Season Length (GSL) and the NDVI Amplitude (or max NDVI) for 2018. We included here as an example figure the core area as it is the study area of research station. On the LSP maps, features such as the rivers, different vegetation types and the topography are clearly seen. The vicinity of the water body and the topography are important influences on vegetation type and phenology, as the vegetation cycle is highly dependent on snow melt and flood events. In general, it can be seen that the SOS has a narrower distribution of day of the year because all vegetation is greening up as soon as snow melts. In contrast, the EOS shows a broader distribution of day of the year as temperature and sunlight are the main constraints. We hypothesize that start of season is most relevant for the crane breeding success as this species migrates from the Kytalyk region by the time the vegetation growth season ends.

The GSL is calculated as a simple difference between EOS and SOS and is therefore directly dependent on these two input values. Therefore, this parameter was not used as an independent measure within this study. Nevertheless, the vegetation types and topographical features are also visible in the GSL. The NDIV amplitude also clearly shows landscape features, since NDVI amplitude is related to vegetation type, but the differences in the plain (or flat) part of the study area (in **Figure 7** the central, upper part of the core area shown) are less pronounced.

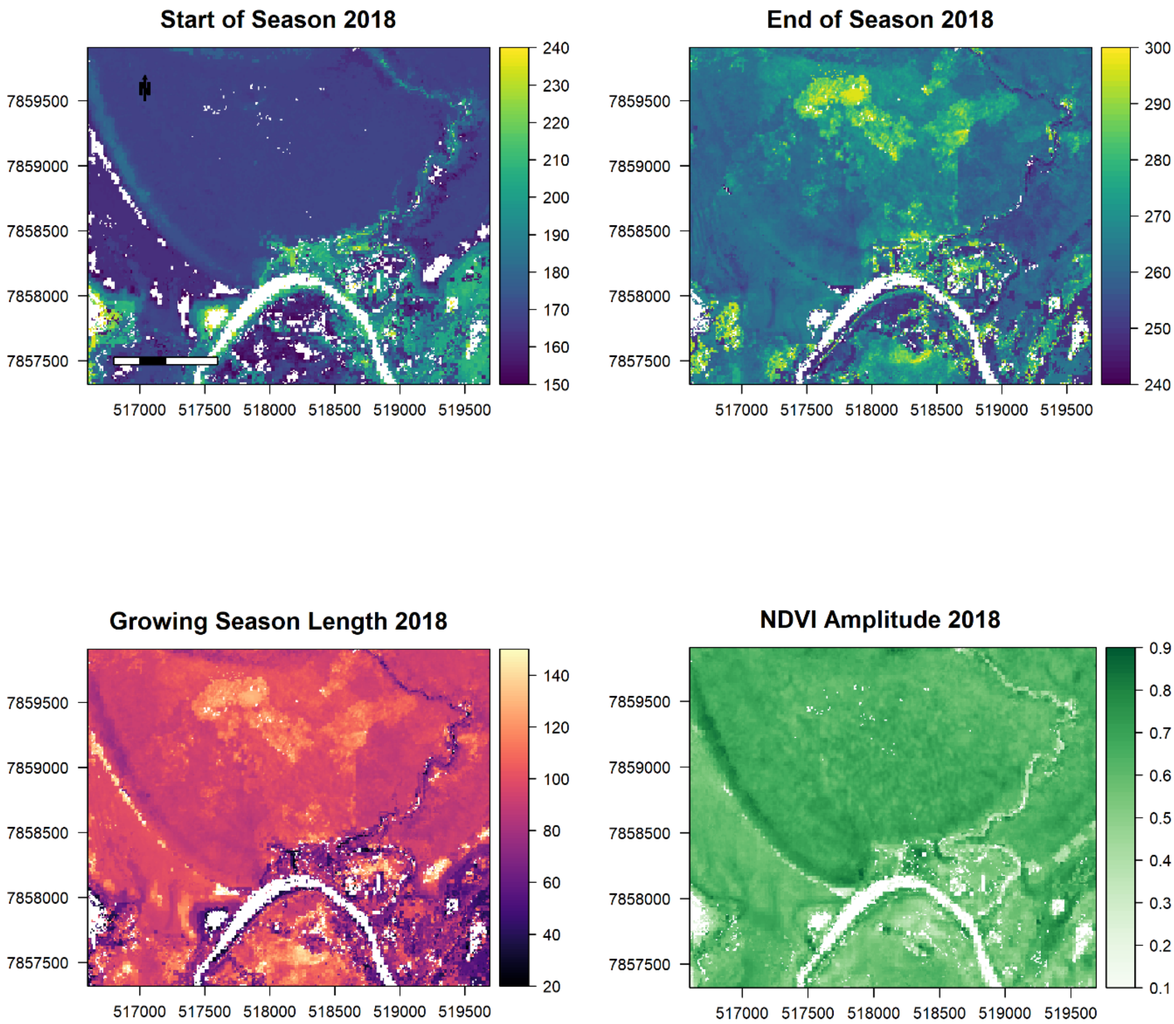

Figure 7: The four LSP metrics investigated in this study for the 2018 period are plotted for the core Kytalyk study area. They include Start of Season, End of Season, Growing Season Length and NDVI amplitude.

In order to get a measure on the LSP metrics over the entire Kytalyk National Park, we calculated a latitudinal north-south transect across the region, shown in **Figure 8**. In the north we would expect a later SOS and a shorter GSL. The transect reveals a heterogeneous gradient in LSP metrics. For instance, in 2017, we find a heterogeneous LSP signal on the transect (**Figure 8**A). In contrast, in 2018, we see a consistent response of LSP metrics, which show an increasing trend with higher latitudes (**Figure 8**B). For example, SOS values in 2018 are greater at high latitudes, pointing to later green-up dates, as expected. The unexpected results for 2017 might be closely connected to the extreme flood event of this year, causing the phenological timing to be dominated by the water cover of large regions and not the latitude. This extreme flood event also needs to be considered for all other results in this study.

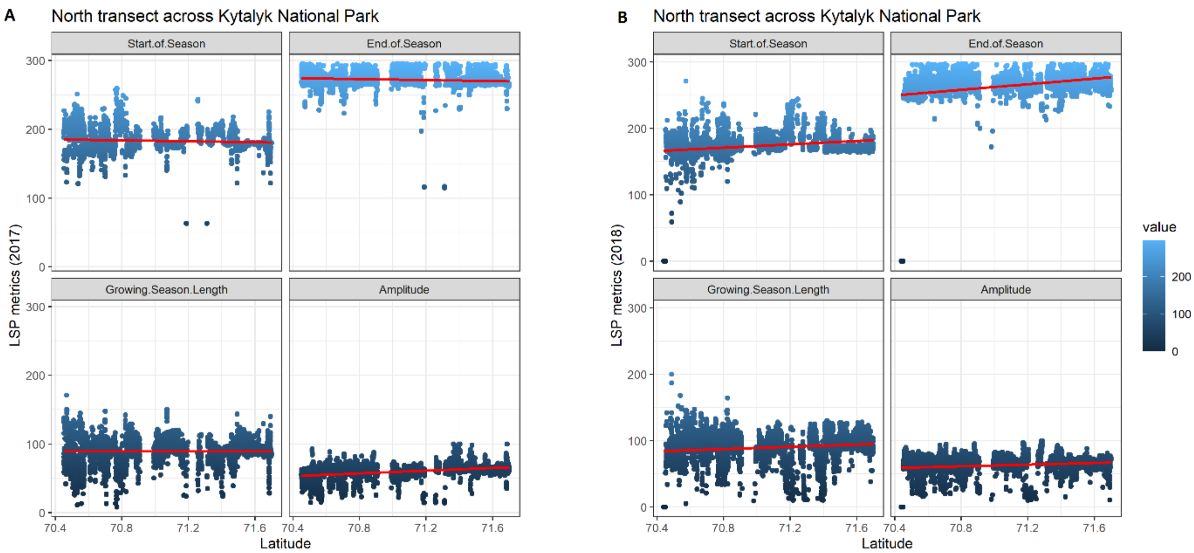

__Figure 8:__ North transect across the Kytalyk area of interest, plotting all LSP metrics against latitude for the years 2017 (A) and 2018 (B).

Statistical correlations between LSP metrics and nesting potential

The spatial correlation between the nesting potential (NPO) spatial dataset and the key LSP metrics Start of Season (SOS), End of Season (EOS), and Amplitude (AMP) was evaluated (**Figure** 9). We computed the overall correlation between NPO and each LSP metric for the years 2017 and 2018 using Pearson's correlation coefficient, and presented the results in two correlation matrices. We found that, of all four LSP metrics evaluated, SOS shows the strongest correlation with NPO, with a coefficient of 0.32 and 0.34 for the two consecutive years. Whilst moderate, correlation of SOS is significantly higher than for the other LSP metrics, confirming our hypothesis that SOS is most relevant for predicting the crane breeding habitats, given the dependence on vegetation green-up and type.

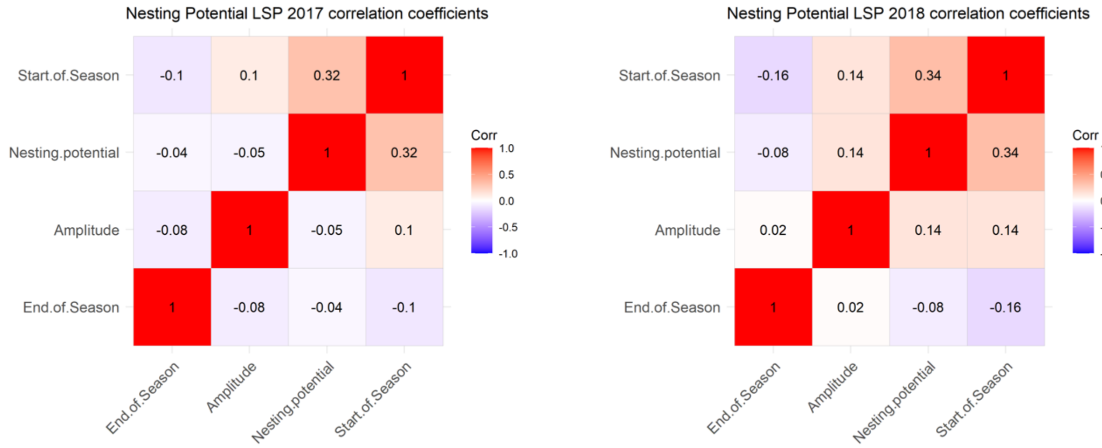

***Figure** 9. The overall correlation between NPO ('Nesting potential') and each LSP metric for the years 2017 (A) and 2018 (B) using Pearson's correlation coefficient. SOS shows the strongest correlation with NPO, with a coefficient of 0.32 and 0.34 for 2017 and 2018, respectively.*

To further illustrate and explore the relationship between NPO and LSP metrics, we plotted the correlation between the two datasets for a subset of the study area known to harbour areas with high NPO. Here, we defined a moving window of 21x21 pixels and subsequently computed the correlation between the values within each window using a correlation statistic. Identifying the local correlation between SOS and NPO was accomplished using the R "focal" function (part of the raster package).

Figure 10A and B shows the NPO and SOS raster dataset, respectively, and the correlation (both positive and negative) between both datasets is shown in

Figure 10C.

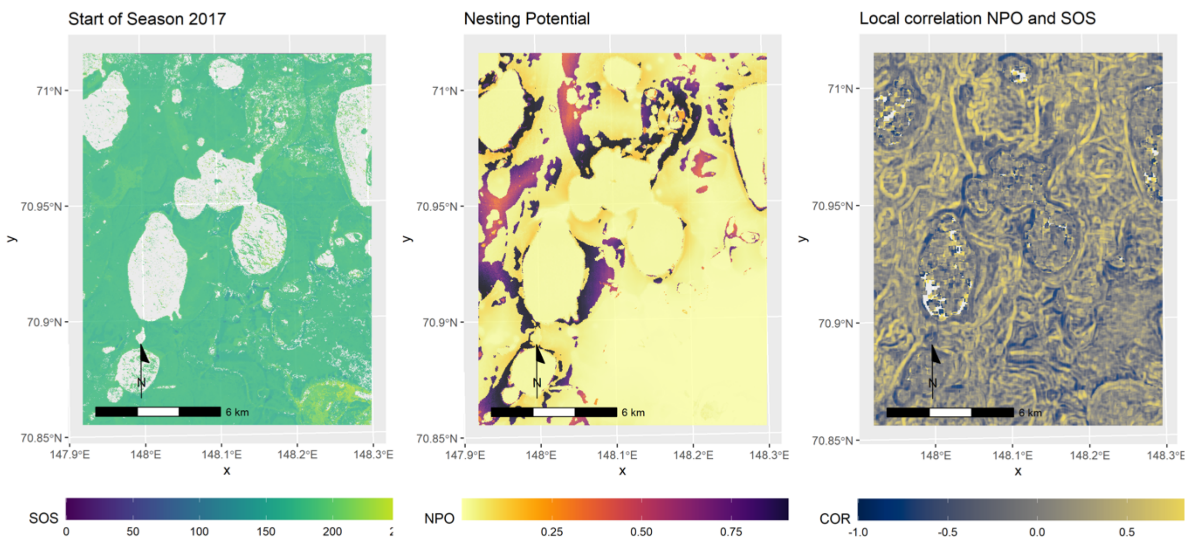

***Figure 10:** LSP product SOS (A), Nesting Potential (NPO) mode output (B), and the local correlation between the two datasets (C), which highlight areas of strong positive (yellow) and negative (blue) correlation between*

datasets. The NPO values in (B) represent the following: 0-0.5 - no potential nesting; 0.5-0.66 - low potential; 0.66-0.75 - medium potential; and 0.75-1.00 - high potential.

LSP metric SOS in comparison to habitat map

The vegetation types identified by the Budischev et al., (2014) habitat map include: the shrubs *Salix pulchra* (which reaches 2 m in height) and *Betula nana*; grasses *Eriophorum angustifolium, Arctophila fulva* and *Arctagrostis latifolia*; several *Carex* sedge species; and *Sphagnum* moss species. *Salix pulchra* is the least suited vegetation type for breeding as the field of view for the nesting birds is limited making it difficult to spot predators.

A comparison of the SOS for the two years 2017 and 2018 with the habitat type map is shown in Figure 7 for the same region of interest as Figure 6. The years 2017 and 2018 (Figure 7A and B, respectively) show a similar phenological pattern, but with a generally later start of season in 2018. This is aligned with the extended flood event in 2017. The corresponding habitat type map shown in Figure 7C detected similar small-scale features as visible with the different SOS for 2017 and 2018. Note, the habitat type map is based on Landsat 8 data from 2014. The SOS maps are based on the higher resolution data from Sentinel-2 (10 m). Therefore, it is expected to have less and/or changed features when comparing with the habitat map.

