



Satellite Observation Requirements of Vegetation Structure

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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

CBD	Convention on Biological Diversity	
COP	Conference Of the Parties	
EBV	Essential Biodiversity Variable	
EO	Earth Observation	
ESA	European Space Agency	
FHD	Foliage-Height Diversity	
FPAR	The Fraction of Photosynthetically Active Radiation	
GEDI	Global Ecosystem Dynamics Investigation	
GEO-BON	Group on Earth Observation – Biodiversity Observation Network	
ICESat	Ice, Cloud, and land Elevation Satellite	
IPBES	Intergovernmental Platform on Biodiversity and Ecosystem Services	
NPP	Net Primary Productivity	
RS	Remote Sensing	
RS-enabled EBV	Remote Sensing enabled Essential Biodiversity Variable	
SDG	Sustainable Development Goals	
SOR	Satellite Observation Requirement	
SRL	Science Readiness Level	
TM	Thematic Mapper	
VH	Vegetation Height	
VS	Vegetation Structure	

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 <i>in situ</i> measurement.
Biodiversity	The variability among living organisms from all sources (including terrestrial, marine and aquatic ecosystems) and the ecological complexes of which they are part, including diversity within and between species and of ecosystems.
Biome	A biome is a specific geographic area where an assemblage of organisms is determined by large-scale climatic and vegetation characteristics. A biome can be made up of many ecosystems.
Biophysical Attributes	A biophysical attribute is a biotic and abiotic component of an ecosystem (e.g., leaf area index, ice-cover, land cover, urban footprint or vegetation height) covering the Earth that incorporates and support biodiversity and has an influence on organisms survival, development, and evolution.
Ecosystem	A functional unit or system of the earth's surface that is the whole system including the organisms, the physical factors and their interaction that form the environment (Basu and Xavier, 2016)
Ecosystem 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 \leq 30 m.	
Satellite observation requirement	The types and detail level of a set of attributes of RS-enabled EBVs that are required by the user community for biodiversity assessment and monitoring.	
Remote Sensing enabled EBVs	EBVs that are directly measurable or derived from Earth observation satellite data.	
RS-enabled EBV product(s)	A product or multiple of products obtained through processing remote sensing data that potentially informs about the RS-enabled EBV.	
Resolution	The ability of a remote sensing device to detect subtle variation regarding energy (radiometric resolution), space (spatial resolution) and time (temporal resolution).	
Satellite RS	Remote sensing (RS) data acquired through earth orbiting satellites.	
Scale	The term scale in this document refers to the scope or spatial extent of the RS- enabled EBVs observation but not to the relationship between distance on a map and a corresponding distance on the ground.	
Spatial configuration	Two dimensional geographic distribution of land cover patterns	
State variables	A set of variables that can be used to describe the "state" of a dynamic system. In the context of a terrestrial ecosystem, state variables are those sets of variables that describe sufficiently the ecosystem to determine its future behavior in the absence of any external forces affecting the ecosystem.	
Terrestrial ecosystem	Communities of organisms and their environments that occur on the land masses of continents and islands (Chapin et al., 2002).	
Thematic accuracy	The degree to which the non-positional characteristic of a spatial data entity (attributes) derived from radiometric information agree with <i>in situ</i> observations.	
Vegetation Height	The observable height of vegetation, relative to the ground.	
Vegetation structure	A class of EBVs related to the horizontal and vertical abundance of canopy material.	





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 vegetation structure.

1.2. Scope

The scope of this chapter is to assemble the satellite observation requirements for the RSenabled EBV-vegetation structure 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, terrestrial ecosystems' vegetation structure. Overall, this document provides the observational requirements needed to monitor vegetation structure 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 the RS-enabled EBV were then synthesized after the expect workshop and revised including the experts' opinion. Finally, the observation requirement document was further improved through open review by expert groups of remote sensing and biodiversity community.

1.5. Clearing up the ambiguity

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

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

- **i. Spatial resolution**: refers to the size of the area covered by a pixel in a satellite image. In optical and thermal remote sensing, each pixel in an image corresponds to a patch on the Earth's surface. It is also known as 'ground resolution' and is usually expressed in meters.
- **ii. Spectral resolution**: refers to the wavelength intervals. It describes the ability of a sensor to define narrow wavelength intervals. The finer the spectral resolution, the narrower the wavelength range for a particular channel or band. The following categories are used in setting the requirement for spectral resolution in accordance with the characteristics of the RS-enabled EBV:
 - Panchromatic 1 band (black and white)





- Multispectral 4 to ±15 bands
- Hyperspectral hundreds of bands
- **iii. Temporal frequency (resolution)**: is the required interval between two successive instances of an RS-enabled EBV measurement in the same area and often expressed on an hourly, daily, weekly, monthly, yearly basis depending on the nature of the RS-enabled EBV.

