Satellite Observation Requirements of Land Surface Phenology

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Authors:	UZH (R. de Jong, C. Röösli and Vladimir Wingate) ITC (Andrew Skidmore, Abebe Ali, Roshanak Darvishzadeh and Tiejun Wang)	
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Acronyms and Abbreviations

AVHRR	Advanced Very High-Resolution Radiometer
CBD	Convention on Biological Diversity
CEOS	Committee on Earth Observation Satellites
COP	Conference Of the Parties
DOY	Day Of Year
EBV	Essential Biodiversity Variable
EO	Earth Observation
EOS	End Of Season
ESA	European Space Agency
FPAR	The Fraction of Photosynthetically Active Radiation
GBO	Global Biodiversity Outlook
GEO-BON	Group on Earth Observation – Biodiversity Observation Network
IPBES	Intergovernmental Platform on Biodiversity and Ecosystem Services
LAI	Leaf Area Index
LPV	Land Product Validation
LSP	Land Surface Phenology
MCD12Q2	MODIS Land Cover Dynamics Product
MODIS	MODerate-resolution Imaging Spectroradiometer
RS	Remote Sensing
RS-enabled EBV	Remote Sensing enabled Essential Biodiversity Variable
SDG	Sustainable Development Goals
SOR	Satellite Observation Requirement
SOS	Start of Season
SRL	Science Readiness Level
TM	Thematic Mapper

Terminology

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

Term	Definition
Accuracy	In this document, accuracy is described as the closeness of variable values estimated from remote sensing to *in situ* measurement.
Biodiversity	The variability among living organisms from all sources (including terrestrial, marine and aquatic ecosystems) and the ecological complexes of which they are part, including diversity within and between species and of ecosystems.
Biome	A biome is a specific geographic area where an assemblage of organisms is determined by large-scale climatic and vegetation characteristics. A biome can be made up of many ecosystems.
Ecosystem	A functional unit or system of the earth's surface that is the whole system including the organisms, the physical factors and their interaction that form the environment (Basu and Xavier, 2016)
Ecosystem function	Processes related to productivity/respiration (biomass build-up function), decomposition (biomass breakdown function), energy transfer/loss and nutrient cycling in an ecosystem (Myster, 2001).

Ecosystem structure	The minimal pattern of organization necessary for an ecosystem function to operate (Myster, 2001).
Essential Biodiversity variable	A variable that is measurable at particular points in time and space and is essential to document biodiversity change.
High spectral resolution	An Earth observation system is assumed having a high spectral resolution if it records spectral information in more than 15 spectral bands.
High spatial resolution	In this document, an Earth observation system is assumed having a high spatial resolution if it has ground (spatial) resolution of ≤ 30 m.
Land surface phenology (LSP)	In this document, satellite-based LSP refers to products which characterize the seasonal shifts in vegetation greenness and photosynthetic activity at the ecosystem scale. It includes metrics such as date of vegetation green-up (start of season), peak of growing season date, date of senescence (end of season) and growing season length (length of season). Phenology metrics are derived from curve-fitting methods applied to vegetation index time-series and therefore my differ between products.. LSP dynamics reflect the response of vegetated surfaces of the earth to seasonal and annual changes in the climate and hydrologic cycle
Satellite observation requirement	The types and detail level of a set of attributes of RS-enabled EBVs that are required by the user community for biodiversity assessment and monitoring.
Remote Sensing enabled EBVs	EBVs that are directly measurable or derived from Earth observation satellite data.
RS-enabled EBV product(s)	A product or multiple of products obtained through processing remote sensing data that potentially informs about the RS-enabled EBV.
Resolution	The ability of a remote sensing device to detect subtle variation regarding energy (radiometric resolution), space (spatial resolution) and time (temporal resolution).
Satellite RS	Remote sensing (RS) data acquired through earth orbiting satellites.
Scale	The term scale in this document refers to the scope or spatial extent of the RS-enabled EBVs observation but not to the relationship between distance on a map and a corresponding distance on the ground.
State variables	A set of variables that can be used to describe the "state" of a dynamic system. In the context of a terrestrial ecosystem, state variables are those sets of variables that describe sufficiently the ecosystem to determine its future behavior in the absence of any external forces affecting the ecosystem.
Terrestrial ecosystem	Communities of organisms and their environments that occur on the land masses of continents and islands (Chapin et al., 2002).
Thematic accuracy	The degree to which the non-positional characteristic of a spatial data entity (attributes) derived from radiometric information agree with *in situ* observations.