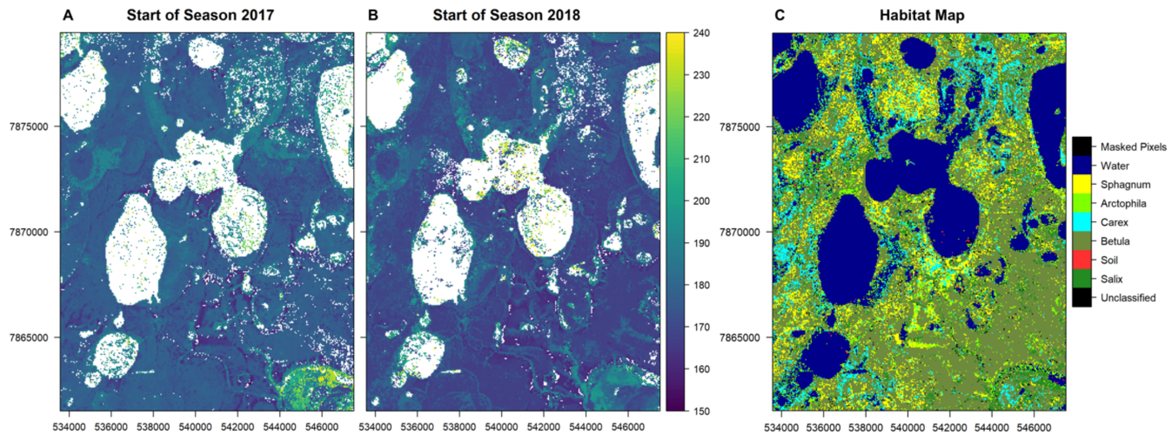

Figure 11: *SOS for the years 2017 (A) and 2018 (B) plotted for a sub-set area of interest; in addition, the corresponding Landsat 8 habitat map (C) is shown.*

In order to evaluate the link between the different habitat types and LSP metrics across the area shown in

Figure 10 and **Figure 11**, we computed the mean and standard deviation of SOS for each vegetation type. As can be seen in the box plot shown in **Figure 12**, the SOS signature for *Salix* stands out for both 2017 and 2018, with a significantly later SOS and higher standard deviation in comparison with other vegetation types.

Additional LSP metrics (i.e. EOS, GSL, AMP) are shown in

Figure 13. *Salix* stands out in all parameters and years against the other vegetation types. *Salix* has a much later SOS than other vegetation types in both 2017 and 2018 and has

slightly higher mean EOS values as well. Consistently, the GSL of *Salix* is shorter than for other vegetation types. Finally, the amplitude values for *Salix* are consistently lower and more spread than for other vegetation types. Nevertheless, this effect is stronger in 2017 when a large flood event had a strong overall effect on the growing season.

*From the plots in **Figure 12** and*

Figure 13, one can conclude that LSP metrics are suited to identify *Salix* vegetation. This vegetation type is characterized by relatively tall shrubs, which provide inadequate breeding habitat for the Siberian white crane. This information can help to further define suitable crane habitats as *Salix* often occurs in close vicinity of rivers which are also not suited for crane breeding due to yearly floods. Further, the distinct LSP metric signature of *Salix* vegetation suggests that LSP could be useful for mapping and monitoring the climate change related process of shrubification in the tundra biomes.

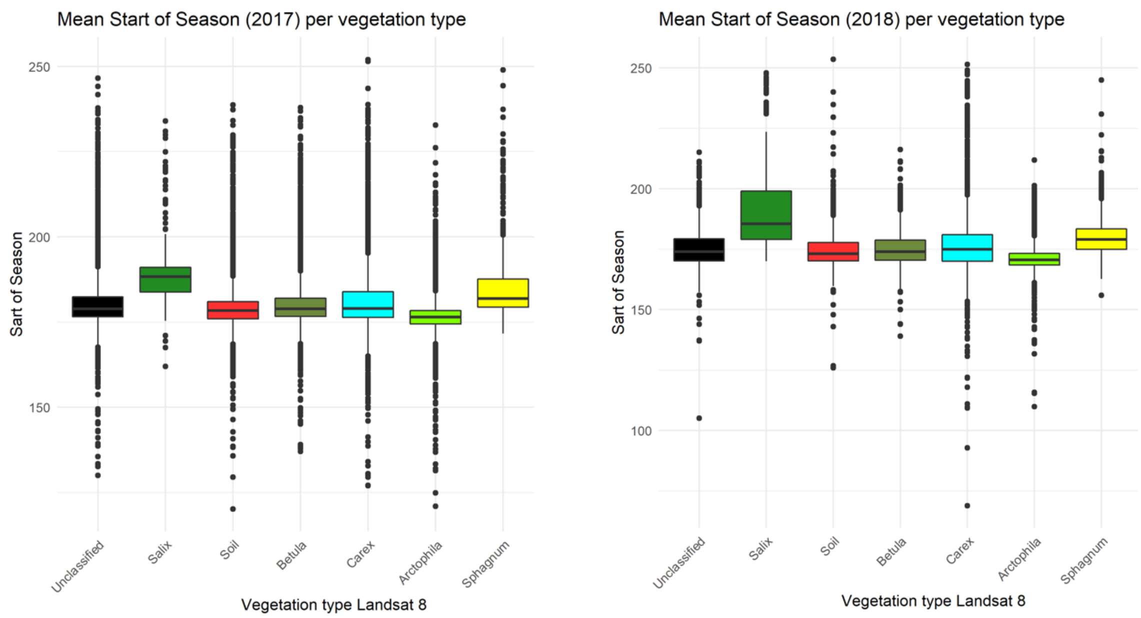

Figure 12. *Mean Start of Season metric values extracted for each habitat (vegetation) class of the Budischev et al. 2014 habitat map for 2017 and 2018, for the same region as shown in the previous figures. The LSP metric signature for the vegetation type "Salix" stands out from other vegetation types.*

	End of Season	Growing Season Length	Amplitude

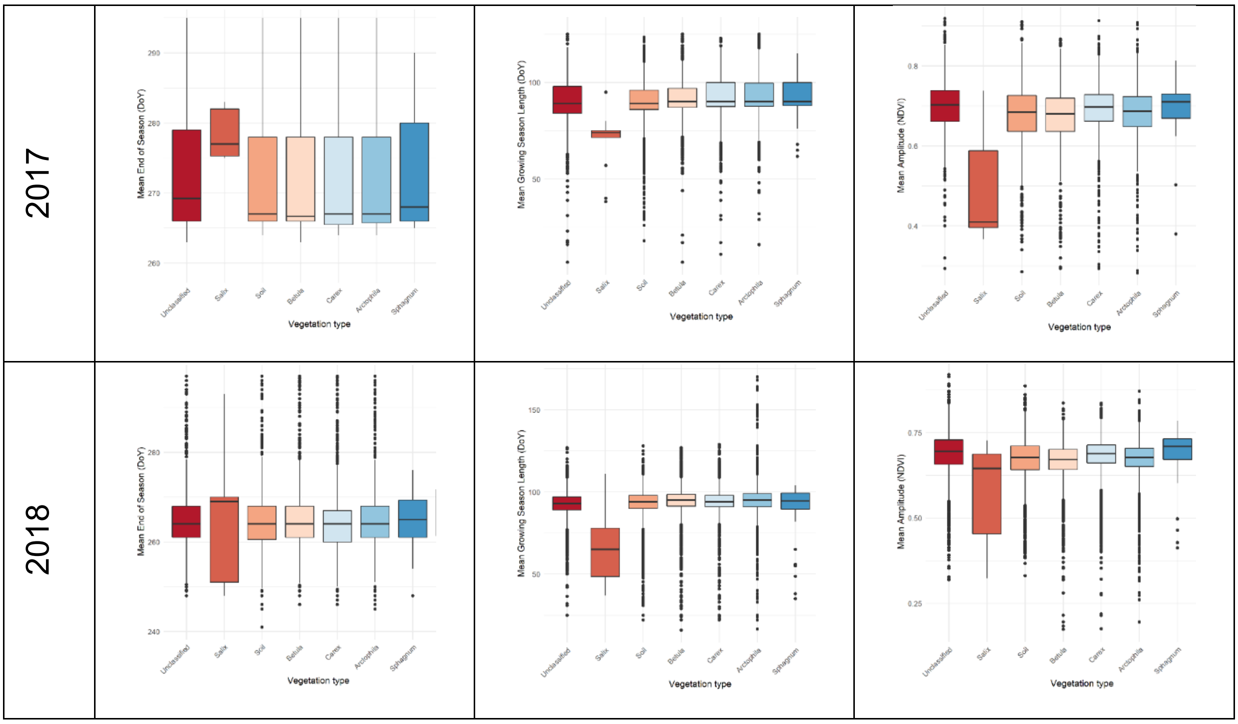

Figure 13. *Mean LSP metrics for EOS, GSL and Amplitude values are extracted for each habitat (vegetation) class of the Budischev et al. 2014 habitat map. The LSP metric signature for the vegetation type "Salix" persistently stands out from other vegetation types.*

7. Conclusions

In summary, the overarching aim of this study was to explore the effectiveness of the RS-enabled EBV LSP at contributing towards the monitoring of biodiversity changes, while simultaneously characterizing the novel LSP product. Secondly, the focus was on evaluating the LSP metrics and their relation to a habitat suitability model characterizing crane nesting habitat potential. Finally, we explored how LSP metrics are correlated to nesting habitat relevant to cranes, and can establish a baseline of ecologically relevant data for future change monitoring.

We find that the RS-enabled LSP product allows local- to landscape-scale land surface phenology to be effectively retrieved, characterized and monitored. In addition, the product can identify inter-annual and intra-annual (seasonal) spatial variation of landscape features and habitats, as well as key vegetation functional types, in particular shrubland. Importantly, the accurate mapping of shrubland is essential to identifying areas that are not suitable as crane habitat, and at the same time monitoring the global change process of shrubification. As such, we show that the LSP product can be effectively employed together with complementary environmental, ecological and climatic variables, such as those used to develop the habitat suitability model.

A key finding of this study, which is of wider relevance, is that the range of LSP metrics can serve as a baseline for monitoring long-term shifts in terrestrial vegetation composition such as shrubification. By providing a finer-scale characterization of local- and landscape-scale variation in phenology, and a new baseline dataset for long-term monitoring, the LSP products based on Sentinel-2 observation open us numerous novel fields of scientific study. Such high resolution information characterizing habitat change is expected to contribute a better understanding of the environmental and ecological changes impacting the Kytalyk National Park, while simultaneously facilitating the conservation of the Siberian white crane.

8. The Siberian crane use case demonstration in the context of the Biodiversity Indicator Development Framework

Understanding the context in which RS-enabled EBVs have been used in relation to the Biodiversity Indicator Development Framework (see section 1.3) will help future potential users to use the RS-enabled EBVs as and where appropriate, and will help ensure the selection of the optimum indicators and underlying data. The following sub-sections place the Siberia crane use case in the context of the purpose of the eventual indicator (red headings), production of the indicator (Blue headings) and permanence of the indicator (green headings).

Main stakeholders/audience for this work

- National park managers
- Foundations such as the International Crane Foundation
- International conservation organisations such as the IUCN and IUCN Red List.
- Researchers from ornithological institutes such as the Swiss Ornithological Institute and Budischev Planck Ornithology.
- Ecological modellers
- Results may inform conventions such as the Memorandum of Understanding Concerning Conservation Measures for the Siberian Crane, as part of the Convention on the Conservation of Migratory Species of Wild Animals or Bonn Convention
- Conservation programs such as the Siberian Crane Wetland Project funded by the Global Environment Facility, and the Western/Central Asian Site Network for Siberian Cranes and Other Water birds

Researchers and national park managers are the main expected intermediate users of this work. For instance, researchers in the domain of Arctic tundra biodiversity-ecosystem functioning, will be able to use the output product of this use case study as baseline data to quantify and monitor environmental and ecological change.

National park managers have only limited possibilities to monitor the nests of the crane in the field mainly due to the very difficult or impossible accessibility of the area due to its remoteness. Therefore, providing information to narrow down potential nesting habitat, and including baseline, high resolution ecologically relevant information to identify habitat type, and their changes through time, may help managers prioritize conservation actions, and indirectly monitoring the development of the population. The long term aim is to, on a yearly basis, predict the probability of breeding success based on weather and flood conditions, as estimated with LSP and other auxiliary data sets, such as flood maps and snow melt.

An important additional end and intermediate user of the work is the International Union for the Conservation of Nature's (IUCN), whose Red List of Threatened Species is the world's most comprehensive information source on the global conservation status of animal, fungi and plant species. The IUCN Red List provides critical indicators of the status of the world's biodiversity, and is a vital tool to inform and catalyse action for biodiversity conservation and policy change. The IUCN aims to provide data on range extent, population size, habitat and ecology, use and/or trade, threats, and conservation actions, all of which help inform necessary conservation decisions. Within this context, this particular use case demonstration is expected to satisfy a number of these data needs, in particular by providing a means to identify changes in habitat and ecology in relation to climate change.

Relevant management objectives or targets

- There are no site-level specific management objectives or policies guiding this work; instead, this work is responding to trends that have been observed in the field over recent years (described in the Introduction), and as such, aims to both back-up the findings with further observations and ancillary datasets, and explain these findings within the context of global change.
- The main directive guiding this work is to demonstrate the effectiveness of RS-enabled EBVs in capturing biodiversity change; in addition, this work attempts to show how RS-enabled EBVs can be used, together with ancillary datasets, to produce changes indicators which are related directly or indirectly to biodiversity.

Key questions being asked

A key question which this project addresses is: how are trends in RS-enabled EBVs related to observed trends in the field; and more specifically, how are trends in RS-enabled EBVs related to habitat changes, for instance, shrubification, which are in turn relevant for a given species (i.e. Siberian white crane)? In addition, we addressed the questions:

- What is the extent and rate of change in RS-enabled EBVs and ancillary satellite-derived datasets, and how are these rates related to global change processes such as greening, and changes in the habitat available for certain species, including the Siberian crane?
- How are changes in terrestrial land surface phenology related to changes in plant community composition, habitat and biodiversity changes?

Information on the timing of melt onset and snow cover retreat over terrestrial biomes and sea ice, is important for understanding the Arctic's changing climate; thus we investigate and quantify trends in growing season length, duration of snow cover and water body melt on-set period. So an additional question addressed was:

- Is snow cover persisting later into the season, or vanishing earlier, over a period of several, leading to a longer growing seasons compared to historical baselines?

