Committee on Earth Observation Satellites

CEOS Ecosystem Extent Task Team White Paper V1.1

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Space-based Earth Observation and Ecosystem Extent: Exploring Opportunities

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Executive Summary

White Paper Purpose and Audience

The purpose of this white paper is to explore and communicate potential new opportunities for using space-based Earth observation (EO) for monitoring biodiversity with a focus on ecosystem extent (the spatial distribution of ecosystems on the Earth). It is part of a new activity of the Committee on Earth Observation Satellites (CEOS), a collaboration of the world's space agencies that facilitates cross-agency coordination of EO. This activity, now manifested as the CEOS Ecosystem Extent Task Team, is focused on increasing the CEOS role in biodiversity applications, initially using ecosystem extent as a vehicle for discussion and exploration of ideas. The audience is two-fold: CEOS Principals that represent their agency, and the biodiversity community with a particular focus on the Convention on Biological Diversity (CBD) and their Parties as well as the UN System of Environmental-Economic Accounting (UN SEEA). Note that as a starting point for further discussion, the focus of this white paper is on terrestrial ecosystems despite the importance of coastal and open ocean ecosystems for biodiversity.

The rationale for increased CEOS engagement with biodiversity is multi-faceted, including the increasing level of threat to the world's biodiversity, the dependency that society has on the services that biodiversity provides, and the essential role that EO plays for monitoring and understanding biodiversity. Ecosystem extent was chosen as an initial topic because it is an Essential Biodiversity Variable (EBV) and has a strong dependency on EO. The threats to biodiversity and their implications for society have been extremely well-documented; for example, a 2019 report by the Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES) provides an extensive assessment. The signing in December 2022 of the CBD Kunming-Montreal Global Biodiversity Framework (GBF)—the Convention's plan for the coming decade and beyond--was another rationale for CEOS engagement. The GBF includes a Monitoring Framework that lays out specific indicators that the Parties must report on; many of these, including ecosystem extent, will utilize EO as an important input.

Mapping and Monitoring Approaches

Space-based EO has been used for mapping land cover--a common proxy for ecosystem extent-- for decades. However, land cover maps typically use generalized depictions of ecosystems, often at fairly coarse levels, and thus may be inadequate for ecosystem management and reporting to the CBD (Parties need to report on "Headline Indicator A.2: extent of natural ecosystems"). Maps are created using measured ecosystem characteristics to classify pixels or groups of pixels into the ecosystem classes of interest. The most common approach is to train a machine learning model with reference data to create a model that then uses EO and perhaps other input data to assign pixels to a class. This approach works because ecosystems differ in their biophysical characteristics; spectral properties have traditionally played a major role in the classification process. Classes are organized around a hierarchical classification scheme, but because each country selects a scheme appropriate for their needs and ecosystems, global maps and comparisons are difficult. To address this shortcoming, the recently developed IUCN Global Ecosystem Typology (hierarchy Level 3) was selected by UN SEEA as a standard to enable cross-referencing among schemes. Note that, while EO data are typically the primary input for creating ecosystem extent maps, creation is highly dependent upon in situ data, particularly for training and quality assessment.

Opportunities from Sensors and Missions

Different types of sensors measure different types of characteristics, as summarized in Table ES-1 (each type is further discussed in Section 3.1). A variety of new and forthcoming missions are creating opportunities for ecosystem extent mapping and monitoring and biodiversity monitoring more broadly. NASA/ISRO, JAXA, and ESA are developing L-band radar missions; the NASA/ISRO NISAR and JAXA ALOS-4 spacecraft will launch in 2024 (TBD), while ESA ROSE-L is one of the six Copernicus Sentinel Expansion missions launching the second half of this decade. These missions will add to the historical and ongoing L-band Synthetic Aperture Radar (SAR) missions operated by JAXA (JERS-1, ALOS, ALOS-2) and CONAE (SAOCOM-1). Although still an emerging field, the increasing number and coverage of hyperspectral sensors are likely to provide a significant change in monitoring capability. In addition to existing missions operated by ASI (Italy), DLR (Germany), and NASA (USA), NASA and ESA are developing missions (SBG and CHIME, respectively) that will provide routine, global coverage in the latter half of this decade. Thermal missions continue and are in development from the US (e.g. Landsat and ECOSTRESS) and additional missions are under development by CNES/ISRO and ESA that will provide insights into ecosystem processes such as evapotranspiration. The NASA/CNES SWOT mission, launched in December 2022, is enabling monitoring of freshwater ecosystems in addition to coastal and open ocean areas. See Section 3.3.1 for a more complete discussion of these and other missions.

Emerging Capabilities

A variety of opportunities are emerging that enable new or improved data products. The increasing availability of hyperspectral data discussed above is enabling advances in biodiversity science and thus leading to new products and improved understanding of the relationships between spectra, traits, and ecosystem processes and, in turn, many EBVs. As the availability of hyperspectral data increases and understanding of how to extract its inherent value is enhanced, this will facilitate its use in combination with other types of data. Similarly, the use of lidar data for characterizing ecosystem canopy height and volume will also enhance the delineation of ecosystem features related to specific vegetation types, especially when combined with other data sources (e.g. optical imagery). In fact, fusing the complementary data that optical, SAR, and lidar sensors provide has not yet been sufficiently exploited, largely

Sensor type	How It Works	Benefits / Limitations
Optical - Multispectral	Passive sensor measuring reflected light in a limited number of spectral "bands", typically in the visible, NIR, SWIR and TIR wavelength ranges.	Benefits: - many platforms - extensive historical data Limitations: - obscured by clouds - canopy surface only
Optical - Hyperspectral	Passive sensor measuring reflected light in hundreds of narrow spectral "bands"	Benefits: - enables biochemical plant analysis ("functional traits") Limitations: - newer modality, less historical record - same limitations as multispectral
Synthetic Aperture Radar (SAR)	Active sensor that emits microwave signals	Benefits: - enables vegetation and terrain structural analysis (short wavelengths sensitive to canopy structure; long wavelengths sensitive to trunk and branch structure) - penetrates clouds, haze and smoke - can image during both day and night - historical data since 1990's Limitations: - initially challenging for ecosystem scientists to utilize
Lidar	Active sensor that emits laser pulses	Benefits: - enables structural forest measurements, such as canopy height and profile Limitations: - point-based sampling - few space-based platforms - limited historical data

Table ES-1. The basic types of sensors and their applicability for ecosystem mapping and monitoring. Note that hyperspectral, SAR, and lidar require their own special processing.

because these data vary widely in the expertise needed to use them and cross-community interaction is not well-developed.

Another opportunity lies in time series analyses that can provide key insights into ecosystem phenology (seasonal timing), an important ecosystem characteristic that can enhance ecosystem discrimination. Such analyses can require significant computing resources as well as special analytical skills and are not yet routinely implemented.

Data can be efficiently stored in a data cube such as an Open Data Cube running in the cloud, this highlights some of the value of data cubes as both a useful data structure but also as a convenient compute platform. Furthermore, data cubes are also an excellent way to store and utilize data from a variety of different sensors, hence, it is a logical approach to support data fusion as well as time series integration.

Lastly, the field of artificial intelligence is rapidly advancing and is expected to play a variety of important roles for ecosystem mapping and monitoring as well for understanding biodiversity more broadly. For example, it is likely that AI techniques will be able to help generate improved maps by identifying patterns hidden in the increasingly diverse suite of data sources. Another important application will be to effectively increase the duration and quality of time series data by reprocessing historical data from a variety of sensors going back into the 1970s. That would enable insights that are not now available into how ecosystem extent and other characteristics have changed.

Taking advantage of these opportunities to advance the quality and availability of ecosystem extent maps is not without challenges and some of the most important ones are summarized in Table ES-2.

Conclusions and Recommendations

Here the white paper steps back a bit to provide some additional comments that help convey how EO fits into the current ecosystem mapping context and how this might change. For example, taken together the current and planned missions should provide most of the basic, core observations for ecosystem extent mapping, although increased spatial and temporal resolution would be a significant and important advance. The biggest observational gap is the need for global, repeat lidar; lidar has emerged as a critical input for ecosystem extent mapping and monitoring as well as many other biodiversity products and a sustained source of lidar data is needed. However, despite the availability of so many important *observations*, there remains a gap between those and the *products* most needed by the biodiversity community. Products such as Essential Biodiversity Variables and the indicators needed by CBD Parties are value-added products further down the processing chain than the products typically made available by space agencies. And because the users needing these products often lack the capacity to generate them, only some of the value inherent in the available observations is extracted. This gap is the basis for some of the recommendations, which follow (Table ES-3).

Summary of Challenges
Limited availability of value-added products. These include Essential Biodiversity Variables and other derived products that would advance ecosystem mapping and monitoring.
Combining data from different types of sensors. Although sensors of different types have complementary characteristics needed to discriminate ecosystems, availability of such “fused” products is very limited.
EO data accessibility, usability and technical capacity of users. Technical capabilities (both knowledge & infrastructure) to process and utilize EO data is often limited.
Ecosystem condition. Condition can affect the ecosystem characteristics used to discriminate ecosystems and thus complicates mapping.
Reference data for training and validation. Insufficient reference data is often the biggest limiting factor to mapping ecosystems.
Scale. The characteristics of ecosystems vary depending on the scale being observed, some being found at a local scale while others are at the landscape scale.