1.6.Chapter outline

The observation requirements are structured into 11 sections and defined for each RSenabled 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 subdefinitions 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 RSenabled 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. Vegetation Structure Satellite Observation Requirement Definition and Analysis





2.1. Definition of vegetation structure

The complexity of terrestrial ecosystems can be assessed in the following domains (McElhinny et al., 2005):

- **Structure** refers to the spatial arrangement of the various components of the ecosystem, such as the **heights** of different canopy levels and the spacing of trees.
- **Function** refers to how various ecological processes, such as the production of organic matter, are accomplished and the rates at which they occur.
- **Composition** refers to the identity and variety of ecosystem components, as characterized by species richness and abundance.

These three ecosystem domains (structure, function, and composition) are closely interrelated. In terms of the availability of satellite-derived vegetation structure observations, vegetation height, is considered the most feasible variable to be retrieved as part of "Vegetation Structure" (Hall et al., 2011, Goetz et al., 2010, Bergen et al., 2009, Goetz et al., 2007, Lefsky et al., 2002). Accordingly, in this document, the term "Vegetation Structure" is used as a container term for a set of variables related to the horizontal and vertical abundance of canopy material. The RS-enabled EBV Vegetation Structure (VS) therefore, contains the observable "height," which is understood to be one aspect of ecosystem structure. However, for the height value to be informative with respect to structure, its distribution, both vertically and horizontally, needs to be measured. In the following sections, we focus on describing 1) measures of vegetation height, as both the vertical variation thereof (e.g., the foliage or the canopy profile, and 2) the horizontal distribution (e.g., surface roughness, vegetation density or fragmentation). These measures have successfully been linked to biodiversity and are in particular relevant for forest biomes with a minimum of tree cover and partly applicable for grasslands. Consequently, the RS-enabled EBV vegetation structure could also be used to inform other RS-enabled EBVs such as fragmentation.

2.2. The role of vegetation structure in assessing and monitoring biodiversity

Vegetation structure is closely tied to ecosystem processes and species diversity (Ruiz-Jaen and Aide, 2005, Naeem et al., 1994). Accordingly, vegetation structure properties may yield information on habitat heterogeneity, the productivity of an ecosystem and its potential successional pathways (Wang et al., 2004, Silver et al., 2004, Jones et al., 2004). Moreover, vegetation structure and derived vegetation structure properties, are closely linked to ecosystem structure, function, and composition, which in turn are strongly interrelated and interdependent. It follows, therefore, that vegetation structure properties that describe habitat heterogeneity can provide insights into ecosystem structure, functioning and composition (Benton et al., 2003, Hinsley et al., 2008). In effect, the horizontal and vertical arrangement of plant communities, and in particular of forests, has a significant impact on ecosystem processes, such as competition, carbon balance, as well as nutrient and water cycling (Benton et al., 2003). Importantly, vegetation structure, notably its complexity, three-dimensional (3D) structure and heterogeneity are tightly linked with biological diversity (Bergen et al. 2009), be it for





plants (MacArthur and Horn, 1969) or animals (Zellweger et al., 2014, Froidevaux et al., 2016).

The arrangement of plants in an ecosystem and their structural complexity is closely correlated with species diversity (i.e., species richness and species evenness). In particular, the distribution of canopy material is a major determinant of potential niches and hence of species richness. In effect, the "habitat heterogeneity hypothesis" is a central premise in ecology; essentially, it considers that the added structurally complex habitats support a larger number of niches, higher niche diversity, more ways of exploiting these niches, increased environmental resources availability, and hence, greater species diversity. Accordingly, in the majority of habitats, plant community composition controls ecosystem structure and therefore has a major influence on the interactions and distributions of species (Macarthur and Wilson, 1967, Tews et al., 2004, Bazzaz, 1975, McCoy and Bell, 1991).

Importantly, the vegetation structural information can be linked to key ecosystem processes (i.e. decomposition, production, nutrient cycling, and fluxes of nutrients and energy) and properties, including niche characteristics described by three morphological traits of plant communities. Niche characteristics may include such properties as vegetation height, vegetation density (canopy cover), and canopy profile or vertical arrangement. Thus, properties describing habitat heterogeneity are directly related to biodiversity metrics, such as species diversity and richness.