Indicators that would answer the key questions

- The intended indicator encompasses a suite of metrics derived from the land surface phenology (LSP) algorithm (indicators derived from FRAG and CCC are not yet addressed in this study). The main LSP metrics retrieved were: Start of Season (SOS), End of Season (EOS) and Growing Season Length (GSL), which are expressed in day of the year (DoY). These properties are correlated to green-up and leaf senescence and the length of the growing season, respectively. Additional properties include maturity onset (DoY), the peak of season (DoY), senescence onset (DoY), rates of green-up / senescence (VI/ DoY).
- Together, these metrics describe parameters related to the vegetated land surface growth cycle, its seasonality and terrestrial vegetation's functional diversity, and can therefore be used as indicators of biodiversity change.
- So far, no single indicator has been produced; instead, a suite of phenology metrics are being generated for a period of several years, which together comprise an indicator of the vegetation growth cycle, its seasonality and terrestrial vegetation's functional diversity.
- At present, The Group on Earth Observations Biodiversity Observation Network (GEO BON) is defining how exactly to compute biodiversity change indicators from EBVs and RS-enabled EBVs. Ideally, these indicators would be computed as a single metric derived from one or more RS-enabled EBVs time-series, and which have been shown to capture changes in biodiversity. Further, such an indicator may encompass RS-enabled EBVs metrics used in conjunction with ancillary satellite-derived or field datasets. Hence, this use-case study is currently attempting to define how such global indicators can be derived and test their relevance for biodiversity monitoring.
- Thus, indicators are intended to be correlated with how much biodiversity is present within a given area, and how much has it changed over time; they comprise a proxy for biodiversity.

Data needed for the above indicator(s), and their availability

- This study primarily used LSP metric time-series data; it focused on the remotely sensed aspects due to time and data availability constraints preventing use of additional data.

- Seasonality or phenology of snow cover and ice melt on-set is a primary dataset used in this study; for this, UZH have access to a large radar time-series dataset.
- Data needed to compute the biodiversity are available; however, the availability of crane breeding success data has been delayed; this has resulted in a shift in the focus of the study, i.e. towards mapping changes in greening/shrubification and looking at the linkages between phenology and changes/shifts/trends in phenology and biodiversity.
- There is currently only limited access to field site data, it has been decided to focus mainly on interpreting satellite RS-enabled EBV time-series, ancillary and historical satellite data and derive change metrics from these datasets, and subsequently investigate how these might be related to biodiversity/habitat changes.

How the final indicator(s) was/were calculated

With the work presented in this document, we have not calculated a final indicator. However, we based our assessment on a model developed by Haverkamp et al. (submitted) in combination with the RS-enabled EBV data sets of Start of Season and other auxiliary data (such as habitat map). To calculate a distinct indicator, the study would need to be extended towards the use of the nesting potential map in combination with a yearly LSP map to judge on a modelled, yearly nesting success.

How operational RS-enabled EBVs could support sustained indicator production

- There would firstly have to be consensus on how to derive indicators from RS-enabled EBVs.
- A key focus of all GlobDiversity use-case studies could be to identify how these indicators are defined and test their validity.
- In terms of operational RS-enabled EBVs, there are some products already available that University of Arizona produce: global start of season/end of season/length of season landscape phenology from 1980 to 2016, incorporating multiple satellites. This demonstrates definite potential, with applications for climate change studies.
- High resolution products are relatively recent, meaning no long time-series hence coarser resolution products are used. NASA is always striving for continuity of products. It is possible to develop products that go back and can be back-calculated in order to have continuity, especially once we incorporate the Sentinel products. The RS community and ecologists will be happy to have an end product that is readily downloadable – inaccessibility of RS data intimidates ecologists so readily downloadable products will be invaluable.

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Annex 2: Use case demonstration – dragonfly habitat connectivity in the Camargue

Abstract

Focusing on the Camargue Delta of southern France, we explore how a habitat fragmentation RS-enabled EBV could be helpful for informing species conservation management. Effective management and conservation of the various ecosystems of the Camargue is essential to protect their biodiversity and to maintain the ecosystem services they provide. This can be supported by remote sensing tools, which provide information on the spatial distribution of habitats and their trends over time, and what these trends mean for the species occurring in those habitats. The main goal of this use case demonstration was to develop and apply a habitat connectivity RS-enabled EBV for a selected taxon of conservation interest: the dragonfly *Lestes macrostigma*). We estimated the impact of the fragmentation of their habitats on the spatial distribution of the dragonfly and its long-term persistence within the Camargue delta.

1. Introduction

Mapping habitat connectivity and fragmentation is highly important for informing species conservation. Identifying critical pathways for these species can help management bodies to avoid or minimize human impacts in the areas concerned, and inform conservation management to increase the size and resilience of species of conservation interest.

We present a use case demonstration of a habitat connectivity RS-enabled EBV developed for the Camargue Delta of southern France and a localized dragonfly species occurring within it: *Lestes macrostigma*, the dark spreadwing. By targeting a species dependent on wetland habitats and their condition, which are dynamic across space and time, we show how such seasonality can be incorporated into the assessment of habitat connectivity and fragmentation, through the application of both field and remotely-sensed data, and how this assessment can have real-world relevance to site management.

The functional biodiversity and habitats of the Camargue are predominantly influenced by the salinity and the quantity and the quality of water that is available year round. In this Mediterranean climate, large areas of the park naturally dry up during the summer period. Through a complex network of irrigation and drainage channels, 730 millions of 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 breeding habitat for waterbirds either for sustaining commercial hunting activity or enhancement of bird populations for conservation. Half of this water is returned to the Rhône through drainage channels, the other half being evacuated to the Vaccarès lagoon. This water, primarily pumped for rice farming, is also used for flooding marshes used for nature conservation, wildfowl hunting and reed harvest, as well as for irrigation of pasture meadows.

2. Location and spatial coverage of use case

The Camargue Delta in the Rhône river, localized in Southern France (Figure 1), covers 135 000 ha and hosts a richness of species typical for Mediterranean wetlands, including 1200 plant species, 43 mammal species, 370 bird species, 10 amphibian species, 19 reptile species, 70 fish species, 1652 beetle species, 52 butterflies and 43 dragonfly species (Blondel et al 2013). It is a complex mosaic of natural and man-made, wet and dry habitats including lagoons, salinas, brackish/freshwater marshes with emergent or aquatic vegetation, as well as halophilous scrubs and steppes. These ecosystems are intermingled with agro-systems dominated by rice fields and other irrigated crops. Wetland habitats of the Camargue are important for a wide range of ecosystem services such as climate regulation, flood mitigation, water purification, nutrient cycling, agriculture, fishing, cattle grazing, wildfowl hunting and bird watching (Vaschalde, 2014).

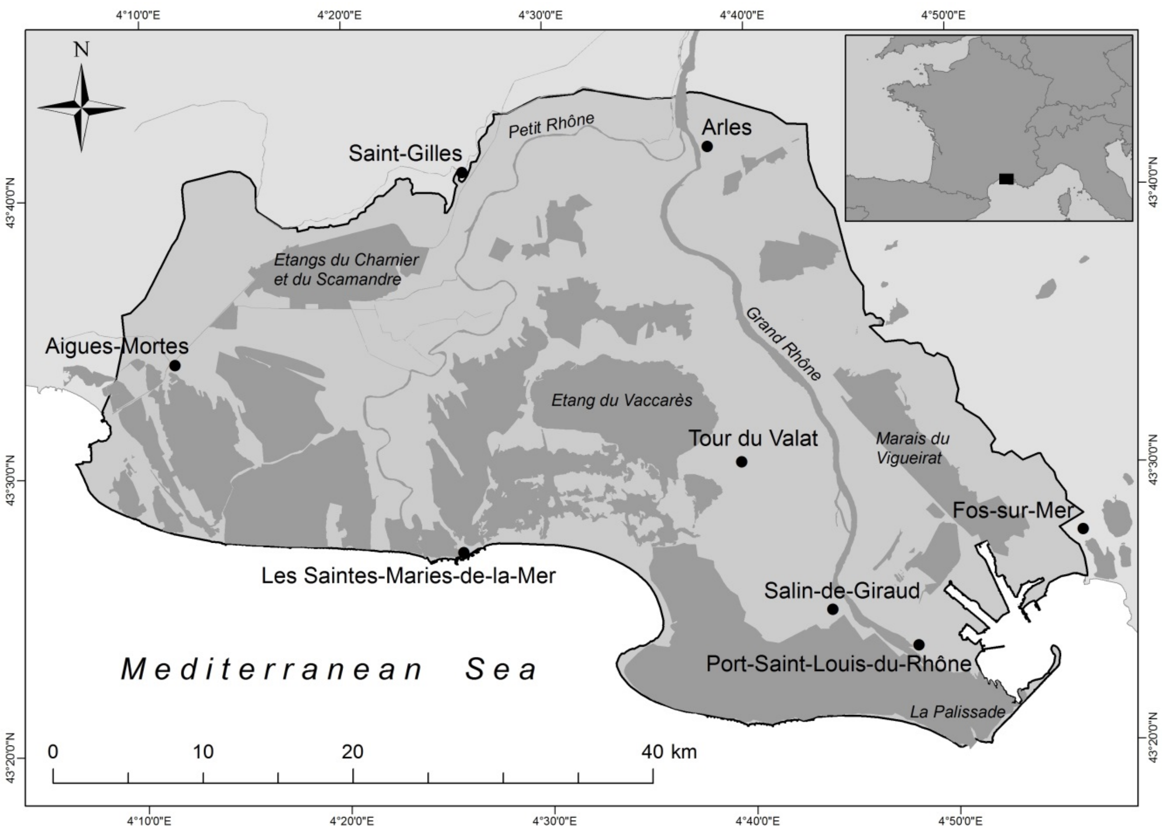


__Figure 1:__ Location of the studied site (the Camargue)

3. Aims/objectives of the use case

Mapping habitat connectivity and fragmentation is very relevant for the conservation of species, especially those representing a high interest regarding their status (e.g. endangered and/or endemic species). Thus, identifying critical pathways for these species can help national authorities and management bodies to avoid or minimize human impacts in nature conservation areas. In general, there are two ways to conserve connectivity in a region: (1) conserve more habitats in key areas that facilitate movement and (2) mitigate landscape features that impede movement, such as roads, railroads, and urban development (Ament et al. 2014).

At the global scale, the Convention on Biological Diversity (CBD) aims to have 17% of land and inland water conserved by 2020 where the connectivity between different habitats is maintained as much as possible. In addition to that, at the EU level, some Directives (e.g. the Habitat and the Water Framework Directives) encourage and push EU countries to adopt policies that take into account the conservation of their biodiversity, for example by ensuring that the ecological continuity is maintained at the national scales. For instance, since 2007 in France, the Green and Blue grid (*la Trame Verte et Bleue*) has been officially designated as one of the major French national projects resulting from the Grenelle de l'Environnement. It consists of the entire network of biological corridors (or ecological corridors, existing or to be restored) that host a large part of the biodiversity.

But how do we know that these conservation efforts are efficient? Hence, three things could be identified as relevant to assess: (1) the location of habitats of conservation importance; (2) how well these habitats are connected for species movement; and (3) where the opportunities are to strengthen this network (Gallo, 2019).

4. Why RS-enabled EBVs were used

For this use case on the Camargue, in addition to the *in situ* data on the dispersal of the targeted species (the dragonfly *Lestes macrostigma*), the assessment of habitat connectivity requires different data and detailed maps of Land Use/Land Cover (LULC) and surface water dynamics at the scale of the whole site. The latter is of especial importance in Mediterranean wetland ecosystems, where intra- and inter-annual dynamics of surface water are naturally observed and the ecology of many species related to these habitats are adapted to such specific regimes. The use of EO-based tools (e.g. satellite image time series) allows having data and information that could capture these trends at different time scales (intra- and inter-annual), with levels of accuracy and cost-effectiveness that would be much more difficult to obtain based on other data sources, for example photographs acquired from airborne and/or drones.

Considering all these reasons, a habitat connectivity RS-enabled EBV is the most appropriate approach for this use case. Moreover, if this method can be up-scaled and implemented at broader geographical regions, the Tour du Valat (as a main user) could also adapt it for application at a pan-Mediterranean scale.

5. Methodology

For the Camargue use case the LARCH-SCAN-Hanski metric was implemented to measure structural ecosystem discontinuity. This metric focuses on the effects of dispersal on persistence of organisms across land-cover types.

The LARCH-SCAN method encompasses three straightforward steps:

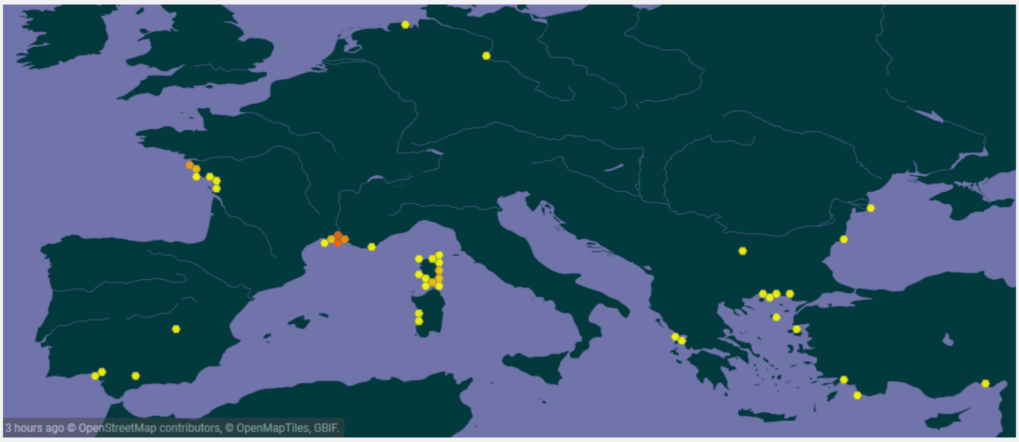
HSI Habitat generation (selection of suitable habitat)

Habitat can be selected from remote sensing based land cover products, directly or by combining them though pre-processing. To serve a variety of potential species ranges, the habitat fragmentation RS-enabled EBV can be calculated for each habitat-class from a chosen product. Individual output cohesion maps can then be combined to represent the habitat and species of choice.

For the Camargue study area, habitat maps where created by combining Sentinel 2/ Landsat-8 derived land cover maps and S2 water-/flooding dynamic data to capture the seasonality of the flood duration. Fragmentation was assessed for the species *Lestes macrostigma*. This dragonfly is a very local species, with a fragmented distribution in Europe occurring in brackish temporal water ecosystems, as represented in the Camargue (Box 1).

Ecoprofile definition

Lestes macrostigma (Eversmann, 1836)



Known distribution of Lestes macrostigma 1999-2019 https://www.gbif.org/species/1423981

Surface water periodicity:

Larvae inhabit temporary brackish waters.

Hatching occurs during the second fortnight of March and wetting of eggs is necessary for embryonic post-diapause development, which lasts ca. 15 days (Lambret et al. 2017). This means that water is "needed" on 1st April. However, an early flooding will allow more eggs to survive desiccation period: eggs flooded in November and February will hatch at 80 and 25%, respectively; note that if flooding occurs as late as April, some eggs will still survive but hatching rate will only reach 5% (Lambret et al., 2018).