Table ES-2. Some of the most important challenges to increased use of EO data for ecosystem mapping and monitoring.

Thematic Recommendation Area	Specific Recommendations
1. User Engagement Increase biodiversity community engagement with EO and CEOS through workshop(s) and other activities to improve ecosystem extent mapping. Key organizations: ● Convention on Biological Diversity ● UN System of Environmental Economic Accounting ● GEO Global Ecosystems Atlas initiative ● Ramsar Convention on Wetlands	1a. Identify specific user requirements and priorities for EO and related value-added products for ecosystem extent. 1b. Establish a sustainable communication channel between CEOS and user communities for continued interaction. 1c. Improve CEOS understanding of technological, socio-political, and cultural constraints for the biodiversity community to use EO data.
2. Technical advances Support development of technical advances to improve utilization of EO for ecosystem mapping.	2a. For each ecosystem class in IUCN's Global Ecosystems Typology (GET) and Ramsar's classification scheme, identify the key EO data sources and mapping approaches needed for its delineation. 2b. Facilitate combining data from different types of sensors to take advantage of their complementarity. 2c. Facilitate time series analysis and its application to ecosystem extent mapping. 2d. Explore ways to utilize EO to characterize ecosystem condition and its relationship to ecosystem extent.
3. Capacity Work to increase capacity of biodiversity users to utilize EO for ecosystem mapping and monitoring.	3. Identify opportunities for capacity development resources, e.g., a training or a Massive Open Online Course (MOOC) focused on the use of EO for ecosystem mapping and monitoring.

Table ES-3. Recommendations for consideration by CEOS.

Preface: White Paper Purpose and Context

Although CEOS has had a Biodiversity Activity for some time the biodiversity area has not yet been a major CEOS focus. Recently, however, the importance of biodiversity to society and the need for improved monitoring have become much clearer. The 2019 Global Assessment Report on Biodiversity and Ecosystem Services developed by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, analogous to the IPCC) provided a daunting assessment on the state of biodiversity and its implications for society. Understanding and appreciation of the interconnections between biodiversity and climate have also advanced, as has the role of nature-based solutions for mitigation and adaptation. A key recent activity has been the update to the UN Convention on Biological Diversity's (CBD) decadal planning, resulting in the Kunming-Montreal Global Biodiversity Framework (GBF) and its Monitoring Framework. The GBF was developed over several years and agreed to by the CBD's nearly 200 Parties in December 2022. It laid out four goals for 2050 and 23 Targets for 2030, many of which are of direct or indirect relevance to Earth observation (EO) from space.

These recent developments and the visibility they provided set the stage for CEOS to start exploring ways to increase its engagement with biodiversity; this led to a proposal to create the Ecosystem Extent Task Team (EETT), approved at CEOS Plenary in 2022. Also significant is that in 2018 the UN CBD's Executive Secretary sent a letter to CEOS suggesting the two organizations explore ways to strengthen their collaboration. The CEOS Chair responded in agreement and acknowledged that much work remains for EO's potential for biodiversity monitoring to be fully realized. Many things have changed since that early exchange and, while in retrospect it may have been ahead of its time, the letter exchange laid important groundwork for future collaboration and the start of this Ecosystem Extent Task Team.

This brief history provides the context for this white paper, which is called out in the EETT's Terms of Reference:

Develop a white paper that will provide an integrated international perspective on how space-based Earth observations can be used to support ecosystem mapping and monitoring with a focus on ecosystem extent.

Keeping in mind these Terms of Reference, the increasing awareness of the importance of biodiversity, and the potential for enhancing the role that EO can play in ecosystem mapping and monitoring, this white paper focuses on two audiences: CEOS Principals that represent their agency to CEOS, and the biodiversity community with a particular focus on the CBD and their Parties as well as the UN System of Environmental-Economic Accounting (UN SEEA).

The Introduction summarizes the broad context within which the work of the EETT sits, explains why ecosystem extent is so important, and discusses the key policy anchors that lay behind it. Section 2 discusses some of the conceptual basis upon which ecosystem extent maps are created. Section 3 then turns to the role of space-based Earth Observation, how it is used, types of sensors, and related information. Recommendations to CEOS on how it might enhance existing ecosystem extent mapping and monitoring activities are then suggested in Section 4.

-- Co-leads Gary Geller, Shaun Levick, Sandra Luque, Roger Sayre

1 Introduction

An ecosystem is a dynamic complex of plant, animal and micro-organism communities and their non-living environment that interact as a functional unit. They and the biodiversity within them play essential roles for human existence and quality of life. Ecosystem services, or nature's contributions to people, are wide-ranging and include food, fiber, water, materials, energy, and medicines, among others. Ecosystems sequester carbon, mitigate impacts of natural hazards, provide pollination and pest control, and are a source of recreation and cultural and spiritual enrichment. To ensure reliable and continued delivery of these societal benefits, ecosystems must be sustainably managed.

Yet it is broadly recognized that ecosystems face serious threats on a global scale (Figure 1-1). At least 25% of species are threatened with extinction and the majority of ecosystem indicators suggest species are in rapid decline (see the [2019 IPBES Global Assessment Report on Biodiversity and Ecosystem Services]). These declines have the potential for dramatic and far-reaching negative consequences for human well-being and environmental security. Although there are several direct and indirect drivers of global change, land use change has had the largest negative impact on ecosystems. Our need to develop better approaches for characterizing, understanding and monitoring the locations and conditions of ecosystems and the services they provide has never been more important. Ecosystem size and distribution, i.e., ecosystem extent, have historically played a determining role in where and how people live, and this role continues today. Ecosystem extent affects the ecological and evolutionary processes within and around an ecosystem as well as other levels of biological organization--most species only live in certain ecosystems, for example. Because of the interconnectedness among the many elements of an ecosystem, including

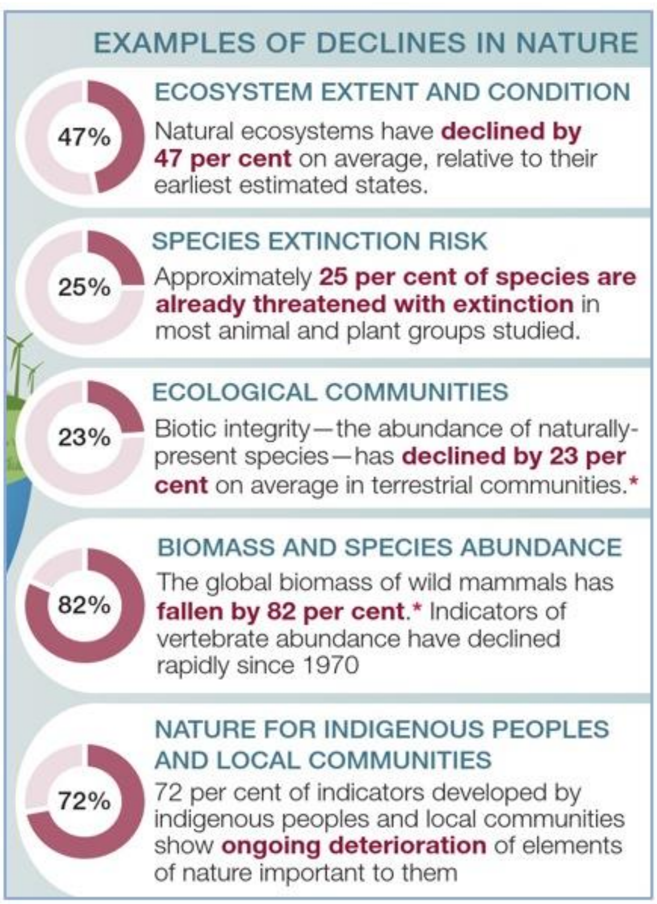

Figure 1-1. Estimated declines in biodiversity, which are having negative impacts on the health and well-being of humans and wildlife. (Source: 2019 IPBES Global Assessment Report on Biodiversity and Ecosystem Services)

humans, changes in ecosystem extent can have dramatic cascading consequences. For example, many anthropogenic activities lead to fragmented ecosystems that detrimentally affect individual species, overall species diversity, and key ecosystem services of importance for human well-being.

Figure 1-2 provides an example of an ecosystem extent map that delineates the boundaries of 14 terrestrial ecosystems in South Africa. Mapping and monitoring ecosystem extent is one of the most basic needs for natural resource management and especially for conservation efforts—planning a management activity, and assessing its impact, cannot be done without it. Area-based conservation, restoration, and management all require accurate information about ecosystem extent and how it is changing over time.