1. Introduction

1.1. Purpose

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

1.2. Scope

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

1.3. Target audience

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

1.4. Method

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

1.5. Clearing up the ambiguity

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

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

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

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

- Multispectral – 4 to ±15 bands
- Hyperspectral – hundreds of bands

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

1.6. Chapter outline

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

1.6.1. Definition of the RS-enabled EBV

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

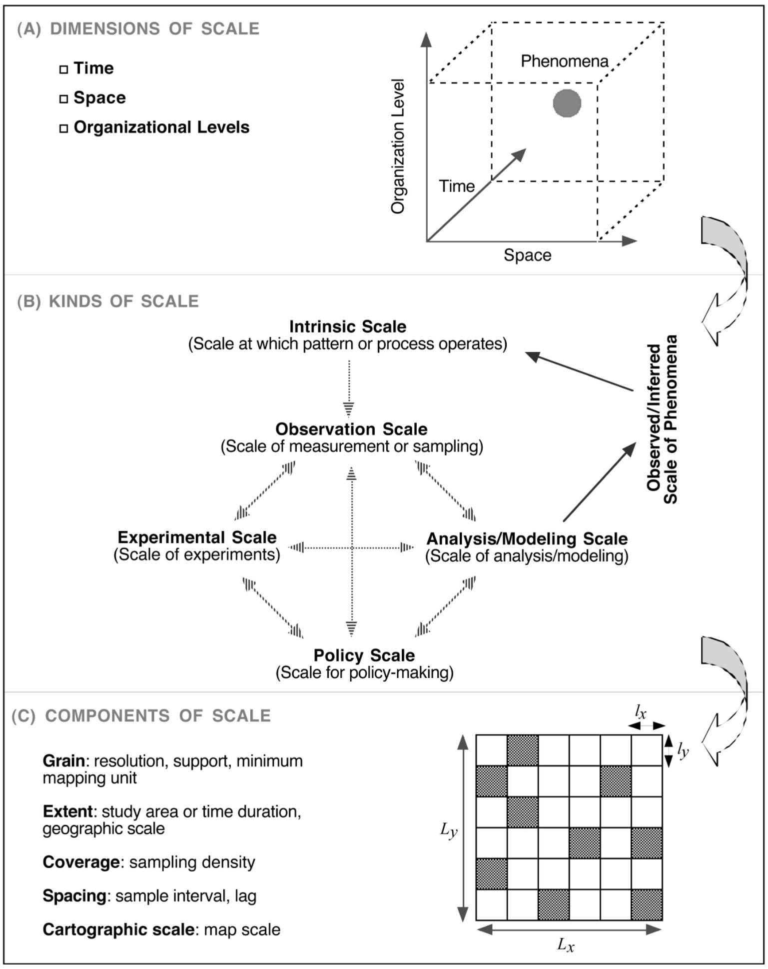

Figure 1: A hierarchy of scale concepts: (A) dimensions of scale, (B) kinds of scale, and (C) components of scale (from Wu et al., 2006).