Emergence starts during the first fortnight of May (depending on mean April temperature) and lasts 15 days (Lambret, 2010). Hence, drought period shall not start before mid-May and a later start allows more adults to hatch (and therefore to disperse and lay eggs).

Ideal flooding period is therefore from November to May (both included). Minimal flooding period is from February to mid-May.

Salinity: It seems from ongoing laboratory experiment, that larvae are better adapted to smoothly brackish waters, compared to fresh, highly brackish and salted waters. Indeed, mortality is 50-100% in fresh water and water containing 16, 24 and 32 g of salt per liter. Mortality is much lower in 4 and 8 g/L.

Box 1: *Ecoprofile definition for* Lestes macrostigma *in the Camargue*

Calculation of spatial cohesion (LARCH SCAN-Hanski metric)

LARCH-SCAN is based on the dispersal capacity of species. The model uses a formula that describes the dispersal curves of birds (Siefke, 1984) and is used for connectivity measures in metapopulation models (Hanski, 1994). The spatial cohesion of a habitat cell *i* is determined by weighting the carrying capacity of all cells within the potential dispersal distance by:

$$SC_i = \sum RU_j \cdot e^{-\alpha \cdot d_{ij}}$$

d_{ij} *is the distance between the contributing cell j and cell i (meters)*
RU_j *is the maximum number of reproductive units in cell j*

Fragmentation for *Lestes macrostigma* was calculated over six distances: 100 m, 500 m, 1 km, 5 km, 10 km and 20 km. The maximum cohesion values of all these distances were chosen to represent the cohesion of *Lestes macrostigma* in the Camargue

Evaluation of cluster size (sustainability)

In the third step cohesion maps were used to derive clusters of connected habitats cells to construct connected (and isolated) habitat areas. Patterns of cohesion values can be used for planning corridors between local patches or to improve weaker spots in networks. Depending on the application, different thresholds can be set to create the clusters. Thresholds usually range across the following values:

0 = no cohesion; < 0.1 = weak cohesion; 0.1-0.5 = higher cohesion values, usually corridors; >0.5 = strong cohesion forming networks.

For *Lestes macrostigma* in the Camargue a threshold of 0.1 was used to derive the connected local habitats.

Data

The following data was used to derive the HSI map

The water seasonality map: based on Sentinel data for 2018, the NDWI (Normalized Difference Water Index https://www.sentinel-hub.com/eoproducts/ndwi-normalized-difference-water-index) was used to derive flooded areas in the Camargue. At 20 m resolution, the NDWI was downloaded for 12 dates: 2018_01_23, 2018_02_22, 2018_03_14, 2018_04_18, 2018_05_18, 2018_06_27, 2018_07_17, 2018_08_16, 2018_09_20, 2018_10_25, 2018_12_04, and 2018_12_29.

These data were combined into one data set showing unique combinations of flooded-non-flooded periods for each 20 m raster cell in 2018, from which flooding suitability (fraction 0 not suitable, to 1 suitable) for *Lestes macrostigma* could be selected (Figure 2).

Table

2018_YRcombi_20m_clip_MNDWI_buffer.tif

OID	Value	Count	2018_YR_20	12_04	12_29	01_23	02_22	03_14	04_18	05_18	06_27	07_17	08_16	09_20	10_25
0	1	5664900	0	0	0	0	0	0	0	0	0	0	0	0	0
1	2	11826	1	0	0	0	0	0	1	0	0	0	0	0	0
2	3	2333831	12	1	1	1	1	1	1	1	1	1	1	1	1
3	4	166	6	1	0	0	0	1	1	1	1	0	1	0	0
4	5	16910	11	1	1	0	1	1	1	1	1	1	1	1	1
5	6	31900	11	1	1	1	1	1	1	1	1	1	1	0	1
6	7	19929	2	0	0	0	0	0	1	1	0	0	0	0	0
7	8	76	9	1	1	0	1	1	1	1	1	0	1	1	0
8	9	78531	1	0	0	0	0	0	0	1	0	0	0	0	0
9	10	1408	10	1	1	0	1	1	1	1	1	1	1	1	0
10	11	15944	3	0	0	0	0	0	1	1	1	0	0	0	0
11	12	905	8	0	0	0	1	1	1	1	1	1	1	0	1
12	13	14	6	1	0	0	0	1	1	1	1	0	0	1	0
13	14	145	4	0	0	0	0	1	0	1	1	0	1	0	0
14	15	751	9	1	1	0	0	1	1	1	1	1	1	1	0
15	16	337	2	0	0	0	1	0	0	0	0	0	0	0	1
16	17	492	3	0	0	0	0	0	1	1	0	0	0	1	0
17	18	478	2	0	0	0	0	1	0	0	0	0	1	0	0
18	19	192	7	0	0	0	0	1	1	1	1	1	1	1	0
19	20	812	9	0	0	0	1	1	1	1	1	1	1	1	1
20	21	544	8	1	0	0	0	1	1	1	1	1	1	0	1
21	22	1282	10	1	0	0	1	1	1	1	1	1	1	1	1
22	23	3848	11	1	0	1	1	1	1	1	1	1	1	1	1
23	24	3618	11	1	1	1	1	1	1	1	1	1	1	1	0
24	25	3113	3	0	0	0	0	1	1	1	0	0	0	0	0
25	26	60	4	0	1	0	0	1	1	0	0	0	0	1	0
26	27	20	6	0	0	0	0	1	1	1	1	0	1	0	1
27	28	2462	10	0	1	0	1	1	1	1	1	1	1	1	1
28	29	1062	4	1	0	0	0	1	1	1	0	0	0	0	0
29	30	75	2	0	0	0	0	1	0	0	0	0	0	1	0
30	31	2757	10	1	0	1	1	1	1	1	1	1	1	0	1
31	32	5071	1	0	0	0	0	0	0	0	0	0	0	1	0
32	33	44	7	1	0	1	0	1	1	1	1	0	1	0	0
33	34	214	5	0	0	0	0	1	1	1	1	0	1	0	0
34	35	306	3	0	1	0	0	1	0	0	0	0	0	1	0

Figure 2: *Input flooding suitability for Lestes macrostigma based on monthly NDWI flooding maps.*

Land cover map: based on Landsat-8 data a classified LULC data set for 2016 was generated using a hybrid nomenclature system that combines CORINE Land Cover classes with Ramsar definitions for wetland habitats, from which land cover suitability for *Lestes macrostigma* can be selected (fraction 0, not suitable, to 1, suitable).

The final habitat suitability (Figure 3) was derived from combining flooding suitability and land cover suitability by multiplying both suitability fractions. This was performed at the scale of the Regional Nature Park of the Camargue Park in Southern France, with a size of 856.9 km^2, and was validated using field observations of the target species (Figure 4).

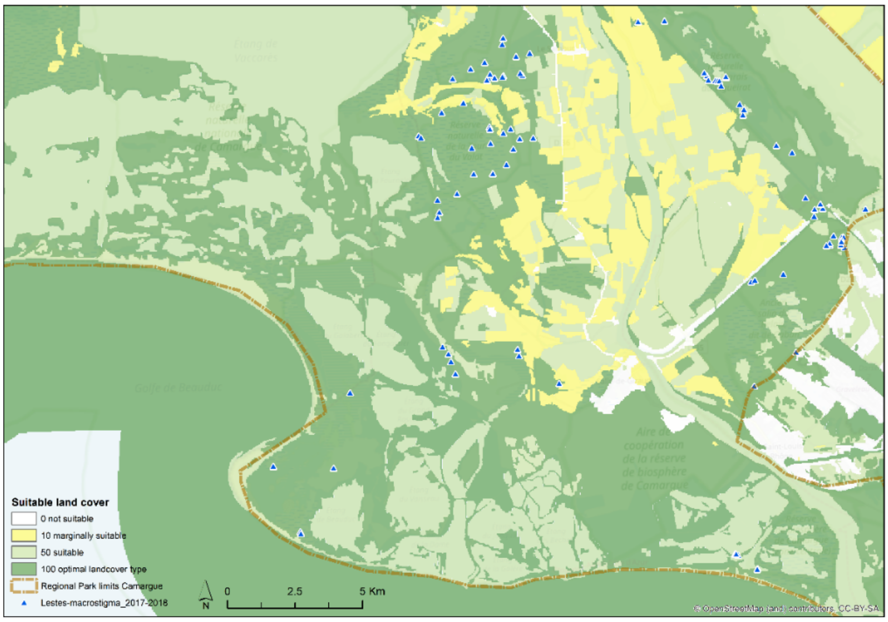


Figure 3: *Input land cover suitability for* Lestes macrostigma

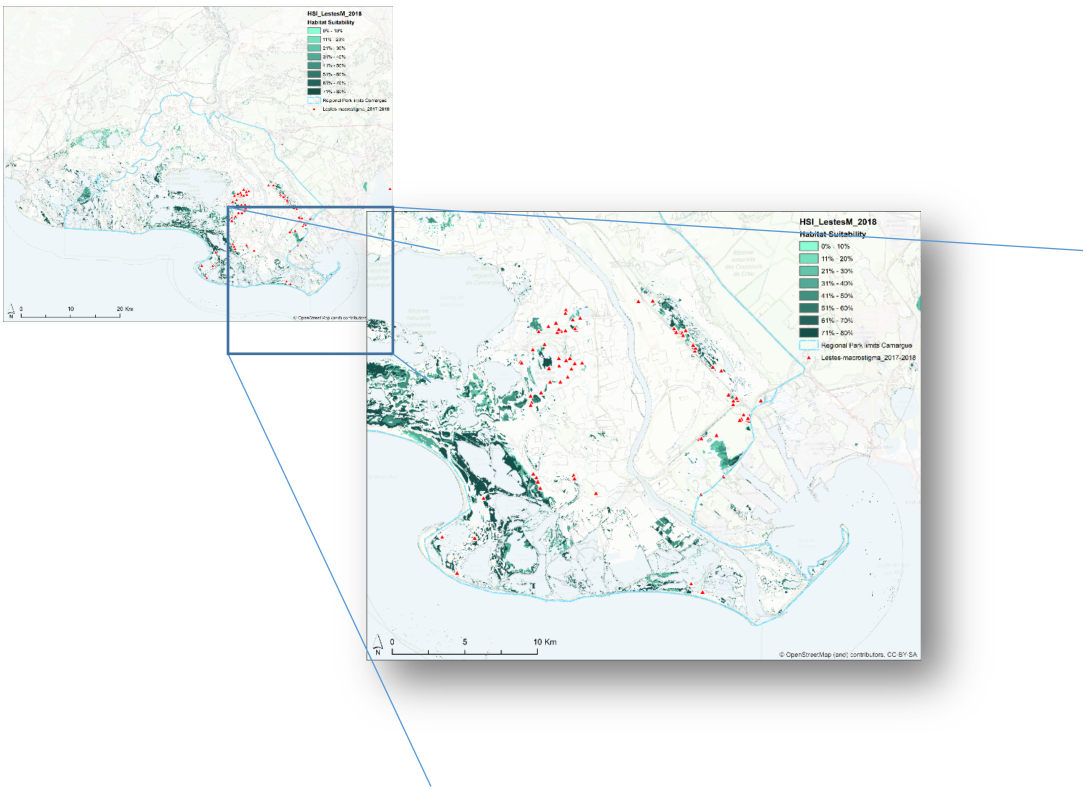


Figure 4: *Input combined habitat suitability for* Lestes macrostigma*, with an overlay of field presence data in 2018 (red triangles)*

6. Results and discussion

The result of the LARCH-Scan fragmentation analysis resulted in three characteristic fragmentation maps for *Lestes macrostigma*: 1) Cohesion values directly coming from the Hanski metric (Figure 5), 2) a map classifying these values into meaningful interpretable classes of fragmentation (Figure 6), and 3) a map showing the connected clusters based on the chosen thresholds (Figure 7).

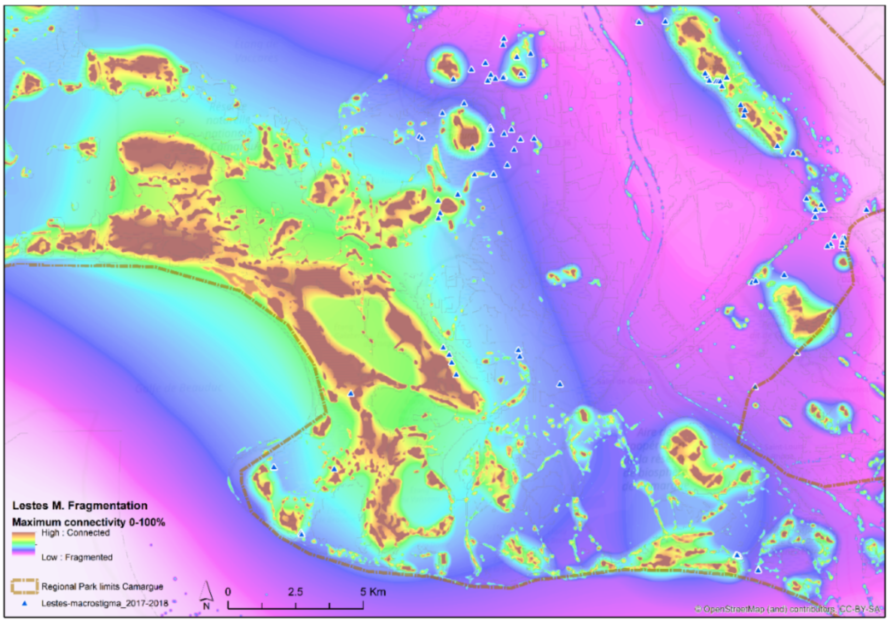


Figure 5: *Zoom in of output cohesion values for* Lestes macrostigma *in the Camargue*

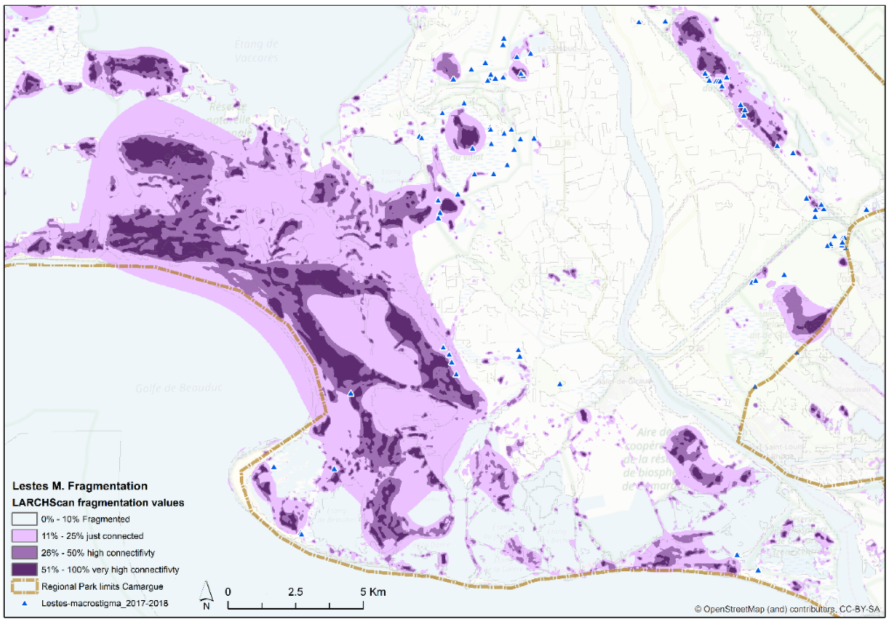


***Figure 6:** Zoom in of output fragmentation classes* for Lestes macrostigma *in the Camargue using a Scan-threshold of 0.1, 0.25 and 0.5 (10, 25 & 50% of Habitat in the defined neighbourhood).*