Many ecosystem disturbances, such as insect pests, may alter forest and vegetation structure (Solberg et al., 2006), for instance, by increasing defoliation or fuel buildup (Bright et al., 2017). These disturbances may have a direct or temporally lagged impact on the biological diversity of a forest ecosystem as a whole, although they might not always be detrimental to species richness or niche availability (Kortmann et al., 2018). Multi-temporal quantification of ecosystem structure offers the potential for the detection of short-term changes in forest canopy structure, such as those results from logging or storm damage. In effect, such disturbances generally result in marked changes in vegetation structure and species composition; however, for such applications, measures such as vegetation activity (i.e., NDVI) may be appropriate (Souza and Barreto, 2000, Bullock et al., 2018). Therefore, measures of vegetation structure, and in particular vegetation height and horizontal distribution, exhibit large potential for assessing and monitoring many aspects directly related to key ecosystem processes and changes, which are in turn strongly linked to measures of biological diversity.

2.3. Remotely sensed EBV vegetation structure products

Vegetation structure, provided ideally in a raster, is one of the main target products, along with canopy cover (vegetation density), as these products allow spatial and temporal analyses, which are valuable for undertaking biodiversity assessment and monitoring. However, already a single value of for instance, vegetation height as a property for vegetation structure without spatial context may provide valuable information on





vegetation and ecosystem structure, e.g., when used in conjunction with the biome type, land cover or land-use.

An additional product shown to be relevant for biodiversity assessment is the vertical canopy profile, which provides of profile of canopy abundance with height. However, as the profile is a vector comprised of multiple values, it is often reduced to the derived single-value metric foliage-height diversity (FHD), reflecting the diversity of height values within the canopy profile (MacArthur and MacArthur 1961; S. J. Goetz et al. 2010). From the vertical canopy profile, other products can be derived, such as the number of canopy layers or the average and maximum canopy height (Morsdorf et al., 2010). The main VS products are listed in Table 1.

Table 1: Properties of Vegetation Structure (VS) and its short definition.

VH Property	Definition
Vegetation Height	Height of the tree canopy above the ground [m]
Canopy profile	The abundance of canopy material along with a vertical profile or its vertical arrangement.
Vegetation Density / Canopy Cover	Density is described as a measure of vegetation elements in a given area and can be provided as a percentage [%] (i.e., fractional cover) or as plant area index (PAI) [-].

2.4. Spatiotemporal coverage

Vegetation structure is relevant for all biomes containing vegetation of minimum height and extent, including forests, other wooded lands like savannahs, and grassland biomes with bushy vegetation. Regarding the temporal aspect, one has to differentiate between (sudden) disturbances (natural or unnatural) and growth. The former needs high temporal frequencies (e.g., weekly to monthly) for continuous monitoring and/or a distinct observation after the disturbance (e.g., a storm) for comparison with a base-line observation from before the disturbance. Capturing the latter (growth) would likely only require one to two plot visits per year (K. Dolan et al. 2009). In general, a too-long revisit time (e.g. several years) would make trend estimation challenging as too few temporal sampling points would support such a trend.

2.5. The spatial extent and temporal frequency requirements

Capturing the latitudinal gradients in vegetation structure, ranging from tropical over temperate to boreal forests and associated grasslands, is highly relevant to the vegetation structure RS-enabled EBV, and therefore approximately global coverage spanning all relevant biomes is fundamental in the context of global-scale biodiversity monitoring (Patterson and Healey 2015; Healey et al. 2012; Pereira et al. 2013, Vihervaara et al. 2017). In addition, local vegetation structure data, for instance, can inform on regional changes due to processes like insect infestations and forest degradation by human-induced landuse change.

Vegetation structure is a rather slowly changing parameter (e.g., no diurnal cycle), but disturbances can cause fast changes. The lowest cycle for continuous monitoring is seasonal in order to catch the effect on the structure between leaf-on and leaf-off





conditions for forest areas with seasonal profiles. For instance, temperate forests exhibit marked and synchronous leaf seasonality, while in contrast, tropical forest biomes exhibit a weak and often asynchronous leaf seasonality. Given the seasonal differences between biomes, a temporal resolution resolving seasonal cycles would be most advantageous (Hall et al. 2011); this could be considered as best-case temporal resolution. Observation intervals longer than ten years would likely not provide meaningful information in most biomes. Nevertheless, if local disturbances need to be detected, higher observation times are required depending on the process, with clearings being visible after a couple of days and insect pests and other natural mortality showing up over months and years.

The spatial resolution required is highly dependent on the fragmentation and structure of the vegetation. In particular, areas with sparse, single tree coverage need a higher spatial resolution if individual trees and shrub areas should be characterised. In contrast, areas with homogenous vegetation cover such as arctic tundra require a lower spatial resolution for biodiversity and habitat mapping.