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

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

1.6.3. Spatiotemporal coverage

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

1.6.4. Remotely sensed EBV Products

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

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

1.6.5. Spatial extent and temporal frequency requirements

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

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

1.6.6. Transferability of retrieval approaches

a) Transferability among biomes

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

b) Transferability across scale

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

1.6.7. Calibration and Validation

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

1.6.8. Existing data sets and performance

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

1.6.9. Feasibility, scientific and technology readiness levels

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

1.6.10. Summary and outlook

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

1.6.11. Specific measurement requirements summary

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

2. Land Surface phenology Satellite Observation Requirement Definition and Analysis

2.1 Definition of Land Surface Phenology

The RS-enabled EBV Land Surface Phenology (LSP) characterizes recurrent events in the annual profile of vegetated land surfaces at the ecosystem scale as observed from RS. LSP is a widely used indicator of terrestrial ecosystem response to environmental change, and useful for biodiversity monitoring for many reasons (Richardson et al., 2013), including its strong link to the climate system and its potential to describe functional biodiversity groups. LSP relates to a plant or community-level phenology but should not be interpreted as a species trait.

2.2 The role of Land Surface Phenology in biodiversity assessing and monitoring

LSP is an aggregated signal consisting of the phenological signatures of species within the observational unit and is, therefore, a functional indicator of the ecosystem or the plant community. The temporal and spatial variation in LSP is partly driven by species traits and ecosystem composition and may be used to define functional groups of vegetation and their dynamics. Spatial distribution of LSP, in particular at high spatial resolution, may provide a measure of the spread of different species and the influence of locally variable environmental conditions, such as soil and topography in natural ecosystems (Schneider et al., 2017).

On a community level, LSP properties have successfully been used to predict plant alpha diversity on a regional scale (Revermann et al., 2016). LSP is commonly represented in scientific studies by different so-called LSP properties such as length of the growing season (GSL) as for instance used in Oehri et al. (2017), who found LSP properties to be positively impacted by species richness biodiversity metrics. LSP-based properties are also relevant for biodiversity studies, for instance by informing empirical and mechanistic species distribution models (SDM) (Chuine, 2010, Gritti et al., 2013). Together with integrals of vegetation activity, GSL could be used as proxies for ecosystem productivity (e.g., Wang and Fensholt, 2017). In addition, the general ecosystem's sensitivity to climatic and environmental variation can be observed and monitored with LSP.

Long-term and short-term responses of an ecosystem to changing climate and other environmental conditions are important factors for the stability of the ecosystem and its plant communities. Changing LSP can, for example, show indications of spatial migration of species (e.g., through invasive species), of species, shift phenological events (e.g., advance their green-up) in response to a changing climate, or of a loss in biodiversity (Wolf et al., 2017). Nevertheless, climate and biodiversity need first to be considered in a consistent way to adequately capture such shifts (Brown et al., 2010). Potentially, one might detect changes in environmental conditions and their impact on the species distribution faster and for larger extents with RS than with *in situ* observations and trends might be visible earlier as well.

Additional applications of LSP may include health monitoring of particular species or input for the prediction of animal phenology. The former uses the amplitude of the phenological signature as an indicator for the health status of pure stands (e.g., Wu et al., 2018), while the latter makes use of the timing of phenological events to predict animal phenology (e.g., Poyry et al., 2018).

Finally, several studies demonstrated the important role of LSP for i) SDM (e.g., Jarnevich et al., 2014, Bradley and Fleishman, 2008), ii) in global-circulation and Earth-system models describing biosphere-atmosphere interactions (e.g., Garonna et al., 2018), iii) as a parameter for productivity estimations in a wide range of fields (agriculture, land degradation, carbon cycling), and iv) as a covariate for mapping ecosystem or habitat extent, among other application domains (e.g., Schwartz, 2013).

2.3 Spatiotemporal coverage

LSP is relevant globally and for almost all biomes and geographical regions. However, most use cases are found in areas with distinct vegetation seasonality. LSP is rarely suitable for biodiversity assessments in biomes without a clear seasonal profile – such as (tropical) rain forests or (arctic) deserts. The focus for generating LSP products should, therefore, be on biomes with a seasonal pattern such as temperate, Mediterranean and subtropical and tropical dry forests, boreal taiga and arctic tundra, wetlands, shrublands, tropical and subtropical savannah. Next to monitoring of natural and protected areas, LSP as input for observation and monitoring of agricultural areas are of high interest to policymakers, for example, it enables them to directly regulate and implement agriculture practices by law to foster biodiversity.