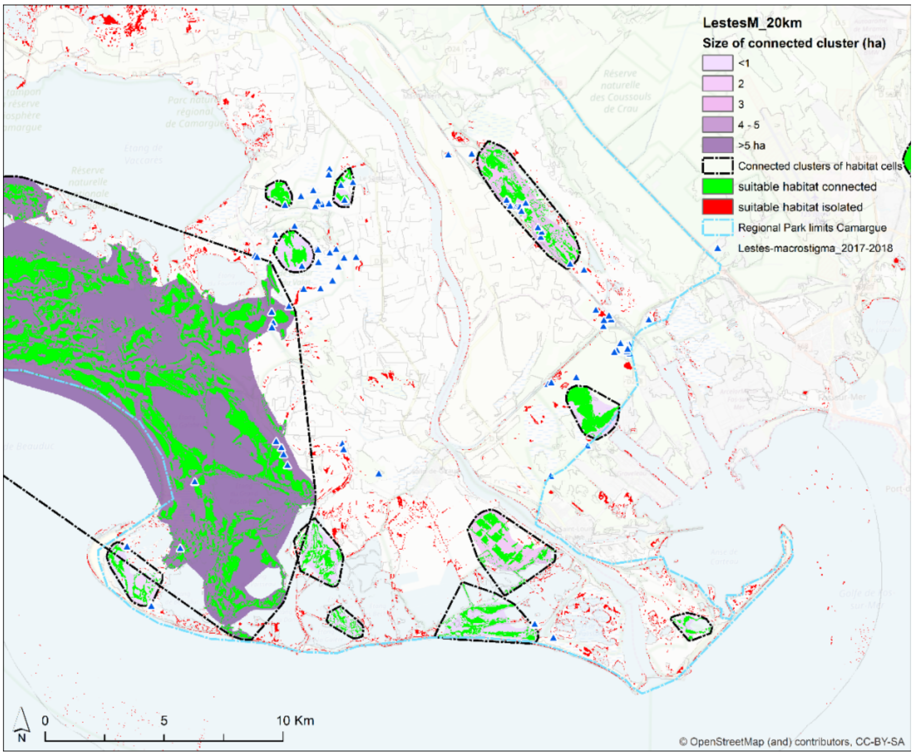


***Figure 7:** Zoom in of output connected habitat clusters for* Lestes macrostigma *in the Camargue and their size in hectares of habitat using a Scan-threshold of 0.1 (10% of Habitat in the defined neighbourhood).*

The map showing the connected clusters based on this chosen threshold (Figure 7) shows a large core area of connected habitat to the west of the study area, with small outlying clusters of habitat that could potentially be joined through some targeted habitat management and restoration. Some relatively large, although more isolated, patches and clusters of habitat are spread further to the east, and these would be a priority for preserving and connecting (for example through implanting ecological corridors) to make a larger network and enhance the resilience of the dragonfly population in the Park.

The results are of potential use by the Tour du Valat and the management authorities of the Regional Nature Park of the Camargue and the National Reserve of the Camargue to assess the impacts of management, conservation and habitat restoration measures for the dispersal of the targeted species. With the functional biodiversity and habitats of the Camargue being largely influenced by the seasonal water dynamics, the map of clusters of connected habitat for the dragonfly *Lestes macrostigma* is one piece of evidence that park managers can use to inform the water management to increase the connectivity and dispersal of this, among other, important species.

7. Conclusions

The aim of this use case demonstration was to develop a habitat connectivity RS-enabled EBV to inform the management actions aimed at the conservation of a species of interest in the Camargue Delta: the dark spreadwing dragonfly *Lestes macrostigma*). This process successfully combined expert knowledge on the habitat preferences and requirements of the dragonfly, with remote-sensing derived data and products to arrive at spatial maps showing clusters of connected habitat. Further interpretation of the output EBV maps is needed to translate this knowledge into implications for reserve management. A habitat fragmentation conservation management target and associated indicator for this or other wetland species could be developed, and the RS-enabled EBV demonstrated here could then serve for ongoing measurement of progress against it. Confirmation was obtained from the local management authorities that the outputs produced are indeed valuable and that they add much additional value to existing habitat surveys and species presence field data. Habitat connectivity assessment, management targets and indicators for wider areas beyond the Camargue Delta may have further utility for regional and even national level conservation planning, and at these larger-scales the benefit of RS-enabled monitoring approach is even more justified, given the excellent data availability and cost-effectiveness of data gathering.

8. The dragonfly connectivity use case demonstration in the context of the Biodiversity Indicator Development Framework

Understanding the context in which RS-enabled EBVs have been used in relation to the Biodiversity Indicator Development Framework (see section 1.3) will help future potential users to use the RS-enabled EBVs as and where appropriate, and will help ensure the selection of the optimum indicators and underlying data. The following sub-sections place the Siberia crane use case in the context of the purpose of the eventual indicator (red headings), production of the indicator (Blue headings) and permanence of the indicator (green headings).

Main stakeholders/audience for this work

The main objective of this use case on the Camargue is to test innovative approaches for the assessment of habitats connectivity and fragmentation for some preselected species and to see whether conservation and water management measures at the local scale have impacted their dispersal over the last years. Thus, the main targeted users here are researchers and site managers (e.g. the Tour du Valat and the management authorities of the Regional Nature Park of the Camargue and the National Reserve of the Camargue). However, as the developed and tested approach here intends also to be up-scalable for wider geographic regions, depending on the availability and the accuracy of the needed input data, additional potential users include government agencies and civil society organizations at national level, and potentially across EU countries or the Mediterranean Basin.

In terms of other stakeholders and potential users:

- As connectivity/fragmentation is one of the main issues for biodiversity being tackled at the European level under the EU nature directives, the habitat fragmentation RS-enabled EBV may be of interest to other governments. There are also a number of stakeholders from a scientific perspective, in particular species experts who were consulted on input data, and who could do further research on population dynamics, species movement and dispersal, including in the context of climate change.
- Consultations to date have primarily been with expert agencies over the species concerned, its ecology and the raw input data. There have not yet been any consultations with potential users such as government agencies. Ultimately, species expert groups of the IUCN would be key stakeholders as they will assess the conservation status of the species studied. Connectivity maps could be used to improve the IUCN species range maps.

Relevant management objectives or targets

- Achievement of site-level conservation targets, including favourable conservation status of habitats and species of conservation interest under the EU nature directives (Habitats and Birds Directives).
- At the national scale, target setting and reporting on connectivity targets within the national biodiversity strategy and in fulfilment of the country's commitments under Convention on Biological Diversity. The study also represents a proof of concept for assessing ecological character for a wetland, under the Ramsar Convention.

Key questions being asked

- What is the effect of habitat connectivity on the persistence of species over time?
- Are the populations viable?
- What are the impacts of habitat change on species dispersal?
- How can we design habitat corridors to promote connectivity?
- What would be the impact of future management and habitat changes on species dispersal?

Although these are questions are specific to a species, if the species is an umbrella species then this approach can be helpful for habitat management.

Indicators that would answer the key questions

An indicator could be developed that not only encompasses the amount of habitat available to a species, but also a distance measurement reflecting parameters critical for species movement and the viability of the species of conservation interest. Such an indicator would have the dual purpose of monitoring progress towards conservation targets, and in a modelling context, examining the results of different management scenarios. The habitat fragmentation RS-enabled EBV provides a measurement, repeatable over time, that could furnish this type of indicator.

Data needed for the above indicator(s), and their availability

Required input for the EBV fragmentation is a raster map that provides information on the area, distribution and configuration of the habitat of a particular species or group of species. In a pragmatic approach, all classified global and regional (land cover) products can be used to derive basic habitat types of certain groups of ecologically-similar species as the input to derive fragmentation indices. Since the habitat fragmentation RS-enabled EBV is scale and resolution independent, it is possible to use and compare numerous land cover products from several sources at multiple scales.

At the local scale, the remotely sensed data still presents some challenges. In the current use case, the fragmentation maps were based on a national Sentinel-derived land cover product (produced by CESBIO). However, the land cover classes of this data set do not match with the habitat definitions of the target species, as defined by local experts. As a result, the input data had to be re-evaluated to create matching habitat classes for *Lestes macrostigma* in the Camargue area. Fortunately, the study area is data- rich so it was relatively easy to gather the necessary species- and habitat information from the field, but this could be more challenging in other, more remote locations

To get good habitat definitions, field data on habitat and species distribution is critical. However, obtaining good field data each year is very difficult. Remotely sensed data is a very useful option to extrapolate field data from one area to other areas with comparable characteristics for the purposes of extracting potential habitat areas and evaluating their fragmentation.

How the final indicator(s) was/were calculated

For the Camargue use case, a final indicator was not calculated, but instead an RS-enabled EBV that can serve for its measurement. The LARCH-SCAN-Hanski metric was implemented as the habitat fragmentation RS-enabled EBV to measures structural ecosystem discontinuity in a quantitative and repeatable way. This metric focuses on the effects of dispersal on persistence of organisms across land-cover types and encompasses three steps:

i. HSI Habitat generation (selection of suitable habitat)
ii. Calculation of spatial cohesion (LARCH SCAN-Hanski metric)
iii. Evaluation of cluster size (sustainability)

How could operational RS-enabled EBVs support sustained indicator production

No system to ensure the sustained production/reporting of the EBV or an eventual indicator has been set up to date – this will depend on the response from the users, as user support for the continued provision of the indicator is required.

The aim would be to be able to produce the same results in a standardized way via cloud computing as long as input data can be uploaded. However, if the output maps are not the end product, an intermediate step of interpreting the results into graphs or other formats useful to the end user may be needed.

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Annex 3: Use case demonstration - Spruce bark beetle attack in the Bavaria Forest National Park

Abstract

The Bavarian Forest National Park (BFNP) is increasingly affected by European spruce bark beetle (*Ips typographus, L.*), a potentially serious invasive species in the UK and North America. An increase in the number of severe bark beetle outbreaks in recent decades leads to gradual forest degradation and significant change in the structure and species composition in forests. There is therefore a strong need for better detection of this insect, in order to understand further the impact of spruce die-back on European forest estates. Here we showcase the potential of remote sensing derived plant trait products of canopy chlorophyll content to detect early bark beetle infestation in the Bavarian Forest National Park. We generated time series CCC maps from RapidEye and Sentinel-2 images of the study area through Radiative transfer model inversion. The CCC products were then classified into healthy, and moderately/severely stressed classes using in situ CCC mean and variance collected in 2016 from infested and healthy Norway spruce trees in the Park. Reference data obtained from processing and interpretation of high resolution (0.1m) colour aerial photographs were used to validate the accuracy of the stress (infestation) maps. Our results demonstrated that CCC products as derived from remote sensing data were a rigorous proxy for the early detection of bark beetle infestation. Validation of the stress maps revealed > 70% classification accuracy throughout the time-space. Hence, CCC products play a significant role to understand the dynamics of the infestation and improve the management of bark beetle outbreaks in forest ecosystems over time.

1. Introduction

A large part of the Bavarian Forest National Park (BFNP) is increasingly affected by European spruce bark beetle (*Ips typographus, L.*) attack resulting in a high degree of heterogeneity and changes in leaf chlorophyll content (hence green cover) as well as forest productivity and phenology across the park. The European bark beetle is already a potentially serious invasive species in the UK and North America, so understanding its biology, as well as developing early detection based on its behaviour in Europe, is an important aspect to its successful management. An increase in the number of severe bark beetle outbreaks in recent decades leads to gradual forest degradation and significant change in the structure and species composition in forests. This has increased the need for better detection of this insect, in order to understand further the impact of spruce die-back on European forest estates. Here we showcase the potential of remote sensing derived plant trait products of canopy chlorophyll content to detect early bark beetle infestation in the Bavarian Forest National Park.

2. Location and spatial coverage of use case

The use case demonstration (UCD) was conducted in the Bavarian Forest National Park in Germany (BFNP), which is located in south-eastern Germany along the border between Germany and the Czech Republic (centre coordinates 13°12'9" E and 49°3'19" N; Figure 1). The Park is a mixed mountain forest with an approximate area of 240 km^2. Elevation varies between 600 m and 1453 m. The park has a temperate climate. Annual precipitation ranges from 1,200 mm to 1,800 mm with temperature averages from 3 to 6 degrees Celsius. At lower altitudes (below 900 m a.s.l) within the park brown soils are the predominant soil types, whilst at high altitudes, brown soils and brown podzolic soils predominate (Heurich et al., 2010a).

There are three ecological zones: valleys, hillsides, and highlands. Natural forest ecosystems vary in each zone (Heurich et al., 2010a). Alluvial spruce forests are dominant in the valleys, mixed mountain forests on the hillsides and mountain spruce forests in the high areas. The European beech (*Fagus sylvatica*), Norway spruce (*Picea abies*) and Fir (*Abies alba*) are the three dominant tree species (Heurich and Neufanger 2005). Due to massive disturbance by bark beetles and wind storms in recent decades, the forest structure in the park is very heterogeneous (Lehnert et al., 2013). Bark beetle attacks only mature Norway spruce trees and, thus, the use case demonstration was limited to coniferous and mixed stands of the park (Figure 1).