Space-based EO are particularly well-suited for mapping and monitoring ecosystems and biodiversity. In particular, they are usually global, periodic, and very often available at no cost to users; these characteristics complement those of in situ observations which are more direct and provide more detail but are relatively expensive and very spotty in space and time. Consequently, space-based EO have been a critical data source for characterizing land use change and ecosystem extent for decades, and more recently to estimate changes in ecological processes that impact biodiversity in those areas. Continued availability of the observations that enable creation of these maps and provide other insights on biodiversity is essential, but there are both unmet user needs as well as opportunities for EO; these are the main topic of this white paper.

1.1 Biodiversity Policy Anchors and Users

Here we focus on two organizations that are particularly important to CEOS and that are likely to be the organizations where initial CEOS activity should be focused. However, it is important to note that the work discussed in this white paper is relevant to a range of other Multilateral Environmental Agreements including the Ramsar convention on wetlands, the UN Convention to Combat Desertification, the UN Sustainable Development Goals, and many others. However, as a starting point for further discussion, the focus of this white paper is on terrestrial ecosystems despite the importance of coastal and open ocean ecosystems for biodiversity.

1.1.1 UN CBD Kunming-Montreal Global Biodiversity Framework and its Monitoring Framework

The CBD’s Global Biodiversity Framework (GBF) is a new, ambitious, and transformative strategic plan for global biodiversity conservation adopted at CBD COP 15 in December 2022. Nearly all of the world’s countries are obligated to address the GBF’s Goals and Targets and report on progress towards achieving them. As such, the GBF will guide ecosystem conservation actions worldwide for the next decade and beyond and its importance as a strategic guide for conservation planning and action should not be underestimated.

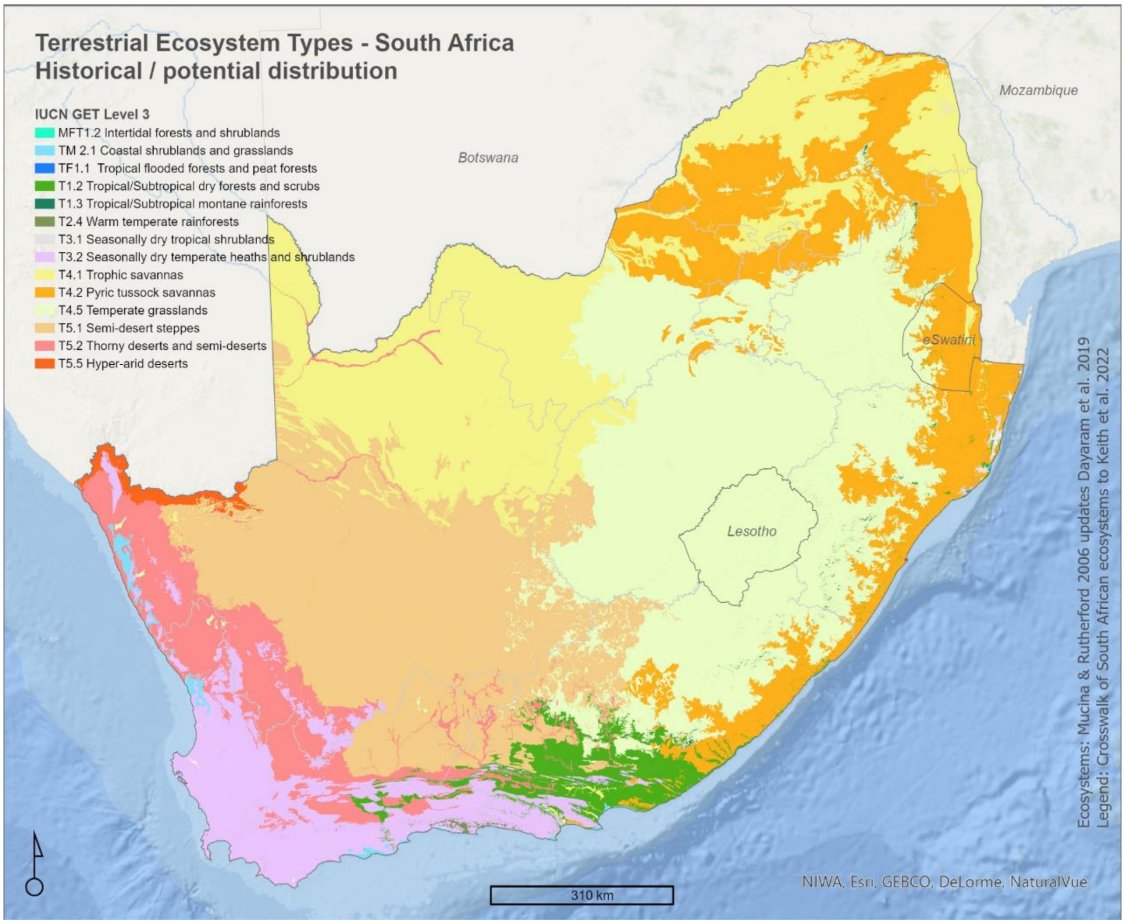

Figure 1-2. Vegetation map of South Africa. (This is intended to provide an example map to demonstrate what an ecosystem extent map is; it is not an official map for South Africa.) Map courtesy of Andrew Skowno (SANBI).

The GBF's vision is *"a world of living in harmony with nature where biodiversity is valued, conserved, restored and wisely used, maintaining ecosystem services, sustaining a healthy planet and delivering benefits essential for all people."* It includes four overarching, long term goals for 2050 and 23 targets for 2030. GBF's Goal A and many of its Targets are directly or indirectly relevant to the work of CEOS and its agencies. Each Target has one or several associated indicators used to monitor and report on progress and many of these, including ecosystem extent, require or benefit from EOs.

A key component of the GBF is the Monitoring Framework that outlines the indicators that Parties (i.e., national governments) are to use when they report on progress towards Goals and Targets. "Headline Indicators" are the top-level standard that all governments must use for their reporting; this enables a global picture of biodiversity status. "Component" and "Complementary" indicators can be aggregated to create Headline Indicators or otherwise used internally by Parties. Headline Indicator “A.2: Extent of natural ecosystems” is of obvious and direct relevance to the work of the Ecosystem Extent Task Team and to CEOS; it directly supports Goal A and is relevant to multiple Targets. Also of relevance to CEOS and the EETT is that the CBD recognizes the importance of aligning national biodiversity monitoring efforts with national ecosystem accounting efforts; this is discussed next.

1.1.2 UN System for Environmental-Economic Accounting (UN SEEA)

The United Nations Statistical Commission recently adopted SEEA Ecosystem Accounting as the new international accounting standard for ecosystem assets and services. As an accounting standard it enables nations to use a common set of rules and methods to track changes in the three ecosystem accounts of particular interest here (Ecosystem Extent, Ecosystem Condition, and Ecosystem Services). The SEEA Ecosystem Accounting guidance, which is applicable to all terrestrial, freshwater and marine ecosystems, including managed ecosystems, describes a rigorous, spatially explicit, integrated framework for developing statistical accounts on ecosystems and their services to society. It also provides a new measurement framework underpinning the development of monitoring approaches for other international agreements including the CBD GBF.

Ecosystem Extent accounts are measured in terms of the spatial areas of different ecosystem types and how these change over time. The International Union for the Conservation of Nature (IUCN) Global Ecosystem Typology (GET) was adopted as a common classification framework to be used for international comparisons. Countries are encouraged to “crosswalk” their national classification schemes, which are likely to be somewhat different and more detailed, to Level 3 (Ecosystem Functional Groups) of the GET (the GET and other typologies are hierarchical and the GET has six levels).

2 Mapping Ecosystems

2.1 Land Cover as a Proxy for Ecosystems

In the absence of detailed maps characterizing the distribution of ecosystems, society has relied for years on satellite image-derived maps of land cover and land use as a proxy for ecosystem distributions. Land cover maps are widely available at many scales and for a wide range of purposes. They usually differ from maps of ecosystems, however, typically representing generalized depictions of ecosystems at coarse levels (forests, grasslands, etc.) and often with classes that may not be directly relevant to the management of natural ecosystems or to specific GBF Targets.

2.2 Mapping Ecosystems from Imagery

During the first few decades of image availability, production of ecosystem maps relied on a human analyst visually grouping pixels with similar characteristics and then drawing polygons corresponding to the ecosystems of interest. Today, however, maps are produced in a digital processing environment where delineation of ecosystems uses, among other information, differences in measured ecosystem characteristics. Historically, these characteristics have most often been spectral features using multispectral data from various space-based instruments such as Landsat. However, as the amount, temporal frequency, and variety of space-based observations and the ability to process large datasets has increased, the range of characteristics that can be used has also increased. For example, seasonal change patterns are an important ecosystem characteristic but it is only in the last decade that computing costs dropped sufficiently to make processing lengthy time series practical. Another important example is the increased availability of data from a variety of sensor types beyond multispectral, such as SAR, hyperspectral optical, and lidar. Appendix 2 lists common ecosystem characteristics that can be measured and monitored using EO.