LSP properties are inherently based on annual profiles, for which the region of interest needs to be observed all year long and with a sufficiently dense sampling interval during the complete growing cycle. Ideally, the observation period is between the start of dormancy of the preceding cycle until the start of vegetation activity of the subsequent vegetation cycle, in order to allow for enough data points during a period (satellite observations often dominated by cloud coverage). Nevertheless, only with a sufficiently long time series (i.e., spanning several subsequent vegetation cycles, e.g., more than a decade) can trend in LSP be adequately detected and related to climate change, changes in biodiversity, or protection efforts.

2.4 Remotely sensed EBV Products

The core component of LSP observations is the yearly evolution of the vegetation activity of a vegetated area of interest with its onset and green-up in spring or wet season and transition from senescence to dormancy in autumn (or dry season) as well as the intensity of vegetation activity. This seasonal profile, often represented by the changes of a vegetation index (VI) depending on date, can be mathematically described by a curve or function for an area of interest (i.e., a geolocated pixel) and the derived properties thereof. In general, the ecological meaning of the extracted dates on a species level is highly debated, and direct relation between remotely sensed LSP properties and *in situ*/visual observations are usually not straight-forward (Keenan et al., 2014a).

The most commonly retrieved properties - extracted and used from the annual VI-profile - are the Start of Season (SOS) and End of Season (EOS) that indicated the start and end of the vegetation season. These properties are highly correlated to green-up (spring) and leaf senescence and dormancy (autumn) of the vegetation. These dates can be expressed as day of the year (DoY) and are highly dependent on the used procedures and model (e.g., Xu et al., 2014).

For instance, extracted LSP properties can be strongly dependent on the chosen VI as they represent vegetation activity differently. In general, two main groups of VIs can be distinguished depending on whether they are based on the spectral reflectance of vegetation (e.g., Normal Difference Vegetation Index NDVI and Enhanced Vegetation Index EVI) or based on (additional) non-spectral model assumptions (e.g., Leaf Area Index (LAI) and fraction of absorbed photosynthetically active radiation (fAPAR)). By defining a curve describing the seasonal vegetation profile for the area of interest (e.g., one pixel), several additional properties can be extracted to characterize the LSP profile. These properties include maturity onset (day), the peak of season (day) and senescence onset (day), rates of green-up / senescence (VI/day), the magnitude of variation (amplitude VI), base VI during dormancy and various VI integrals (e.g., Wu et al., 2018). In conclusion, LPS properties of different studies might be difficult to compare when different VIs, curve models or retrieving methods have been used.

Depending on biome and land cover type, also the number of growing seasons per year needs to be considered as a parameter or for the extraction of the other properties. This is, for instance, the case in agricultural areas and areas with summer drought (Garonna et al., 2016).

Additional properties such as length of season (LOS, also GSL) derived as mathematical difference between EOS and SOS or the amplitude as the difference between peak VI and winter VI are simple, derived metrics that may be of high interest to the users. Table 1 summarizes possible LSP properties that are used and useful for LSP studies.

Table 1: List of LSP properties and their definition

LSP Property	**Definition**
SOS	Start of the season, start of green-up [DoY]
EOS	End of season, the start of dormancy [DoY]
LOS / GSL	Length of the season / Growing Season Length (EOS minus SOS) [DoY]
Maturity-onset	The onset of summer [DoY], e.g., end of green-up phase
Peak of season	Time of peak of the season [DoY], e.g., time of peak of vegetation activity
Winter VI	The minimum level of VI index Low/no vegetation activity [VI unit]
Peak VI	Maximum level of VI index, amplitude [VI unit]
Amplitude	The magnitude of variation (Peak VI – Winter VI) [VI unit]
Rates of green-up	The incline of vegetation activity from SOS [VI unit/day]
Rates of senescence	The decline of vegetation activity until EOS [VI unit/day]
Integral	Different integrals can be extracted from the profile as a measure for the vegetation activity over a certain period of time [VI/time]
# growing seasons	Number of growing seasons per yearly profile [-]