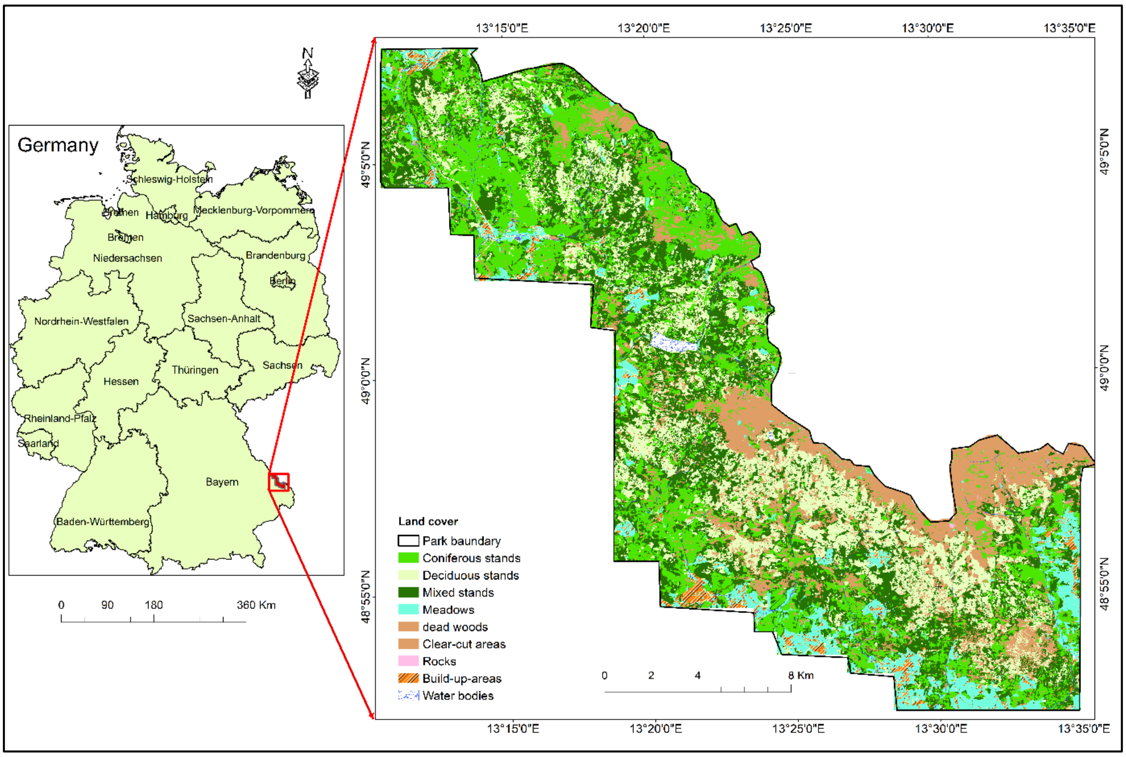


Figure 1: Location and land cover map of the Bavarian forest national park (land cover data have been obtained from the National Park administration office).

3. Aims/objectives of the use case

Policy or management question framing the use case are:

- How can the RS-enabled EBV-canopy chlorophyll content (CCC) 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?

This work has a profound importance for local, national and international organizations affiliated with biodiversity assessment and monitoring in minimizing the cost of in situ data collection and analysis to inform about biodiversity change.

An EBV of CCC could inform potential indicators on terrestrial ecosystem health and status. Chlorophyll is one of the plant pigments that provide valuable information about plant physiology and ecosystem processes (functions) enabling ecologists, farmers, and decision-makers to assess the influence of climate change, and other anthropogenic and natural stressors on plant functions and plants adaptation (Féret et al., 2017).

4. Why RS-enabled EBVs were used

Bark beetles *(Ips typographus*, *L*., and *Dendroctonus spp.*) are natural biotic disturbance agents in coniferous stands of temperate forest. Forest ecosystem disturbances induced by insect outbreaks including bark beetles have increased over the past decades, and a further increase in bark beetle outbreaks' frequency and severity is expected due to global climate change (Bentz et al., 2010, Raffa et al., 2015, Netherer and Schopf, 2010). Bark beetle infested forests (trees) go through three stages: green, red and grey attacks (Wermelinger, 2004). During the early stage (green attack), the foliage is still physiologically green and very much alive. In this stage, the newly hatched generation of beetles is developing within the inner bark of the infested trees. The changes in foliage colour become apparent during the last two stages of the attack. The bark beetles have already left their host trees and started to attack new trees at the red attack stage (Abdullah et al., 2018).

Therefore, to minimize economic loss and prevent a mass outbreak, management interventions should be taken at an early stage. Infested trees removal at the green attack stage is crucial to effective and timely forest management. However, it is difficult to detect the early stage of the attack by the human eye (Wulder et al., 2006). Traditionally, foresters perform field surveys to identify infested trees during the early green-attack stage using conventional survey methods (looking for sawdust). Such surveys are very laborious and therefore make screening large areas for green attack difficult (Abdullah et al., 2019).

Alternatively, remotely sensed plant traits that are indicative of vegetation stress can play a key role in providing timely, accurate and cost-effective information to mitigate and control bark beetle outbreaks. Previous studies of bark beetle attacks at different stages have revealed that the effects of bark beetles on trees can be detected by remote sensing (Meddens et al., 2013, Filchev, 2012). This is because the infestation causes changes in the biochemical and biophysical characteristics of the entire tree. These changes include alteration in canopy chlorophyll content (CCC), water, dry matter and nitrogen content (Abdullah et al., 2018) and have a direct impact on the tree's optical properties (McDowell, 2011, Lawrence and Labus, 2003). Bark beetle attack causes a significant reduction in leaf foliage chlorophyll content (Figure 2) during the infestation time (Abdullah et al., 2018). Hence, CCC, which can be accurately retrieved from remote sensing (e.g., Peng et al., 2017, Darvishzadeh et al., 2012, Atzberger et al., 2010, Gitelson et al., 2005), can be used as a better proxy to discern healthy and bark beetle infested spruce trees than conventional ground surveys when there are no apparent visual symptoms in needles.

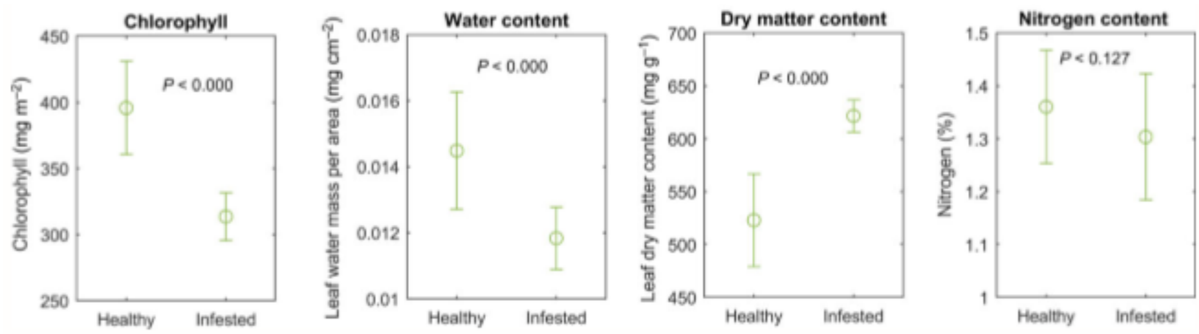


Figure 2: *Boxplot of plant traits alteration due to bark beetle infestation. The box plots are based on traits in situ measurement from 93 healthy and 63 infested trees (taken from Abdullah et al., 2019).*

Since the bark beetle attack management requires a timely acquisition of high-resolution remote sensing data, airborne hyperspectral sensors and Unmanned Aerial Vehicles (UAVs) are ideal platforms. However, such data are too expensive to acquire at large scale and in dense time series. The use of satellite remote sensing data, such as from Sentinel-2 complemented with Landsat 8, provides adequate spatiotemporal resolution, long-term datasets, and free access for a more effective and operationally feasible approach.

5. Methodology

Data

The CCC products obtained from a time series of high-resolution images were used for trend analysis of bark beetle infestation. For this purpose, historical records of the bark beetle attack and aerial colour photographs collected by the park management staff and other researchers as well as remote sensing derived CCC products that correspond to the timing of the historical field observation (2011-2018) were the input for the case study.

High spatial resolution RapidEye images of June/July 2011, 2013, and 2015 as well as Sentinel 2 images of June/July 2016, 2017, and 2018 were utilized to generate a time series of CCC products. Remote sensing images with ≤ 20% cloud cover were not found for the year 2012 and 2014 and hence these years represent gaps in the time series. Field measurements of leaf chlorophyll, as well as leaf area index collected during June/July2015/16, in infested and healthy spruce stands, were used to produce in situ derived values of CCC. The latter canopy parameters were then used to determine threshold values in generating the stress maps.

For each year, the remotely sensed maps of infested areas were validated by interpretation of colour aerial photographs from June/July of the following year, i.e, post-infestation (Heurich et al., 2010b). For instance, reference data from interpretation of colour aerial photographs acquired in June 2016 were used to validate the stress product produced for 2015. Table 1 elucidates the different datasets utilized for this use case demonstration.

Table 1: *Overview of datasets acquired in June/July of each year and utilized for the use case demonstration*

Data	**Spatial resolution**	**Time period**	**type**	**Notes**
Sentinel 2 images	20m	2016-2018	Input RS dataset	Cloud free images acquired in June or July were used to generate the required RS-enabled EBV-CCC products of the pilot site.
RapidEye images	6m	2011-2015	Input RS dataset	
Leaf chlorophyll content (LCC)		2015-2016	In situ calibration dataset	In situ, CCC computed as a product of average plot LCC and LAI
Leaf area index (LAI)		2015-2016	In situ calibration dataset	
Colour aerial photographs	0.1m	2012-2019	RS validation dataset	Used to validate the accuracy of the stress maps

Analytical framework

The early-stage bark beetle infestation (stress) mapping was undertaken using a hierarchical approach with a number of steps, including image selection and image processing, to produce the stress maps and trends. The analytical framework is presented in Figure 3. The steps are described in more detail in the following subsections.

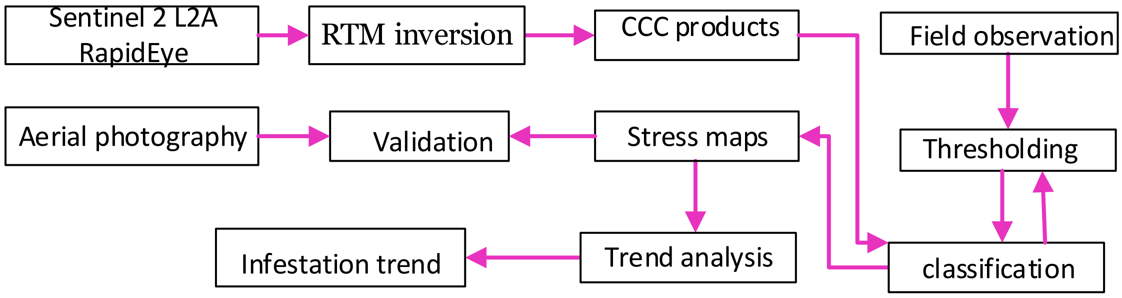


***Figure 3:** Analytical framework of the use case demonstration.*

Generation of CCC products from Sentinel 2 and RapidEye images

The generation of the CCC products was performed by inversion of the Invertible Forest Reflectance model "INFORM" (Schlerf and Atzberger, 2006, Atzberger, 2001) radiative transfer model (RTM) over the atmospherically corrected top of canopy reflectance spectra of Sentinel-2 and RapidEye images for the stands of the Bavarian Forest National Park. Two look-up tables (LUT) (one based on Sentinel-2 sensor configuration and the other based on RapidEye sensors configuration) together with other model input parameters were generated using the INFORM model. An inversion algorithm, which searches for the most accurate best match between simulated and actual reflectance spectra, was applied to map CCC products from Sentinel-2 and RapidEye images. Details of the INFORM input parameters, forward simulation to generation LUT, and inversion of the model for the prediction can be found in the Algorithm Theoretical Basis Document (ATBD). Generation and inversion of the RTM model was performed in ©MATLAB R2017b software.

Threshold determination

The threshold values that were used to separate the stressed (infested) and healthy (non-infested) pixels were approximated by looking into the distribution of their values in the calibration dataset (in situ CCC observations). As shown in Figure 2 there are ranges of CCC values that can be linked to the two classes. To determine the thresholds, the calibration data (obtained from field observations in 2015/2016) were used (Table 2). The development of the thresholds was an iterative process. The optimal threshold values determined by Abdullah et al., (2018) were used as a starting point. The threshold was then varied, using ± one standard deviation of the in situ calibration dataset (Table 2). The distribution of infested and healthy sample from the calibration data provided insights on where to place the thresholds (i.e., Iterate with different possible threshold values to determine the best possible thresholds). Then, The thresholds for three classes of the stress status maps (i.e., severely stressed, moderately stressed and healthy) were fixed up after observing the performance of the ground truth ranges with ± standard deviation. Finally, stress maps of the several years produced using the selected threshold value(s) and their accuracy assessed using interpretation results of the aerial photographs.

***Table 2:** summary statistics of the ground truth data collected in 40 healthy and 21 infested plots during the 2015/2016 field campaign.*

Statistics	CCC	
	Healthy	Infested
Min	0.94	0.64
Max	2.73	1.16
Mean	1.62	0.76
Std. deviation	0.44	0.22

Accuracy assessment

The infestation maps produced from visual image interpretations of colour aerial photographs acquired yearly in June/July (after one year) were used to validate the accuracy of the stress maps generated in this UCD. Thus, the generated stress maps were compared to reference data obtained from processing and interpretation of colour-infrared (VIS and NIR) aerial photographs which have 0.1m spatial resolution. The park administration undertakes aerial photograph acquisition campaigns every year, and archives infested trees location through aerial photograph interpretation. Details of the Bavarian Forest National Park aerial photographs processing and interpretation for detection of dead trees location due to bark beetle infestation can be found in Heurich et al. (2010b). The reference data (dead trees location due to infestation) from aerial photography were in the form of polygons. They were rasterized and resampled into 20 m X 20 m grid cells to match the cell size of the stress maps we produced (Table 3). Finally, accuracy measures between the independent reference data and our stress map products were computed, and the potential contribution of the RS-enabled EBV-CCC in detecting early-stage bark beetle infestation was evaluated.

Table 3: *reference infestation data obtained from aerial photography interpretation and conversion to pixels*

Year	2011	2013	2015	2016	2017	2018
Total Infested pixels	**629**	**282**	**248**	**408**	**348**	**713**

Trend analysis

Statistical techniques were applied to the time series of stress maps to establish trends in infection over time. Trend estimation was used to make and justify statements about tendencies if the infestation in the national park decrease/ decrease over the study years.

6. Results and Discussion

RS-enabled products

There was a significant variation in CCC products in space and time (Figure 3). CCC was high in mixed stands where spruces and beech grow together. Figure 4 illustrates the magnitude of CCC variation across four sample pixels in mixed and coniferous stands. The bark beetle-infested trees are expected to exhibit relatively lower CCC values compared to healthy trees. However, it is worth noting that the high CCC of beech trees compared to coniferous trees (even when the latter are not affected by bark beetle) in mixed stand substantially raised the CCC of pixels in mixed stands irrespective of the infestation, and that may compromise the overall accuracy of the classification in those stands in our next step.