Currently, the most common approach to generating ecosystem (or land cover) maps is based on machine learning (ML). A “supervised” approach is one where the ecosystem classes are known “a priori” and for which sufficient training (reference) data are available. Although there are many variations, in general a ML model is trained using a set of reference data that contains examples of each ecosystem class of interest. The reference data are then correlated with EO and other measurements using a ML algorithm to create a multidimensional data space that classifies each pixel or group of pixels as one of the trained ecosystem types. However, emerging technologies, particularly artificial intelligence approaches such as deep learning (discussed later), are gradually becoming more common.

The development of ecosystem extent products requires calibration data composed of reference samples that are used to train the model. The reference dataset is a collection of pixels whose ecosystem classes have been identified and labeled--machine learning and other AI approaches cannot be done without it when an a priori approach is used. The data can be obtained in a variety of ways including direct field measurements and visual assessment of high-resolution images; although there are some automated approaches, development of a training dataset is primarily a manual process and is generally the biggest limiting factor to high quality ecosystem classification. Ideally, reference samples should be stratified to keep the number of samples for each class in balance. The reference dataset also provides the data for validating the resulting map and providing an accuracy assessment; typically, it is divided into training and validation subsets with 20-30% of the samples used for validation.

Users and user needs vary widely and, consequently, so do the type and scale of the map they need. These commonly vary from the local maps a county manager might need to country-level maps needed by national governments to regional and global maps that provide the larger perspective needed by some policy makers.

Whereas supervised approaches require reference data to create the classification model, “unsupervised” approaches are also possible that rely solely on machine learning and statistical clustering routines. Unsupervised approaches can have some significant drawbacks, including an inconsistent match to the ecosystem labels that a user may need and difficulty in quality assessment due to the lack of reference data. However, generating them does not require reference data.

2.3 Ecosystem Characteristics Useful for Mapping

The approaches discussed above are commonly based on the spectral characteristics of individual ecosystem classes as captured in the reference data. While this works well for many classes, for others (e.g., specific types of forest, and shrub or grassland ecosystems) information that is more directly related to the ecological characteristics of the ecosystem itself is needed. Traditionally, these characteristics are grouped into three basic categories of ecosystem properties, each of which is represented across the Essential Biodiversity Variables (EBVs).

- **Structure** refers to the types and spatial arrangement of the various components of the ecosystem both vertically and horizontally. This includes important variables such as canopy height, leaf area index, woody biomass, or number of canopy layers.
- **Function** refers to various ecological processes such as productivity, biomass accumulation, or fire dynamics; many of these have a diurnal or seasonal cycle. Ecosystem function is particularly relevant to ecosystem services.
- **Composition** refers to the species or other taxonomic groups that reside in and form ecosystems. In addition to taxonomy, composition can be characterized by more general measurements of biological diversity, such as species abundance, rarity, evenness etc.

Because EO is able to provide insights into each of these complementary categories, they are useful as we consider ways for EO to improve the quality of ecosystem maps (see Section 3.2).

2.4 Ecosystem Mapping Typologies

National governments use classification systems that are appropriate for their country’s ecosystems and applications, leading to a diversity of systems and legends. Most such systems are hierarchical (coarser levels can be disaggregated into finer levels), making them useful for a range of conservation and other applications. However, the many national systems in use currently make comparisons among countries difficult and global assessments challenging. With the recent adoption by UN SEEA of IUCN GET Level 3 as a common classification and reporting framework, it is likely that countries will use GET Level 3 for their CBD reporting. This may require them to “crosswalk” their national system to GET Level 3, although this may not always be a straightforward process. The GET is only one of multiple global classification typologies with the appropriate approach depending on the objectives of the user; several of these are compared in Table 2-1.

Typology	Conceptual Basis
World Terrestrial Ecosystems (WTE)	Structural approach based on climate setting, terrain setting, and vegetation/land cover
WWF's Global Ecoregions	Composition-based approach
IUCN Global Ecosystem Typology (GET)	Mixed approach emphasizing, function and composition

Table 2-1. Comparison of some Global Ecosystem Typologies

It is important to recognize that in the "real world" many ecosystems lack crisp boundaries and transitions between ecosystems are often gradual. Delineating ecosystems on a "continuous" basis that captures such gradual transitions is possible and can better reflect what is happening on the ground. However, this can complicate the visual depiction of ecosystems on a map and can complicate decision making; consequently, it is generally not included in the maps that decision makers use.

Other Activities Relevant to Ecosystem Extent Mapping

Understanding and monitoring biodiversity is a big topic and there are many activities relevant to the work of the EETT and to CEOS more generally. Two key activities are summarized here.

The Group on Earth Observations Global Ecosystems Atlas is a new activity whose concept is being actively developed as this white paper is being written. The Atlas is a major effort to collect and reconcile (conceptually and spatially) the many different maps of ecosystem extent at global, regional, and national scales into an emerging resource. It is envisioned as a platform which both 1) compiles and serves existing ecosystem maps at national, regional, and global scales and 2) supports users in the production of new ecosystem maps, primarily at the national level.

The GEO Biodiversity Observation Network (GEO BON) is the biodiversity arm of GEO and a GEO flagship. One of the most important activities of GEO BON was to create a suite of Essential Biodiversity Variables (EBVs) analogous to the GCOS Essential Climate Variables. These capture the most basic dimensions of biodiversity and as such provide key guidance for biodiversity monitoring. Because they are the basis for a wide variety of biodiversity indicators they are specifically called out in the GBF Monitoring Framework. Of direct relevance to ecosystem extent is the class of EBVs called Ecosystem Structure which contains the EBV called Ecosystem Distribution, identical to ecosystem extent.

Although remotely sensed imagery is commonly used to produce wall-to-wall maps that include multiple ecosystem types, it is also useful for mapping individual ecosystems in a binary separation of the targeted ecosystem from all other ecosystems. This has some advantages because a multi-ecosystem mapping approach requires a more comprehensive set of reference data. Approaches to mapping single ecosystems are the basis behind operational ecosystem monitoring initiatives like Global Mangrove Watch, Global Forest Watch, and the Global Forest Observations Initiative.

Section 1 has summarized the importance of ecosystems to society and the policy drivers behind the need to monitor ecosystem extent. Section 2 discussed the different approaches to mapping ecosystem extent and some of the key ecosystem characteristics used for delineation. With that as background we now turn to the core topic of this white paper--the role that space-based EO has for ecosystem mapping and the potential for enhancing mapping and monitoring capabilities. After providing an overview of the basic types of sensors it then explains why their complementarity is important and summarizes some forthcoming missions and emerging technologies that create new opportunities for ecosystem extent monitoring. With that as context the challenges to realize some of these opportunities are discussed.

3 Space-based Earth Observations for Mapping and Monitoring Ecosystem Extent

3.1 Types of Sensors

Spacecraft carry a variety of types of sensors that image different parts of the electromagnetic spectrum. Passive optical sensors typically capture reflected light in the visible and near infrared wavelengths that are suitable for differentiating and mapping general Earth surface features, including vegetation. In contrast, “active” systems such as SAR and lidar send a pulse of energy to the surface and then record the reflected energy as it returns to the sensor. Table 3-1 summarizes these sensor types and some of their benefits and limitations. These are discussed in more detail in the sections that follow (a brief overview of Earth observations and their use for land management can be found here). Note, however, that in situ data are of critical importance for utilizing EO for biodiversity and ecosystem applications.

3.1.1 Optical--Multispectral

Unlike the cameras on, for example, most mobile phones, instruments with passive optical sensors actually have a suite of individual sensors, each of which measures a particular wavelength “band” of light. This helps discriminate different types of materials because many have a unique reflectance spectrum, sometimes called a material’s “spectral signature”.

Sensor type	How It Works	Benefits / Limitations
Optical - Multispectral	Passive sensor measuring reflected light in a limited number of spectral "bands", typically in the visible, NIR SWIR and TIR wavelength ranges.	Benefits: - many platforms - extensive historical data Limitations: - obscured by clouds - canopy surface only
Optical - Hyperspectral	Passive sensor measuring reflected light in hundreds of narrow spectral "bands"	Benefits: - enables biochemical plant analysis ("functional traits") Limitations: - newer modality, less historical record - same as limitations as multispectral
Synthetic Aperture Radar (SAR)	Active sensor that emits microwave signals	Benefits: - enables vegetation and terrain structural analysis (short wavelengths sensitive to canopy structure; long wavelengths sensitive to trunk and branch structure) - penetrates clouds, haze and smoke - can image during both day and night - historical data since 1990's Limitations: - initially challenging for ecosystem scientists to utilize
Lidar	Active sensor that emits laser pulses	Benefits: - enables structural forest measurements, such as canopy height and profile Limitations: - point-based sampling - few space-based platforms - limited historical data

Table 3-1. The basic types of sensors and their applicability for ecosystem mapping and monitoring. Note that hyperspectral, radar, and lidar require their own special processing.

Instruments such as Landsat or Sentinel-2 might have a dozen or so bands and are called multispectral instruments.

Sensors such as these provide measurements for each individual pixel, which can vary in size from less than one meter for some commercial data, to 10-30 meters for instruments such as Landsat or Sentinel-2, and to 100-1000 m or more (see Appendix 2). It is useful to think of every measured pixel as a biological data point as this emphasizes EO's role in understanding and monitoring the state of ecosystems from space.