2.5 Spatial extent and temporal frequency requirements

A dense time series with sufficient temporal sampling is required to generate an accurate LSP profile, in particular during green-up and senescence phases due to the fast increase or decrease of vegetation activity during this period; it defines, therefore, the reliability and accuracy of the extracted properties. These transition phases in vegetation activity, i.e., between start and peak of the vegetation season and between the onset of senescence and dormancy, are most sensitive for changes in the ecosystems and therefore also most important for biodiversity studies. Ideally, the sampling frequency during these transition phases is at least double to the total transition time. Depending on the biome, in particular, the green-up rate can be high, for instance after snowmelt. Therefore, a higher sampling frequency may be required in certain biomes and certain times of the year.

In general, characterization of the phenological transition events requires sub-weekly temporal resolution. During growing seasons, temporal sampling can be lower (e.g., weekly) and during dormancy even lower (e.g., bi-weekly). Additional attention and ideally denser temporal sampling are required in regions where multiple vegetation seasons occur and – if of interest – for heavily managed land types. Observations are needed year-round and for multiple years in order to capture long-term changes and to study the interaction with biodiversity changes.

If the sampling frequency is too low for a reliable model fit and representation of the profile, the time series needs to be flagged as invalid. A sufficient sampling frequency strongly depends on the green-up/senescence rate and on the precision of the individual measurements (scattering) and/or outlier detection.

The required spatial resolution for LSP products depends strongly on the application and the level of detail that should be characterized. Coarse spatial resolution products (ecosystem level) can be used for assessing vegetation-climate interactions and for the detection of hotspots of change. In turn, moderate spatial-resolution products can be used for the documentation of large-scale ecosystem dynamics. High spatial-resolution images (30 m and less) can be used to observe links to community phenology (consisting of several species) and ecosystem composition. Specifically, when spatial resolution increases, the information content increases non-linearly and the gap between LSP and individual plant phenology narrows.

2.6 Transferability of retrieval approaches

a) Transferability among biomes

When transferring the retrieval approach (i.e. processing chain and mathematical model) among biomes, most difficulties regarding the vegetation activity profile arise from i) the different speeds of change between low and high vegetation activity and vice-versa, and ii) the different amplitude between low and high vegetation activity. Some biomes are characterized by low vegetation amplitude (e.g., semi-arid grass, scrublands), where the same vegetation amplitude would indicate a mixed pixel (e.g., with street) or invasive species and disease for other biomes' vegetation. A retrieval approach needs, therefore, to consider possible differences in (biological) meaning of extracted VI properties (see Chapter **Error! Reference source not found.**) in different biomes depending on the biomes' specific activity profile.

In addition, extreme weather like drought and flooding can alter a vegetation profile in an unknown way and might also induce additional vegetation seasons. Detection and definition of multiple vegetation seasons are challenging as the transition between lower summer amplitude of vegetation activity, for instance, due to summer drought and a double vegetation season (e.g., for crop fields), is smooth.

b) Transferability across scale

Two types of upscaling-effects should be distinguished: First, phenological processes are inherently scale-dependent, and different processes may, therefore, be observed at various spatial data resolutions. While resolution increases, the information content increases non-linearly and thereby narrows the gap between LSP and individual plant phenology. An example is the mixture of phenological profiles of species within an observational unit when changing the size of that unit (e.g., pixel size). Scaling between these different resolutions requires a sound understanding of the processes and their impact on the LPS signal (e.g., Vrieling et al., 2017, Fisher and Mustard, 2007).

The other, more straightforward, type of upscaling is enlarging the spatial extent in terms of the number of observational units. Commonly, LSP retrieval uses a per-pixel approach, which makes this type of upscaling highly dependent on the computational power when the spatial resolution or spatial extent increases.