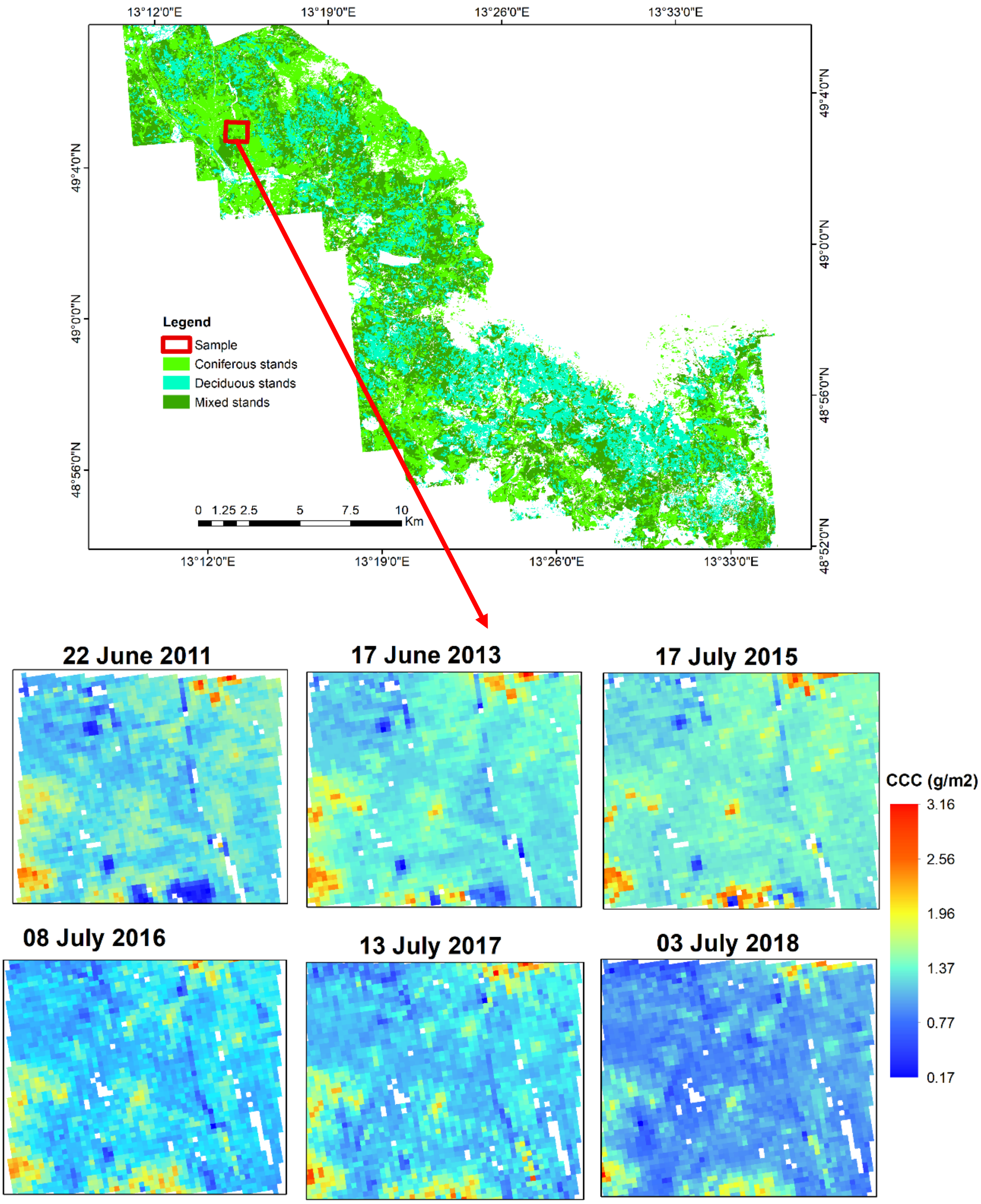


Figure 3: *Canopy chlorophyll content (CCC) distribution variability in space and time (2011 -2016) within a sample mixed stand of Bavarian Forest National Park.*

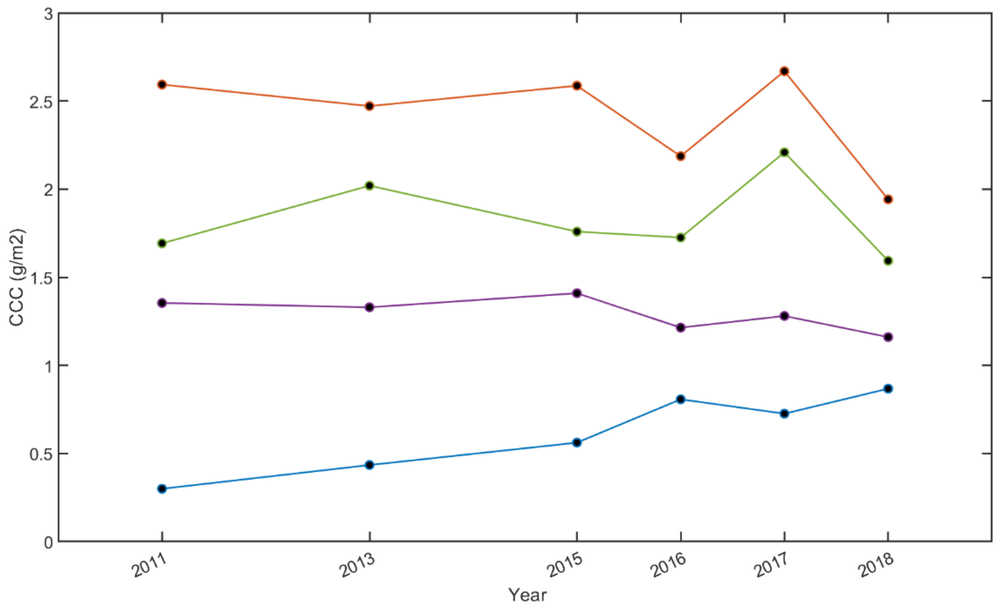


Figure 4: *Spatio-temporal variability among four pixels of mixed and coniferous stands. There is high CCC in mixed stands (the top two lines) than coniferous stands (the bottom two lines) because of the high CCC of beech trees in mixed stands.*

Threshold values and stress mapping

The six years of stress products are presented in figure 5. The products show different stress levels over time (Figure 6), which confirm the significance of the canopy level variable for successful classification of stressed and healthy vegetation. The spatial distribution exhibits consistency in time. Specific sites with stress status in 2011 appeared stressed throughout the six-year study period although there are shifts between severely and moderately stressed status. Temporal trends show positive slopes for CCC that are significant ($p < 0.05$) over time (Figure 7).

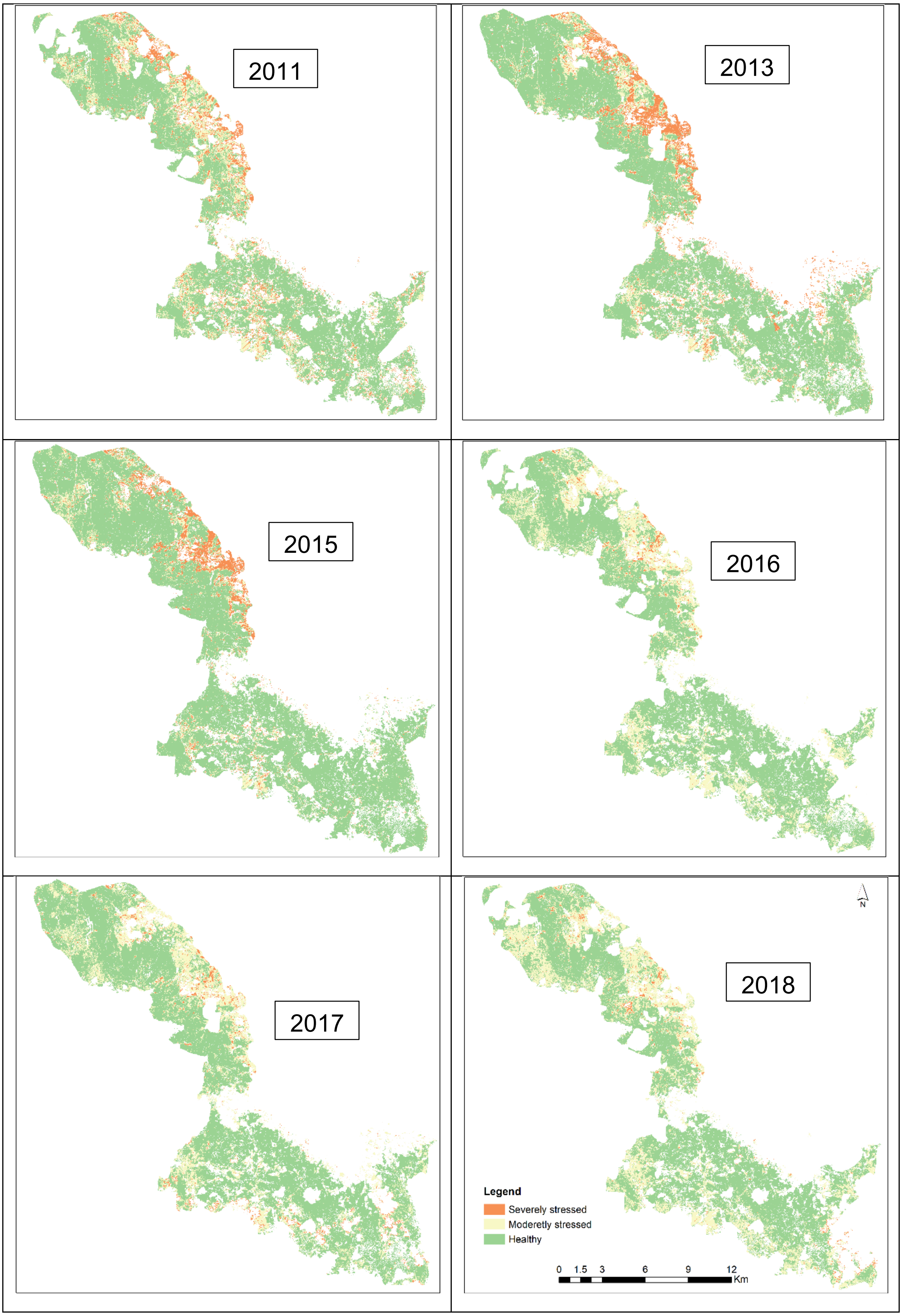


Figure 5: *Spatio-temporal distribution of vegetation stress in Bavarian national park as predicted by CCC during the study period (2011-2018) (the non-forest landcover types are not included).*

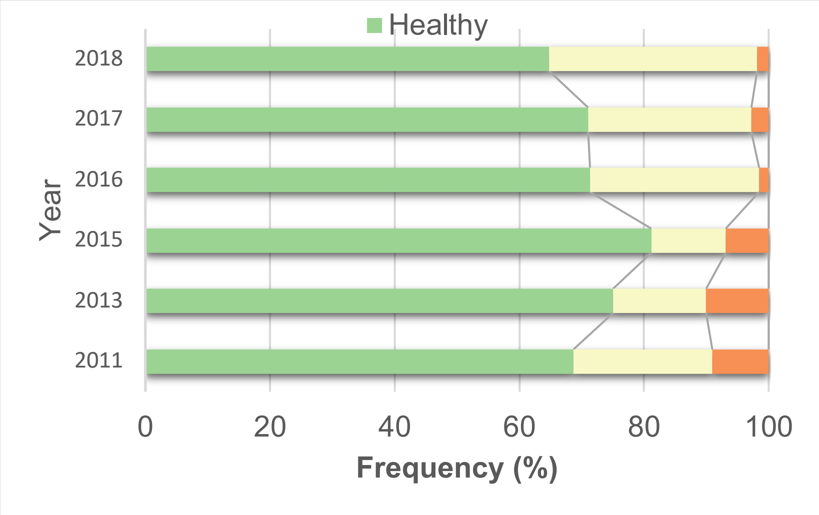


Figure 6: *Proportion of pixels classified as stressed and healthy vegetation in the Bavarian Forest National Park when CCC is used as the predictor.*

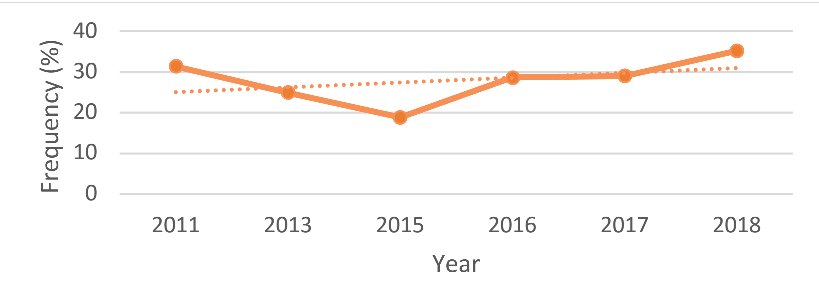


Figure 7: *Trend of (severely and moderately) stress detected using the plant trait-CCC. The broken line shows the trend of stress detected over time.*

Validation

The accuracy assessment result of one of the classified products is illustrated in Figure 8. Most of the bark beetle infested trees (>70%) identified through the high-resolution aerial photographs were classified either severely or moderately stressed category (Figure 9). However, it is worth noting that other plant traits other than CCC may play a significant complementary role in detecting bark beetle infestation. Thus, using additional plant traits such as dry matter content and Nitrogen content (which can be reliably estimated from RS data) as predictor may considerably improve the accuracy of early detection of bark beetle infestation using remote sensing. Nevertheless, trees which are classified as healthy in our products while identified as infested in the colour aerial photograph are not necessarily considered to be an accuracy error. Some trees may be healthy during the acquisition of the remote sensing data in June/July and are infested later before the colour aerial photographs acquired in June/July one year later.