The Landsat and Sentinel-2 missions provide an important source of EO data for ecosystem monitoring and vegetation seasonality, and these satellites are currently the main providers of medium spatial resolution imagery, acquired globally with a revisit time of five days for the Sentinel-2 system, and eight days for Landsats 8/9.[1] The combination of temporal, spatial and spectral data provides the basis for information on vegetation phenology, horizontal structure, ecosystem productivity dynamics, and other ecosystem characteristics. Products from the MODIS (NASA), VIIRS (NOAA) and Sentinel-3 (ESA) missions have also been broadly used and, although their larger pixels provide coarser spatial resolution, they enable much more frequent temporal resolution, providing global coverage on a near-daily basis.

3.1.2 Optical--Hyperspectral

Hyperspectral sensors take measurements in many, often hundreds, very narrow spectral bands, similar to the desktop spectrometers used in chemistry laboratories. Thus the information content of their data far exceeds that of multispectral instruments, greatly increasing the ability to identify the content of surface materials such as a plant canopy. (It should be noted that dealing with so much data can be cumbersome and requires specific skills and handling.) Use of hyperspectral data is an emerging science and there are a number of very active research areas with tremendous potential. For example, for plants that have an identifiable spectral signature it is becoming possible to identify species or somewhat higher taxonomic levels from space. Hyperspectral data can also provide information on the physiology and biochemistry of the canopy, including variables such as leaf water or chlorophyll content, leaf mass per unit area, or nutrient content; these are called "plant functional traits" and are starting to provide insights into ecosystem health as well as the processes and functions that help to understand not just the types of plants living there but also why they are there. Water and atmospheric characteristics can also be described with these data and can be key to understanding ecosystem health.

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[1] Recently, NASA has supported the Harmonized Landsat-Sentinel-2 (HLS) project which will provide global observation of the Earth's surface every 2-3 days with 30-meter spatial resolution. ESA's Sen2Like framework is also relevant here.

3.1.3 Synthetic Aperture Radar (SAR)

Radar are "active" sensors--unlike passive optical sensors that measure reflected sunlight, radar sensors emit their own electromagnetic energy in the microwave domain and then measure the properties of electromagnetic waves that are received (backscattered energy) following

> **The importance of in situ data**
>
> In situ data are essential for nearly all applications of space-based Earth observations to biodiversity and ecosystems. For example, for 10-30m data it is difficult or impossible to identify species and even higher-level taxa, yet these comprise the Composition component of an ecosystem and are increasingly important as one moves down the typology hierarchy to finer-grained classifications. But space-based EO generally cannot resolve even large animal species and many, if not most, ecosystem processes and functions are not observable at all (fire and flooding being exceptions). While hyperspectral data are starting to be used for both composition and function, with tremendous potential, this remains an emerging technology.
>
> Given its importance it is fortunate that there are a variety of databases providing in situ data, including GBIF, OBIS, BIEN, and TRY. This information can be incorporated into machine learning models or incorporated in other ways (e.g., see Appendix 1 on mapping in Liberia). Beyond ecosystem extent mapping, these databases are essential for estimating species distribution, abundance, and other EBVs.
>
> However, despite these important databases, in situ data are often a limiting factor in creating ecosystem extent maps and for understanding and monitoring ecosystems. Improving the availability and quality of in situ data is one of motivations behind GEO BON's concept for a Global Biodiversity Observing System (GBiOS); other motivations include greater integration across the great diversity of data sources, including space-based Earth observations.

interactions with surfaces or objects. Surface roughness (e.g., of vegetation) and dielectric properties (e.g., of soil or vegetation water content) influence the microwave energy backscattered by the landscape elements and enable radar to be used for mapping multiple components of ecosystems, including vegetation and terrain structure and soil moisture. SAR is the type of radar used for EO such as for vegetation. The depth of penetration of SAR signals through target objects depends on the sensor's wavelength, with longer wavelengths penetrating deeper into vegetation canopies. Thus L-band sensors such as those currently operated by CONAE (SAOCOM-1; Argentina) and JAXA (ALOS-2; Japan) as well as the forthcoming missions discussed later are advantageous for forest height and biomass mapping. L-band sensors, due to their enhanced penetration capacity, can also provide information about inundation extent under a closed forest canopy. Shorter wavelength sensors such as the C-band used in Sentinel-1 can achieve higher spatial resolution surface characterization but do not penetrate the canopy as deeply. DLR's Tandem-X, which uses the even shorter X-band is thus very sensitive to topography and may be useful for wetland mapping. A key property of SAR is that it is not affected strongly by clouds--particularly important for tropical areas--but also, being an active sensor, it is possible to take measurements both day and night.

3.1.4 Lidar

Lidar is a remote sensing technology that emits laser pulses and, by measuring how much light is reflected and how long it takes to get back to the sensor, provides an estimate of how vegetation density varies with canopy height. Such information about the physical structure of an ecosystem is a key component for several ecosystem characteristics and EBVs, getting at the “structure” component of an ecosystem. For example, lidar-derived information has been widely used to determine key ecosystem characteristics such as canopy height or how leaf area density or plant biomass varies with height (an EBV).

GEDI, the Global Ecosystem Dynamics Investigation mission, was active on the International Space Station (ISS) from 2018 to 2023 and may be reactivated when space on the ISS becomes available. It was the first lidar mission primarily designed to study forest ecosystems and its data have been invaluable for a range of applications because they fill a critical niche for 3D ecosystem structure; consequently, these data have been a widely used input for ecosystem mapping. GEDI clearly demonstrated the need for space-based lidar data, and particularly the need for a mission providing global periodic data.

Space-based lidar instruments remain uncommon and for the most part only the GEDI instrument has been used for ecosystem mapping. Aircraft-based data are increasingly available and some countries have sponsored nationwide airborne lidar coverage, however, coverage remains limited and lidar tends to be expensive, particularly since periodic repeat coverages are needed for most applications.

3.2 Sensor Complementarity and Synergy

While the data from an individual sensor are undoubtedly useful when used alone, combining them with data from other types of sensors can take advantage of sensor complementarity. This is because different types of sensors measure different ecosystem properties (see Section 2.3 describing ecosystem structure, function, and composition). For example, lidar provides direct information on structure, whereas optical data, particularly hyperspectral, can provide information on composition and some functional traits, a contributing factor to many aspects of ecosystem function (Figure 3-1). Consequently, combining data from different types of sensors enables us to measure a wider array of ecosystem characteristics and potentially increase our ability to discriminate one ecosystem from another.

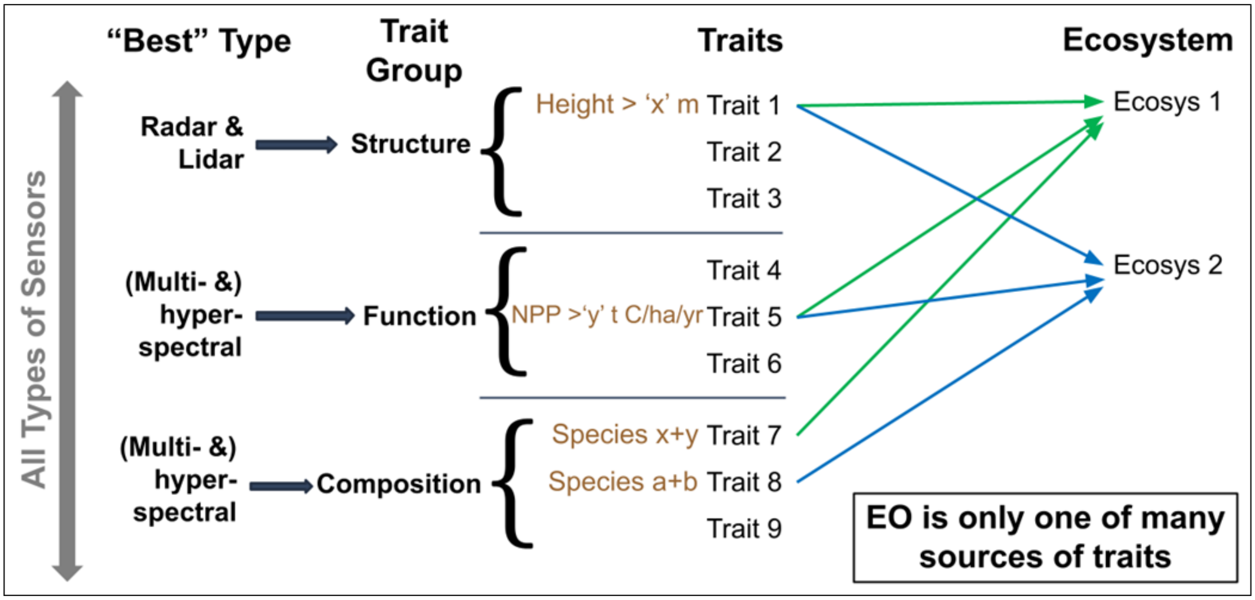


Figure 3-1. Different types of sensors measure different ecosystem characteristics, thus, combining them, such as in this very simple example, provides a more complete characterization of the ecosystem and enhances delineation capability. Here, NPP (Net Primary Productivity) is a characteristic common to both Ecosystem 1 and Ecosystem 2, but these ecosystems differ in their taxonomic composition, enabling discrimination.