2.7 Calibration & Validation

The most common current approach for validation of LSP is the use of ground-based phenocams. They are installed either on the ground or a tower above the canopy, at a known location and angle of view and repeatedly observe the vegetation. Several PhenoCam networks exist, each is composed of webcams that regularly take digital photographs in the visual bands and in some cases in near-infrared. The most common approach is using the visible channels for calculating the Green Chromatic Coordinate (GCC) for comparison with satellite-derived GCC or other VI values. The NIR-channel for extracting the vegetation activity is still seldom used, as the few cameras with NIR-channel available are in addition mostly uncalibrated for using RGB and NIR channels together. Calibration would be needed if a VI based on NIR and RED, such as NDVI, is used. LSP validation with phenocams has been successfully applied for MODIS time series on ecosystem-scale (Browning et al., 2017). However, an even higher correlation between phenocam observations and satellite-derived LSP properties can be expected when using higher spatial resolution satellite data, such as Sentinel-2 with up to 10m pixel-resolution (Lange et al., 2017). By using ground-based images, the influence of the atmosphere on satellite images can be investigated. Nevertheless, the highest uncertainties are the transformation of the phenocam field of view to the pixel raster of a satellite image.

Also, validation data for LSP can be acquired by Unmanned Aerial Vehicles (UAV). UAVs are now often used in agriculture and crop monitoring (Torres-Sanchez et al., 2014, Bendig et al., 2014, Michez et al., 2016). However, only a few studies exist about LSP validation of satellite data because of the high costs and effort for repeatedly acquiring UAV observations (Klosterman et al., 2018).

A similar approach to the validation with UAV observations follows the idea of the comparison of multiple-resolution results observed from different satellites. The approach can be used to enhance the reliability of phenological products and for detecting outliers (e.g., Liu et al., 2017). Differences due to varying spatial resolution, spectral resolution and geographic reference systems and ground projections need to be taken into account.

Plant phenology is observed by *in situ* measurements at various sites and for selected species. The connection between LSP properties and plant phenology, i.e., from a single tree to the pixel level, is challenging due to the different processes that both approaches observe (e.g., Keenan et al., 2014a). Nevertheless, approaches with local phenological observations (e.g., Revermann et al., 2016, Verger et al., 2016), existing phenological databases (Lange et al., 2017), or citizen science (Kosmala et al., 2016) have been used for validation already. In addition, on-ground carbon flux measurements have been used to validate LSP observations of coarse-resolution (e.g., Melaas et al., 2013, Gonsamo and Chen, 2016).

In general, most of the above-mentioned *in situ* based validation approaches were applied to local or regional areas. A validation approach at a global scale is currently challenging due to sparse coverage with ground observations (Keenan et al., 2014b). Standards and data access for *in situ* phenology observations can be different among the local and regional networks, which further complicates validation at a large spatial coverage.

The Committee on Earth Observation Satellites' (CEOS) working group on calibration and validation with its Land Product Validation Subgroup is also developing a "validation good practice" for phenological data. The group identified the large variation in existing definitions and retrieval algorithms for the start and end of the season as major concern and source of uncertainty. In addition, a standardized database including species-level field observations and standardized processing of phenocams shall be developed. They list on their webpage the currently best available reference data sets for LSP validation (https://lpvs.gsfc.nasa.gov/Pheno/Pheno_home.html).

2.8 Existing data sets and performance

Many studies demonstrated the extraction of LSP properties from coarse and moderate resolution data (500-1000m). Various methodological approaches are well established and have been compared (White et al., 2009). Global products exist at coarse spatial resolution (Garonna et al., 2016) and moderate resolution, for instance, the MODIS product (MCD12Q2[1]) that is currently being updated (Friedl et al., 2018). At high spatial resolution, extraction algorithms have to rely on irregular time series and although first steps have been taken (Vrieling et al., 2017), large-area products are not yet available.