2.6. Transferability of retrieval approaches

a) Transferability among biomes

Vegetation structure properties are physical characteristics of vegetation, which can be measured and include, for example, height in meters; therefore, there are generally no limitations regarding transferability among biomes. However, for biomes with very sparse and/or low canopies such as grass and shrublands, the transferability and retrieval of canopy height estimates may be limited by the spatial resolution (Lefsky et al. 2002). In contrast, in very dense forests (i.e., tropical humid), there might be the potential to miss the ground return in a remote sensing signal and therefore, either a bias could be introduced, or the derivation of vegetation height could become impossible (Lefsky et al. 2002; Hall et al. 2011).

b) Transferability across scales

Vegetation structure is scale-invariant, however, depending on the spatial scale at which a property is estimated, different semantics may be used, for example, when referring to stand height or individual tree height (Nilsson 1996). For the latter, the range of observed values might differ between scales as well, e.g., for smaller scales, the ranges of observed canopy cover might be between 0 and 100 percent (e.g., gap vs. no-gap), but for larger scales, closed-canopies will be less prevalent.

2.7. Calibration and validation

Airborne light detection and ranging (LiDAR) observations with high spatial resolution footprints are often used to retrieve vegetation structure properties; in turn, these can serve to validate retrievals of current and future space-borne missions (Khalefa et al., 2013). Moreover, airborne LiDAR can be used for validation at the product level (i.e. canopy cover, vegetation profile), and can also be used to simulate and thus validate a





space-borne LiDAR level-o product (i.e., the waveform) directly. Such a dual-tier validation approach was chosen for the NASA mission Global Ecosystem Dynamics Investigation (GEDI) (Hancock et al., 2019).

Cross-comparison of different LiDAR data products is, however, challenging where they have substantial spatial and temporal variation, and where they are sensitive to different sensor and survey configurations. While, for instance, vegetation height products are more robust with respect to canopy changes, other LiDAR-based, structure-related observables, such as canopy cover, are more affected by changes in instrumentation (Korhonen and Morsdorf, 2014). Validating vegetation structure products using direct field observation networks is not a suitable strategy in such cases, due to the mismatch of spatial and temporal scales. However, a viable validation strategy could be either (i) thematic validation of derived structure variables using observational networks, or (ii) product forward validation by radiative transfer modeling. In the case of the first point, a global validation (plausibility test) using the derived product(s) in the context of a usecase demonstration study, for example, as input to an ecosystem model, may be performed. In the case of the second point, the best practice may be to use radiative transfer models to simulate Earth Observation (EO) data and its derived products and then use the derived virtual domain as a reference. Such an approach has been applied in the ESA 3DVegLab project, as demonstrated in Schneider et al. (2014).

2.8. Existing data sets and performance

Up to now, no satellite mission exists to assess vegetation height from space. The available space-borne LiDARs were not initially aimed at providing vegetation height estimates; for instance, the Ice, Cloud, and land Elevation Satellite (ICESat) with the Geoscience Laser Altimeter System (GLAS) instrument on-board, launched on the 12 January 2003, was operational for seven years, however, had an orbit optimized for polar coverage in order to measure ice sheet elevations and changes in elevation through time, which resulted in large across-track gaps in the tropics (Zwally et al., 2002). The present GEDI mission, in contrast, aims to help to quantify the aboveground carbon balance of the land surface, explore the role of the land surface in mitigating atmospheric CO₂, and map canopy height, canopy vertical structure and surface elevation, in order to investigate how ecosystem structure links to habitat quality and hence biodiversity (Duncanson et al., 2014). GEDI has a footprint of about 25 m diameter and better coverage in the tropics, but with a latitudinal limitation at above $\sim 60^{\circ}$, the coverage of boreal areas is restricted. The instrument has been in operation onboard the International Space Station (ISS) since March 2019 and is restricted to the ISS's flight path, however, will be providing data for two years (Qi et al., 2019).

Deforestation and forest degradation, which lead to drastic changes in forest height, can be detected by high spatial and temporal resolution multi-spectral missions such as Sentinel-2, even though it will be difficult to obtain a direct height difference using passive optical data only. Such datasets can nevertheless make a significant contribution towards informing forest structure estimates from space-borne LiDAR missions, which comprise





spatial point coverage and low temporal resolution (Hansen et al., 2016). Characterization of the canopy profile can be obtained by LiDAR instruments and to a certain degree by multi-frequency Synthetic Aperture Radar (SAR) approaches - preferably in a tomographic configuration. Mean and maximum canopy height can also be derived from stereo images of passive optical and Interferometric Synthetic Aperture Radar (InSAR) data; since these methods only provide surface elevations, they must be used in conjunction with terrain models. For LiDAR, in contrast, the recorded waveform often facilitates the detection of the ground, so that the height of the profile corresponds to the height above the ground. Occlusion causes the LiDAR waveform to deviate from the actual canopy profile, and this is especially the case in denser forests (Morsdorf et al., 2010). However, how this impacts the meaningfulness of the canopy profile for biodiversity assessments needs still to be evaluated (Bergen et al. 2009).