3.3 Opportunities

As discussed above, global ecosystem maps are frequently created using multispectral datasets and conventional classification approaches, but both observational data and classification capabilities are evolving and creating opportunities for improved products. This section discusses some of the key opportunities. Here, we first review the new and forthcoming space-based sensors relevant to ecosystem classification and then some of the emerging classification approaches, such as artificial intelligence and the underlying technical capabilities that enable them. The synergism among these new, developing, and varied capabilities is enabling improved as well as new capabilities to monitor ecosystems and support the Global Biodiversity Framework.

3.3.1 New and Forthcoming Missions

Multispectral Missions

The Landsat Next mission, planned for launch in 2030, will ensure the continuity of the longest space-based record of Earth's land surface. It has been designed as a triplet set of satellites which will produce higher temporal resolution imagery (reduced revisit time) and higher spectral resolution (more bands). These enhancements should allow for improved characterization of ecosystems and changes in ecosystem extent.

Hyperspectral missions

These new missions will make hyperspectral data routinely available globally and set a new standard for optical sensors for Earth monitoring. In early 2024, NASA's PACE Mission is expected to launch. It will provide global hyperspectral data aimed at measuring Earth's aquatic, atmospheric and land properties and will offer UV to NIR and SWIR spectral and polarimetry data. ESA's CHIME is a Copernicus Sentinel Expansion mission and will consist of two satellites equipped with a visible to shortwave infrared (VSWIR) imaging spectrometer, with the first launch expected in 2028. SBG consists of two spacecraft, one with a hyperspectral VSWIR sensor (by NASA) and the other with an 8-band thermal sensor and a 2-band VNIR sensor (by ASI). Launch is planned for2029. Both CHIME and SBG will acquire images with 30m spatial resolution (60m for the thermal) and together have revisit times of several days. In the commercial realm, Planet Labs Tanager constellation will begin in 2024, providing about 400 5-nm bands from 400 - 2500 nm and a spatial resolution of 30 m.

Several sub-global hyperspectral missions are currently operating, including Prisma (ASI), DESIS (DLR), EnMAP (DLR) and EMIT (NASA); these missions will contribute to preparing for the integration of high dimensionality data into processing frameworks dedicated to ecosystem mapping and monitoring.

L-band SAR missions

ALOS-4 PALSAR-3 (JAXA), planned for launch in 2024, will continue the legacy of L-band SAR missions (JERS-1, ALOS, ALOS-2) operated by Japan for over three decades with particular focus on global forest- and wetland ecosystems. ALOS-4 will continue the historical long term global L-band data record with a capacity for global 6m observations. NISAR is planned to launch in 2024 and has both L-band (NASA) and S-band (ISRO) SAR instruments on board. The L-band data will have global coverage with a repeat cycle of 12 days; data will be made available at no cost. It has a planned mission lifetime of three years but is likely to be operated for longer. Developed by ESA, ROSE-L is a Copernicus Sentinel Expansion mission planned for launch in 2028 that will monitor land, oceans and ice and enhance imaging capabilities in areas of heavy vegetation coverage. The mission includes a constellation of two satellites, with a spatial resolution of 25 m when imaging on a regional scale, and a resolution of 50 m on a global scale. Together, these missions will greatly improve the global availability of frequent L-band data and thus help improve the characterisation of vegetation communities around the globe.

Thermal missions

Thermal missions use infrared sensors to measure land surface temperatures. This information, along with derived evapotranspiration, reflect key ecosystem processes and will help characterize and discriminate ecosystems. Trishna is being developed by CNES and ISRO and will launch in 2025, and LSTM is another Copernicus Sentinel Expansion mission planned for launch in 2029-2030. The US's NASA SBG will also include a thermal instrument, and is similarly expected to launch in late 2020s, currently set for 2028-2029. The three missions, LSTM, SBG and Trishna, collectively, aim to acquire daily global thermal imagery at 60 m spatial resolution. The Landsat Next mission aims to synergize with these missions in constellation as well.

NASA/CNES Surface Water and Ocean Topography (SWOT)
SWOT was launched in December 2022. A radar altimeter, it provides Near Real Time assessment of global Surface Water Extent and thus helps to delineate and monitor freshwater ecosystems including rivers, lakes, and wetlands.

Other forthcoming missions
ESA's Biomass mission will use a P-band SAR instrument to assess the global distribution of forest biomass by reducing the uncertainty in the carbon stock and fluxes associated with the terrestrial biosphere. ESA's FLEX mission will provide global maps of vegetation fluorescence, a direct measure of photosynthetic efficiency and an important indicator for vegetation functioning. Both Biomass and FLEX are Earth Explorer missions. JAXA's Multi-footprint Observation LIDAR and Imager (MOLI), now under development, is planned as an ISS-based lidar mission. Because these missions measure different types of ecosystem characteristics it is expected that they will be useful for ecosystem extent mapping.

To wrap up this section it is important to comment on mission and data continuity over time because space agencies have different mission categories with different goals and lifetimes. ESA's Sentinel missions and the NASA/U.S. Geological Survey Landsat Next Program are specifically designed for continuity into the foreseeable future. ESA's Explorer missions and many NASA missions are research-oriented or designed to demonstrate new technologies and may have a "design lifetime" of 3-5 years. However, the actual lifetime is typically much longer—MODIS, for example, had a design lifetime of six years but continues to provide data despite being launched more than two decades ago. The NASA ECOSTRESS mission had a planned lifetime of 1 year, however, now is planned to continue through 2029 and bridge the data gap for multispectral and thermal data. Even so, sustained continuity of the data stream is a common concern for users since they are understandably hesitant to expend resources developing an application that depends on data whose availability may be limited and end.

3.3.2 Emerging capabilities and opportunities

Use of hyperspectral data
Because of the dense information content of hyperspectral data there are perhaps two approaches for its use in creating ecosystem extent maps. One is to use the spectral data in a "traditional" approach for creating maps by training a model and then running the model to label the pixels in an image. This is not yet a mainstream activity in part because working with hyperspectral data is a technical specialty and in part because the availability of such data is not as widespread as, for example, Landsat or Sentinel-2.

Alternatively, as discussed in Section 3.1.2, hyperspectral data can be processed into variables that capture specific ecosystem characteristics, particularly in the composition and function areas[2]. These characteristics can then be used directly in a ML model, potentially with better results but also with insights into the ecosystems themselves. Such an approach can also identify which characteristics are most important to measure to generate quality maps. As CHIME and SBG come on line later in this decade they will greatly increase the availability of hyperspectral data and the ecosystem characteristics, particularly composition and function[3] that can be derived from it. Although their likely ~30 m pixel size will often result in "mixed pixels" (i.e., those that contain multiple species), work is exploring ways to unmix these pixels using spectral databases.

Combining data from different types of sensors

Despite the complementarity of sensors discussed above and how their measurements are associated with certain ecosystem characteristics (see Section 3.2 and Figure 3-1), ecosystem mapping approaches do not yet routinely combine data from complementary sensors. As a result, some types of characteristics are not used during classification despite their availability. Using a more complete range of the characteristics that EO can measure, in particular, SAR or lidar with optical, is likely to improve classification. This is particularly true for certain ecosystems, such as forests where vertical structure can be evaluated from space.

Time series analysis

Vegetation phenology--the seasonal timing of growth, senescence, and dormancy—provides insights into key characteristics that can be used to discriminate one ecosystem from another. Environmental changes over relatively short timespans can also be very important and are particularly relevant for wetlands since these may only be periodically flooded. However, the hidden value within time series has not yet been fully exploited. In part this is because processing long time series is a compute-intensive activity and only became practical in the last decade or so. But also, extracting signals from a time series so they can be used as characteristics for ecosystem mapping can be challenging and require specialized knowledge. Additionally, the frequency of available observations is not always adequate for a time series analysis, indicating another opportunity for space agencies. One approach is to improve consistency across sensor datasets to enable effectively longer time series such as has been done with the Harmonized Landsat-Sentinel-2 data.

Artificial intelligence and machine learning

Use of Artificial Intelligence techniques for ecosystem classification, such as to help combine data from different sensors, fill gaps where data are missing, and harmonize spectral signals between platforms is one of the most active emerging areas, and one with great potential for

[2] In a machine learning context this could be considered a form of "feature engineering"

[3] Note that the IUCN Global Ecosystem Typology includes function as one of its discriminating criteria

ecosystem extent mapping. One particularly interesting approach takes advantage of the increasing number and type of sensors in space that has led to multiple sensor acquisitions often being available for the same location and time. At the same time the amount, types, and availability of in situ data are also expanding. This provides a wonderful diversity of data but combining these sources to provide new and additional insights into ecosystems and their characteristics is complicated. However, AI techniques are now emerging that can help extract those insights by, for example, clarifying or enhancing characteristics that better discriminate ecosystems, thus leading to improved ecosystem maps. One offshoot of this emerging capability is to consolidate, improve and expand the time series' that historical satellite data currently provide. The result would be a longer, more complete, and higher quality "effective" time series that would improve information on seasonality (see above) as well as understanding of ecosystem change. One important challenge is to address the transferability of AI models from one area to another or to the same area but at a different time--by expanding the application of AI such transferability would expand the value and impact of EO data for ecosystem classification and biodiversity conservation more broadly.