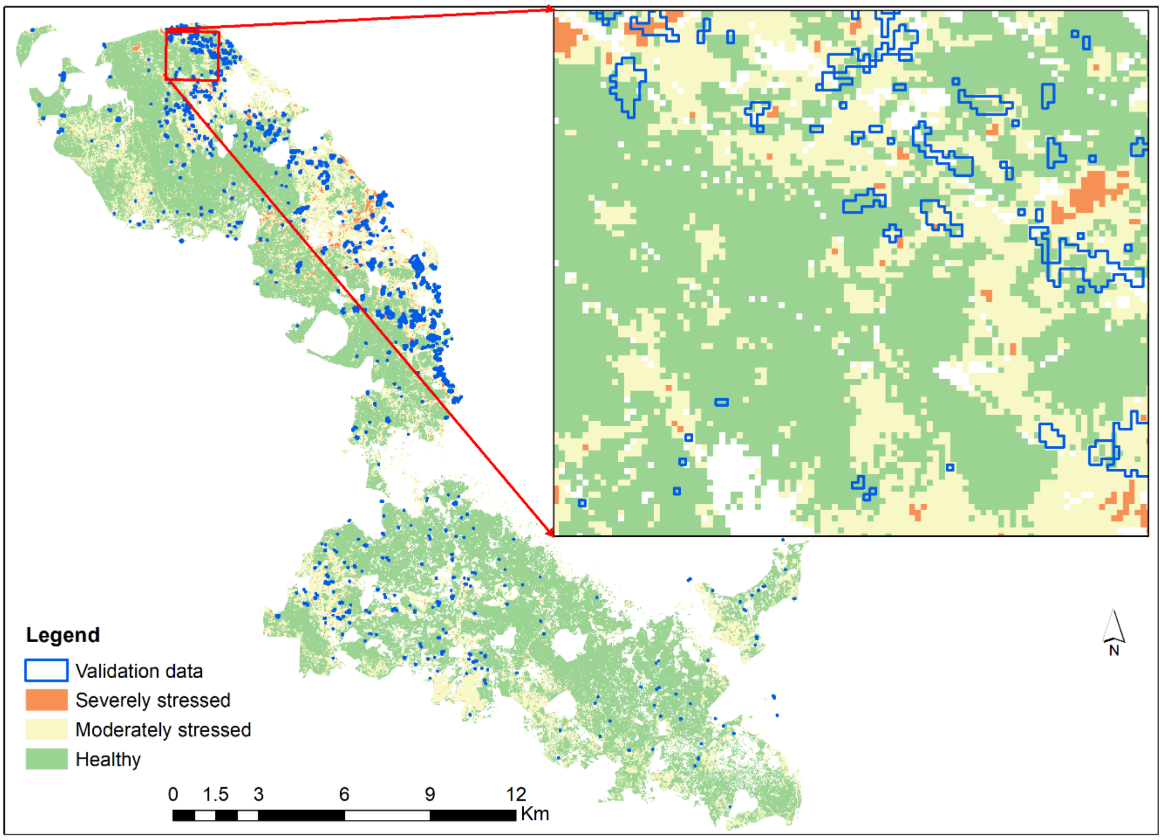
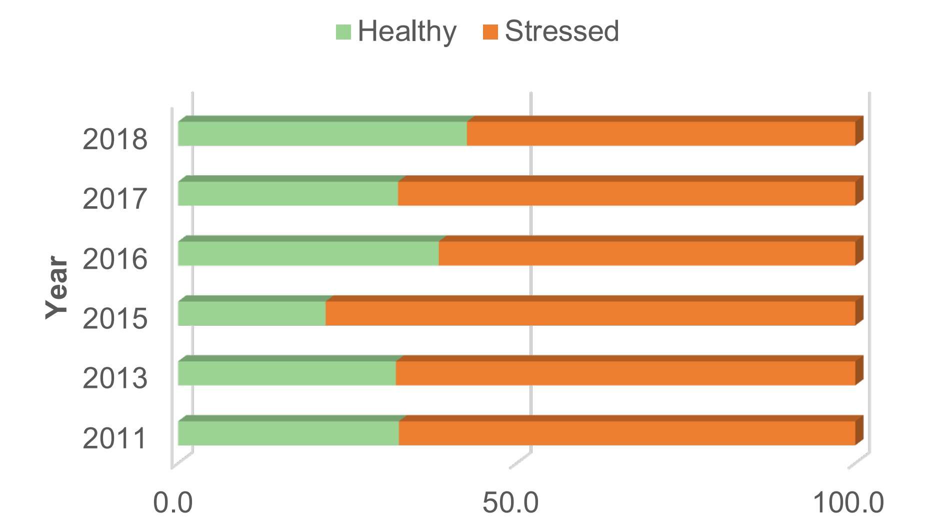


Figure 8: *Location of the bark beetle infestation reference data for 2016 overlaid onto the classified product using CCC as the predictor.*



	2011	2013	2015	2016	2017	2018
Healthy	32.6	32.2	21.8	38.5	32.5	42.6
Stressed	67.4	67.8	78.2	61.5	67.5	57.4

Frequency (%)

Figure 9: *Bar chart of the proportion of the bark beetle infestation (reference data) classified as healthy and stressed using CCC as a predictor.*

7. Conclusions

The CCC RS-enabled EBV developed in this use case study can help foresters, natural resource and protected area managers take informed intervention actions. Stress maps can 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 supported by the approach demonstrated here is much more cost-effective and practicable than conventional surveys required at the early stage of bark beetle infestation. 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 spatiotemporal 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.

8. The Spruce bark beetle attack use case demonstration in the context of the Biodiversity Indicator Development Framework

Understanding the context in which RS-enabled EBVs have been used in relation to the Biodiversity Indicator Development Framework (see section 1.3) will help future potential users to use the RS-enabled EBVs as and where appropriate, and will help ensure the selection of the optimum indicators and underlying data. The following sub-sections place the Siberia crane use case in the context of the purpose of the eventual indicator (red headings), production of the indicator (Blue headings) and permanence of the indicator (green headings).

Main stakeholders/audience for this work

This work has a profound importance for local, national and international organizations affiliated with biodiversity assessment and monitoring in minimizing the cost of *in situ* data collection and analysis to inform about biodiversity change. Specifically, foresters, natural resource and protected area managers benefit from this work to address challenges when assessing the condition of forest ecosystems including water and nutrient stress caused by biological invasions such as pests in mature spruce trees.

Researchers in a wide range of realms including ecologists, biologists and earth's natural resource managers that endeavour towards biodiversity conservation and sustainable development need to develop indicators for biodiversity policies and strategies. A CCC RS-enabled EBV could inform potential indicators on terrestrial ecosystem health and status. Chlorophyll is one of the plant pigments that provide valuable information about plant physiology and ecosystem processes (functions) enabling ecologists, farmers, and decision-makers to assess the influence of climate change, and other anthropogenic and natural stressors on plant functions and plants adaptation (Féret et al., 2017).

- The target audience for this work is the National Park Administration. Other potential audiences include the Federal Agency for the Environment and Forest Administations.

Relevant management objectives or targets

- This work does not respond to specific targets but it is a highly relevant and current topic. The Federal Minister for Agriculture recently announced a forest summit due to severe drought impacts on the forest, which are leading to major bark beetle outbreaks in the park and throughout Central Europe. The summer of 2019 was exceptional in having temperatures >40°C for three consecutive days within Germany.

Key questions being asked

- Why are some ecosystems affected worse by bark beetle infestations than others?
- How can we detect infestation early?
- How can the CCC RS-enabled EBV be used for detecting the impact of infestation on the health and vitality of the world's forests?
- What is the potential of CCC products derived from remote sensing datasets to understand the dynamics and improve the management of bark beetle outbreaks in forest ecosystems over time?

Indicators that would answer the key questions

The ideal indicators for answering these questions are:

- Pressure of bark beetle infestation on the state of ecosystem.
- Early “green” stage of bark beetle infestation
- Heat stress that could lead to long term decrease in CCC in the forest.
- CCC an indicator of forest health in general.

The indicator that was produced was:

- Trends in bark beetle infestation (ecosystem health).

Data needed for the above indicator(s), and their availability

- CCC products together with *in situ* data and maps obtained from colour aerial photographs were the data used. CCC products were derived from RS data. *In situ* leaf level measurements were scaled up to canopy level. The different year aerial photography processed and interpreted by park staff. The required data are not readily available.
- Other products such as canopy nitrogen, dry matter and water content may improve the results

- It was found that remotely assessed plant traits could be used to predict early infestation of bark beetle. However, it would be useful to understand how early the infestation can really be detected based on these parameters. Early detection is the Holy Grail and for this, enforced infestation (experimental treatment) can be used to see exact timing of infestation detection in RS imagery.
- All data can be made readily available by cooperating with ITC and the park administration.

How the final indicator(s) was/were calculated

- The *in situ* data of CCC collected from infested trees were used to determine the threshold values used to generate healthy, moderately/and severely stressed classes from the remote sensing CCC products, and aerial photographs were used for validation of the final binary maps.

How could operational RS-enabled EBVs support sustained indicator production

- The method presented here is fast and effective, providing a dense time series of information that can be used for timely management intervention and decision making. In future, at least from a Central European perspective, dry years and droughts will become more important, and CCC is probably an important indicator for such developments. Chlorophyll will likely decrease as it becomes dryer and hotter. The RS-enabled EBV could therefore support a long term perspective.
- There is wider issue of broad biotic disturbances in temperate forests. In 2019, the bark beetle was the biggest issue. Connected to increasing temperature, general mortality of spruce trees are expected, but other species are also affected, including beech trees losing leaves, since they are not resistant to dry years. Different insects on pine trees, such as bud worms and caterpillars (e.g. procession moth) could prevail as forest pests. Impatiens glandulifera (a fungus from Asia) grows along the rivers and kills maple and ash trees (ash dieback disease). This is all connected to the droughts of 2019. A central EU perspective needs to be taken to track and manage these infestations.
- An indicator should be transferable to other temperate systems (e.g. eastern US forests) and boreal zones (e.g. in Russia) where there are vast areas of spruce trees.

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Annex 4: Utility of RS-enabled EBVs in ecological modelling

Summary

We conducted a series of explorations of the usefulness of the RS-enabled EBVs for ecological modelling. These were 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. Here we report on the results from the Kruger case study only.

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 here suggests that this does not translate into significantly improved model performance.

1. Expert consultation

We ran a short consultation exercise with Prof. Colin Prentice (Imperial College), Prof. Almut Arneth (KIT), Prof. Thomas Hickler (Senckenberg Institute for Biodiversity and Climate Research), Prof. Ben Smith (Western Sydney University) and Dr Andrew Friend (Cambridge University). We asked the group of researchers for their perceptions of the usefulness of the three RS-enabled EBVs generated by the GlobDiversity project. In general, the researchers agreed that Earth Observation data are a very useful input to models. Land surface phenology was already being used, for example MODIS 10-day FAPAR composites. However, the case was made that current phenology products are not particularly good, so an improvement upon them is badly needed. The need for a high resolution product was considered questionable unless accompanied by an equally high resolution land cover product, in which case useful applications would emerge, such as allowing plant scientists and ecologists to explore drivers of phenological features. There was less consistent support for the usefulness of Canopy Chlorophyll Content. Several members asked why chlorophyll was a target of the project, as it varies through the canopy and is not a measure of photosynthetic capacity. Prof Prentice suggested that FAPAR would have been a better variable to produce.

2. Relationship with standard environmental variables

Using the Udzungwa and Kruger National Parks as case studies, we assessed the degree to which LSP and CCC provided novel information relative to conventional environmental variables. We compiled datasets for elevation (SRTM) and bioclimatic variables (CHELSA climatology for 1979–2013 period, http://chelsa-climate.org/about/) across the national parks at 1 km resolution. We then aggregated LSP (start of season, end of season, length of season and amplitude) and CCC (annual median, minimum and maximum across the year 2018) variables to the same spatial resolution. To assess the covariance of information in the different variables we performed a principal components analysis (PCA). This suggested that for Udzungwa LSP and CCC variables covaried with each other and relatively closely with elevation (Figure 1). However, this cluster was nearly orthogonal to almost all of the bioclimatic variables, to which the RS-enabled EBVs showed different spatial patterns. For Kruger National Park, all variables were less clustered, particularly CCC and LSP. These analyses therefore suggest that the RS-enabled EBVs could offer additional information to more traditional environmental variables.

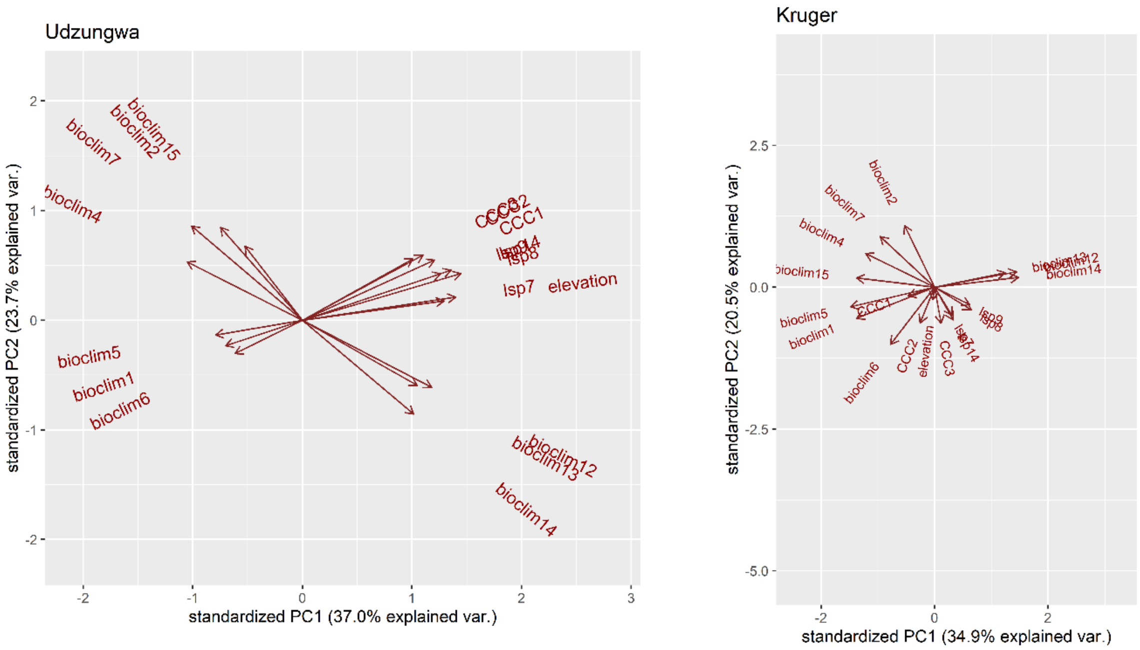

Figure 1. Visualisation of bioclimatic variables, elevation and remotely sensed CCC and LSP at 1 km resultion, on the first principal components.

3. Kruger population abundance modelling

To explore how the remotely sensed variables might inform ecological modelling of species abundances, we used flight transect data recorded over Kruger National Park for the year 2017. We ran individual species models for the spatial pattern of abundance across the Park and compared models using conventional environmental predictors with those that also included remotely sensed variables, and with models that only included remotely sensed variables. Models were fitted for species that had a large number of flight encounters (greater than 200 observation records across the whole National park). These species were elephants, zebra, impala, kudu, wildebeest and giraffe.

The standard environmental predictors used in the models were elevation, annual mean temperature, mean diurnal temperature range, temperature seasonality, max temperature of warmest month, temperature annual range, annual precipitation, precipitation of the wettest month, precipitation of the driest month and precipitation seasonality. The remotely sensed variables were CCC and LSP. To account for non-linearities and because this was largely a data exploration study, we used a machine learning approach to derive the relationship between abundance and the predictor variables. We used a repeated k-fold cross-validation methodology to estimate how good the models were at predicting data subsets that were not used in model fitting. Using this approach we compared the three model types: environmental variables only, environmental and remotely sensed variables, and remotely sensed variables only.

We found that for three species (elephants, kudu and giraffe) the remotely sensed data improved the model performance, whilst for zebra, impala and wildebeest the opposite was found (Figure 2). However, none of these changes was significant.