Airborne LiDAR, with its many forestry applications, has been a key contemporary research focus, with many countries owning wall-to-wall datasets that provide valuable forest structure information. However, access to these data is not streamlined, although some countries recently started to make them freely available (UK, Finland, Spain). Thus, airborne LiDAR currently often contributes only a partially complete information source for policymakers and stakeholders at any level above national. In the context of a global RS-enabled EBV assessment, the role of these datasets is primarily in up-scaling, calibration and validation (Cal/Val), as well as for building better science cases to support future space-borne mission designs. As all space-borne LiDAR missions so far have been point-based sampling designs, spatial extrapolation of the derived information is mandatory to derive wall-to-wall maps (Hansen et al. 2016). Such up-scaling should best use data that is directly linked for instance, to surface height, e.g., Polarimetric Interferometry (PolInSAR), InSAR or stereo imagery (Qi et al. 2019). Alternatives may include, the use of empirical models that link vegetation height with multi-spectral reflectance derived by high-resolution missions such as Landsat 7/8 and Sentinel-2 (Hansen et al. (2016).

2.9. Feasibility, scientific and technology readiness levels

The LiDAR technology is mature and already an integral component in the EO toolboxes of regional to national authorities. For instance, many countries in Europe use airborne LiDAR to inform and regularly update their national forest inventories. The technological readiness level of space-borne LiDAR is currently more limited, especially with respect to a power supply and laser longevity, while the sampling design is generally not considered a limitation (Healey et al. 2012). The GEDI mission, however, will demonstrate the technology to derive high-quality estimates of canopy structure and facilitate data fusion approaches enhancing the potential for future radar missions. The GEDI Lidar is generating high-resolution estimates of canopy vertical structure and will contribute to understanding how ecosystem structure affects habitat quality and biodiversity (Stavros et al., 2017). Finally, current and future space-borne designs are likely to be limited in the reliable detection of canopies with very low height (i.e. < 1 m) in biomes with very sparse tree cover (e.g., desert shrub) (Lefsky et al. 2002).





2.10. Summary and Outlook

The structural complexity of vegetation canopies has been extensively linked to biodiversity and ecosystem processes in a large body of historical and contemporary studies. As such, the retrieval of various vegetation structure products has proved pivotal for quantifying key ecosystem variables as vegetation height, canopy cover and vegetation density; concurrently, these have provided detailed insight into structure, function and composition of terrestrial ecosystems. In particular, they have enhanced our understanding of the global patterns, processes and controls on vegetation and ecosystem structure, and their impacts on biodiversity (Goetz et al., 2010, Bergen et al., 2009, Goetz et al., 2007, Lefsky et al., 2002, Macarthur and Wilson, 1967, MacArthur and MacArthur, 1961). The present challenges of retrieving vegetation structure properties synoptically are related to the low spatial and temporal density of observations currently available. However, the new LiDAR missions such as GEDI are expected to bridge this gap together with past space-borne and a range of air-borne datasets; in effect, they will provide global observations of ecosystem structure at a high spatial and temporal density, from which key vegetation structure properties can be derived at a global scale (Stavros et al., 2017, Abdalati et al., 2010). It is therefore anticipated that such global vegetation structure datasets will, when combined with ancillary vegetation structure properties such as those retrieved from optical and SAR sensors, contribute substantially toward the generation of an annual, synoptic and continuous RS-enabled EBV Vegetation Structure product in the near future.

2.11. Specific measurement requirements summary

The satellite measurement specifications and delivery format for the four RS-enabled EBV are tabulated in Table 2. The specific measurements requirements are provided for ICESAt-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.

Requirement	VS
Spatial extent	All terrestrial ecosystems
Temporal extent	2 years
Spatial Resolution	25 m
Spectral Resolution	1064 nm LiDAR
Temporal Resolution	2 years
Thematic Accuracy	N/A
Geometrical Accuracy	5 m
Spectral domain	LiDAR
Existing RS data	ICESat-1, ICESat-2, GEDI, air-borne, SAR
Delivery mode	Level 3A-B
Product format	GeoTiff, ESRI Grids, others on request
Reference system	UTM

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





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