Data cubes

The growing availability of different types of EO data offers great potential for advancing the mapping and monitoring of ecosystem extent. However, this also presents challenges for end users who need to query ecosystem attributes in comparable ways across diverse sensors, geographic regions, and temporal epochs. Data cubes are multidimensional data structures used for storing, organizing, analysing, and visualising data from a diversity of sources. They are gaining traction in the EO community because, along with Analysis Ready Data (ARD), they simplify accessing and utilizing the diversity of data now available (e.g., the Open Data Cube). Data cubes are well-suited for use on cloud-based systems and, in addition to providing a platform to generate products they also provide a playground for exploratory data analysis and can facilitate communication of results with the biodiversity community. Increasingly, there is a rise in the interactive nature of these outputs, and new visualization tools enable non-specialist users and decision makers to interact with terabytes of data through relatively simple web interfaces (e.g., see the Earth System Data Lab).

3.4 Challenges

Over the past five decades, remote sensing has contributed substantially to improved understanding of vegetation structure, function, composition, and dynamics, and as discussed above there are a number of opportunities for additional contributions. There are also challenges, and some of the most important ones for improving ecosystem mapping and monitoring are discussed here; many of these are interrelated.

Limited availability of value-added products

Ecosystem and land cover maps are most commonly created using surface reflectance products from instruments such as Landsat and Sentinel-2, as described earlier. However, such spectrally based ML approaches are conceptually removed from the biological and environmental characteristics of the ecosystems they classify. Direct use of ecosystem characteristics such as canopy height, vertical biomass profiles, various functional traits, and perhaps any of the Essential Biodiversity Variables (EBVs) or their derived products, is likely to improve classification accuracy[4] as well as enable improved understanding of the ecosystems and--significantly--which characteristics are most important to measure and monitor. However, these are nearly always derived, value-added products that may combine several data sources and are not generally or operationally available.

Operationally providing such value-added products can be challenging, however, an alternative approach is to provide software tools that can create the needed products rather than providing the products themselves. That is not without its own challenges--for example, different ecosystems may need somewhat different algorithms for the same product, and tools vary in the knowledge required to properly use them. In any case, tools for many important products, such as EBVs to use as feedstock for ML-based ecosystem classification, are not generally available, in part because their creation often requires close understanding of the underlying EO data. Where they do exist, they are often developed by space-agency-funded research.

Combining data from different types of sensors

As explained in Section 3.3.2, fusing data from different types of sensors is an important opportunity, however, it presents challenges including that each sensor type is associated with its own development and user community. For example, optical sensors are a very different technology than radar sensors and the “radar community” tends to be more engineering-focused than the community around multispectral sensors. As a result of these very different technologies and their associated communities, products that combine both types of data are relatively rare. Hyperspectral and lidar data also tend to have their own communities, with similar results. To address this, algorithm developers need to be motivated to actively look at ways to combine different types of sensor data, for example, by working with a partner having complementary expertise.

Furthermore, whilst inter-sensor community fusion is challenging, consideration must also be given to cross-compatibility of sensors within a particular community. Ensuring that higher level products (e.g., GBF indicators or fractional cover) derived from different sources are comparable across space and through time is fundamental to systematic ecosystem extent mapping. This applies both to compatibility between satellite programs (e.g., Landsat vs Sentinel-2), and within particular satellite programs (e.g. Landsat-8 vs Landsat-9, or Sentinel-2a

[4] As mentioned in 3.3.2, this can be considered a form of “feature engineering”

vs Sentinel-2b). Robust calibration of sensors and consistent/transparent processing of raw signals to ARD standards (commonly referred to as "cal/val") has always been critical for reliability and repeatability in EO science, but becomes even more important with the rapid expansion of different sensors in space, and with the increased footprint of the "New Space" industry. The US Joint Agency Commercial Imagery Evaluation (JACIE) consortium has been dedicated for more than 20 years to evaluating data quality and characteristics in 'new space' (https://www.usgs.gov/calval/past-jacie-workshops). Recently, the European Very-High resolution Radar and Optical Data Assessment (VH-RODA) has been created to also evaluate 'new space' systems (see: https://earth.esa.int/eogateway/events/vh-roda). Such activities aim to both evaluate EO data and educate users of the data.

EO data accessibility, usability and technical capacity of users

The rapid expansion of EO technology and the broad range of missions is resulting in a tremendous increase in the types and amounts of data available and, consequently, the potential to map and monitor ecosystem extent as well as other EBVs and indicators. At the same time EO is often considered to be a technical specialty outside the scope of many potential users who lack the technical expertise to utilize it. This lack of capacity is not limited to developing countries since, for example, "traditional" ecologists everywhere may not have the needed EO expertise. There are several facets to this challenge, including:

- Lack of basic technical knowledge relevant to EO
- Lack of products that provide the needed ecosystem information (e.g., EBVs)
- Inability to process available data into the needed products
- Unfamiliar data formats
- Finding and accessing the needed data
- Free and open data policies not universal

There are perhaps two basic, non-exclusive paths to addressing this challenge. One is to build capacity among users via training of various types. The other, which should be pursued in parallel, is to make the data easier to understand, use, and apply to the problem at hand (i.e., creating an ecosystem map). Analysis Ready Data (ARD) is helpful here, but providing user-friendly tools that make it easier to access, explore, process and visualize data would assist users who may not have access to, or perhaps a desire for, training. And as mentioned above, tools that generate products that are not otherwise available would fill an important gap. All such tools are particularly well-suited to cloud-based systems that enable co-location of friendly tools with the needed data. (The JACIE effort provides a mission search tool. Users can filter by data desired, data cost, availability, orbit and more.
https://calval.cr.usgs.gov/apps/compendium)

Ecosystem condition

Ecosystem extent and condition are both essential ecosystem properties that describe aspects of an ecosystem's state, and both are captured in indicators in the GBF Monitoring Framework.

While this white paper focuses on extent, ecosystem condition can complicate the delineation of ecosystems as well as the value of ecosystem extent as an indicator for the GBF Monitoring Framework. For example, at what point should a degraded ecosystem be classified as a different ecosystem? The answer depends on the purpose of the classification and cannot be answered here but it is important that this complication be recognized. What can be said is that as an ecosystem is degraded some of its characteristics will change and this will have implications for how it is classified. More broadly, from the standpoint of ensuring indicators are useful, an ecosystem extent indicator, by itself, may be insensitive to ongoing ecosystem degradation and thus may not properly represent actual ecosystem state. In any case, ecosystem condition is a key parameter, is closely related to ecosystem extent, and is also one for which EO is very important and would benefit from additional work.

Reference data for training and validation

As explained in Section 2.2 the most common approach to creating an ecosystem extent product is a machine learning-based supervised classification that must be trained using reference data. AI approaches such as deep learning also require training data. However, availability of high quality training data remains a common limiting factor for ecosystem extent product generation, for a variety of reasons. These reasons include the usually manual process to create it; access to remote sites if in situ data are used; limited data standards that, along with sometimes limited sharing of existing datasets, limit access and usability; and the non-static nature of ecosystems that results in training data going out of date.

To address these challenges a variety of approaches for training data collection have been developed, including crowd-sourcing and citizen science (e.g., NASA GLOBE; IIASA Crowdland; iNaturalist). These are now increasingly available as shared and open databases. Also, some automated processes have been developed but these are not widespread. If adequate training data are not available, an alternative is to use an unsupervised approach, which does not require training, however, the product quality tends to be lower, validation is challenging, and the resulting ecosystems may not reflect the ecosystems of interest to the end user.

Scale

Ecosystem properties vary with scale, and not all ecosystems need to, or should, be mapped at the same scale. This has implications for the EO data used and how they are utilized to generate maps of ecosystem extent. The spatial resolution of EO range from a few decimeters to a kilometer or more (see Appendix 2). At the same time, the size of the species dominating a target ecosystem varies considerably. A typical 10 m x 10 m image pixel may contain the canopy of a single tree in a forest ecosystem or a whole community of herbs and grasses with more than 100 different species in a grassland. Consequently, mapping ecosystems and their extent at a single spatial scale results in thematic inconsistencies and trade-offs. There are several ways to address this complication. One approach is to simply limit the range of ecosystems included in a study, while another is to identify a spatial resolution that is a practical compromise for a wide range of ecosystems. Nonetheless, for a comprehensive assessment of ecosystem extents, a multi-scale assessment is desirable. This can be enabled through the use of data cubes and perhaps AI (see Section 3.3.2) as these can facilitate multi-scale analyses.