Currently available datasets include 34+ year time series at coarse resolution (based on AVHRR), 17+ years at moderate resolution (based e.g., on MODIS, SPOT VEG) and decades of high resolution (based on Landsat 4-8, Sentinel-2) although only sufficiently dense since the launch of Landsat 8 (2013, 30m resolution) and Sentinel-2 (2015, 10m resolution) and with substantial data gaps in the 1990s due to the Landsat commercialization strategy at the time. Regarding achievable performance, this can be considered "very good/mature" for coarse and moderate spatial resolutions LSP, where the main product uncertainties are caused by cloud cover and over-generalization of the retrieval algorithms. For high spatial resolution time series with irregular sampling, the achievable performance is substantially weaker, although developments in this field are fast.

Other systems than multi-spectral sensors, such as synthetic aperture radar (SAR) or hyperspectral data, were also used for LSP assessment. With the SAR technology and the Sentinel-1 satellite, cloud cover could be overcome and the high repetition time would be very well suited. Rice crop monitoring is already operationally tested using Sentinel-1 (e.g., Nelson et al. 2014) and first phenological studies for crop classification (e.g., Veloso et al. 2017) and forest classification (Rüetschi, Schaepman, and Small 2018) exist using polarized SAR data. The technique, nevertheless, is still very data-intensive and systematic processing of larger areas is challenging. In contrast, hyperspectral observations are easier to process than SAR data sets, however, not available for satellite remote sensing.

2.9 Feasibility, scientific and technology readiness levels

LSP retrieval by remote sensing is non-taxon specific and therefore suitable for observing community and stand-level variation, rather than a species-specific variation. So far, LSP derived from RS is mostly based on spectral vegetation indices and a chosen mathematical model to represent the annual variation in vegetation activities. Mathematical models (e.g., double-logistic, harmonic or spline curves) are selected and adapted depending on local vegetation and conditions (e.g., biomes) and therefore do not directly represent a specific eco-physiological process. The vegetation indices are often based on spectral information that is derived from the integrated absorption of electromagnetic radiation at different wavelengths by the top layers of the canopy and may be interpreted as 'vegetation activity'. The correlation to biophysical events is made in a second step and interpretation of this signal can be use case-specific and requires expert knowledge.

[1] https://lpdaac.usgs.gov/dataset_discovery/modis/modis_products_table/mcd12q2

LSP as commonly understood assumes certain yearly amplitude in vegetation activity and cannot cover other types of cyclicality, for instance, induced by climatic oscillations. Biomes with minimal or no seasonality (e.g., desert or rainforest) are commonly excluded, or retrievals may be accompanied by significant levels of uncertainty.

In general, LSP retrieval algorithms are mature and have been successfully applied on a wide range of vegetation-index time series from regional to global scales. The algorithms have mostly been developed on coarse- to moderate-spatial resolution RS data for global applications. High-resolution products at local scales were, however, often developed biome-specific only. These LSP retrieval algorithms need still some adaptation for high-resolution products with global coverage derived from modern multispectral satellites with high repetition rates such as Landsat 8 and Sentinel-2. Rapid developments in computational power (e.g., cloud computing) make the global processing of LSP retrieval algorithms feasible.

2.10 Summary and outlook

From the biodiversity monitoring point of view, the high potential of LSP lies in narrowing the gap between plant-level and ecosystem-level traits. It is currently recommended to interpret LSP at the ecosystem level because of its demonstrated links to ecosystem functioning. However, application at high spatial resolution opens doors to a multitude of new ecological applications and to a better description and understanding of functional biodiversity. A most important development is to design an algorithmic approach to assess a global dataset among all biomes and regions that can be validated by ground measurements and provide quality measures.

2.11 Specific measurement requirements summary

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

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

Requirement	LSP
Spatial extent	All terrestrial ecosystems
Temporal extent	5 – 10 years
Spatial Resolution	10 – 30 m
Spectral Resolution	Broad band
Temporal Resolution	1 -2 times/week
Thematic Accuracy	≥ 80 %
Geometrical Accuracy	1 pixel
Spectral domain	400 – 2500 nm
Existing RS data	S2, S3, Landsat & MODIS
Delivery mode	
Product format	GeoTiff, ESRI Grids, others on request
Reference system	UTM

Reference

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