4 Conclusions and Recommendations

This white paper began by providing background information on why ecosystem extent is an important element of biodiversity and why that matters to society. It then discussed two key users--the UN Convention on Biological Diversity's Global Biodiversity Framework—a key policy anchor with end users embedded in country/Party obligations, and the UN Statistical Division's Ecosystem Accounts that are part of the UN System of Environmental-Economic Accounting. Both of these entities have identified ecosystem extent as a key ecosystem characteristic that needs careful monitoring. Ecosystem extent is an important variable for a range of other Multilateral Environmental Agreements as well but these two are likely to be the organizations where initial CEOS activity should be focused. After summarizing some of the basic techniques currently used to classify ecosystems the role of various types of sensors in classification was discussed. Section 3, as the core of this white paper, then went on to explore a variety of opportunities for EO--and CEOS--to enhance the quality of ecosystem classifications. These opportunities include new and forthcoming sensors as well as a variety of advances in technology and the capabilities they have enabled. A range of challenges was then discussed, many of which can be addressed by the opportunities discussed earlier--if appropriate action is taken. The recommendations that follow below are intended to take advantage of some of the opportunities and to address some of the key challenges, but first, several additional points will be made.

If we step back and assess the overall status of observations relevant for ecosystem extent mapping--and biodiversity monitoring more generally--we see that current and planned missions provide most of the basic, space-based observations the biodiversity community needs. Although higher spatial and temporal resolution for these observations would provide significant benefits, with one important exception most of the basic observational needs are met. The exception is for global, periodically repeated lidar data; the value of space-based lidar observations for ecosystem extent mapping as well as overall biodiversity monitoring has been clearly demonstrated by the GEDI mission.

As discussed in Section 3.4 there is one other important gap, though it is not an observational one--instead, it is a gap in the availability of value-added products. Earth observations are a key input into many EBVs, indicators, and other products and are the primary input for ecosystem extent as well as other products. These derived, value-added products are needed by the biodiversity community not just for creating maps of ecosystem extent but more generally for monitoring and managing the living world. Even so, they are often not available, hampering progress as well as reporting on progress towards the GBF Goals and Targets. Indeed, a similar situation exists for UN SEEA's ecosystem accounts and for many Multilateral Environmental Agreements. The limited availability of value-added products is arguably the biggest barrier to greater use of EO by these communities and thus limits the value that society is extracting from EO. Technical capacity goes hand-in-hand with that barrier—if capacity was higher the lack of these derived products would be less of a barrier.

Here, a set of recommendations to improve ecosystem classification and the quality of ecosystem extent maps are proposed for CEOS to consider (Table 4-1). It is worth noting that during the course of the EETT's work and its focus on enhancing ecosystem classification and mapping, several other areas perhaps of future interest to CEOS emerged. This reflects the inter-connectivity of the many facets of biodiversity as well as the common challenges that countries face in effectively mapping and monitoring ecosystem extent.

The authors invite comments and welcome feedback on the recommendations that follow as well as the other topics discussed in this white paper.

Thematic Recommendation Area	Specific Recommendations
1. User Engagement Increase biodiversity community engagement with EO and CEOS through workshop(s) and other activities to improve ecosystem extent mapping. Key organizations: ● Convention on Biological Diversity ● UN System of Environmental Economic Accounting ● GEO Global Ecosystems Atlas initiative ● Ramsar Convention on Wetlands	1a. Identify specific user requirements and priorities for EO and related value-added products for ecosystem extent. 1b. Establish a sustainable communication channel between CEOS and user communities for continued interaction. 1c. Improve CEOS understanding of technological, socio-political, and cultural constraints for the biodiversity community to use EO data.
2. Technical advances Support development of technical advances to improve utilization of EO for ecosystem mapping.	2a. For each ecosystem class in IUCN's Global Ecosystems Typology (GET) and Ramsar's classification scheme, identify the key EO data sources and mapping approaches needed for its delineation. 2b. Facilitate combining data from different types of sensors to take advantage of their complementarity. 2c. Facilitate time series analysis and its application to ecosystem extent mapping. 2d. Explore ways to utilize EO to characterize ecosystem condition and its relationship to ecosystem extent.
3. Capacity Work to increase capacity of biodiversity users to utilize EO for ecosystem mapping and monitoring.	3. Identify opportunities for capacity development resources, e.g., a training or a Massive Open Online Course (MOOC) focused on the use of EO for ecosystem mapping and monitoring.

Table 4-1. Recommendations for consideration by CEOS.

Appendix 1: Pilot Study in Liberia

Mapping Ecosystem Extent using Earth Observations and Ecosystem Modeling Techniques: A Pilot Study in Liberia

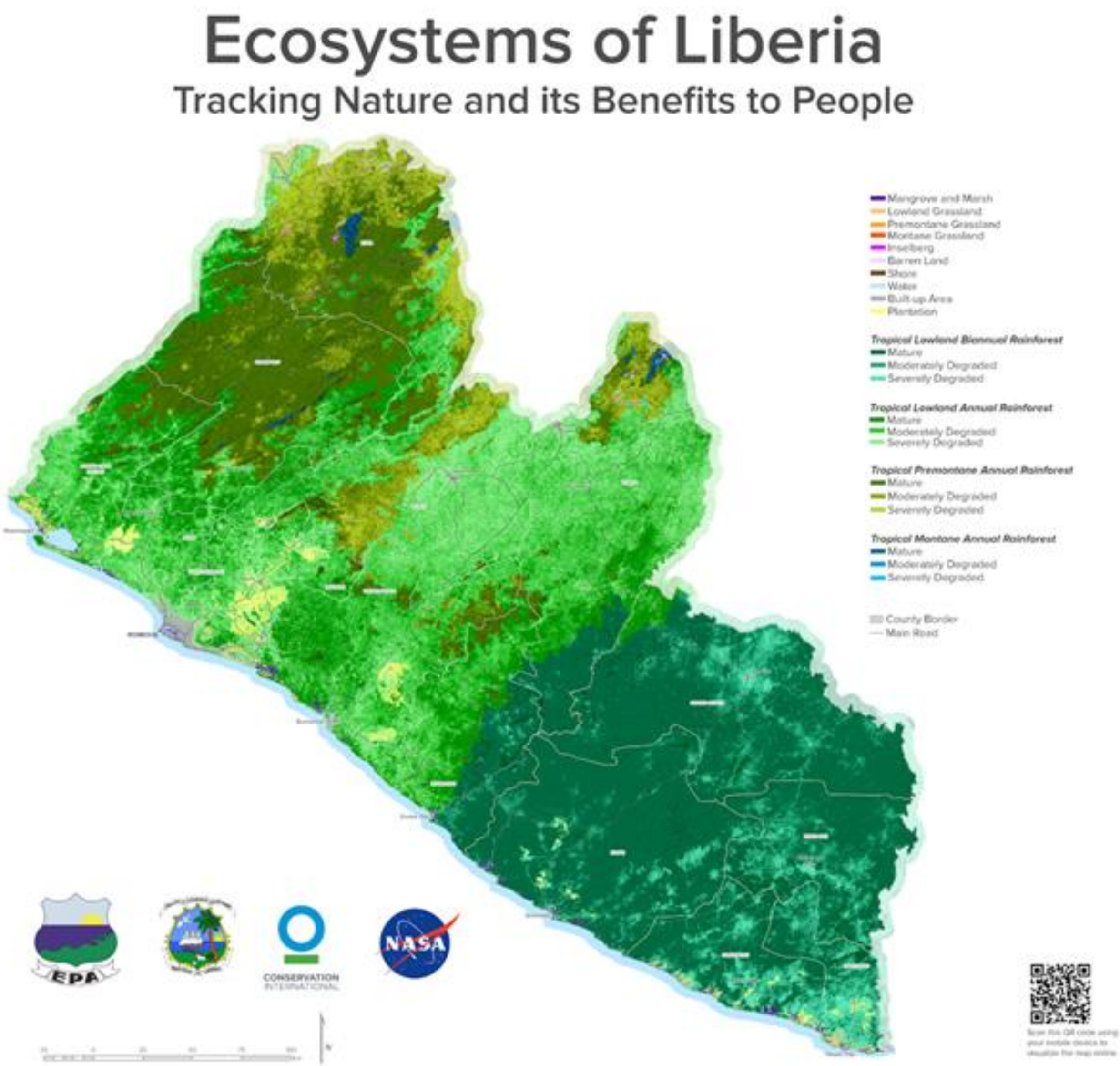
Many countries have been successfully using earth observation data to produce land cover/use maps, but have yet to produce ecosystem extent maps. To address this issue, NASA partnered with Conservation International (NASA 2018), to develop a powerful and easy-to-implement approach for deriving an ecosystem extent map suitable for implementation at national and sub-national scales. The method was successfully piloted in Liberia in collaboration with the Government of Liberia. The text below briefly describes the approach and shows the resulting map.

The approach, consisting of three steps, extends land cover mapping to ecosystem mapping using information derived from earth observations, available plant species distribution data and a set of environmental variables.

- Step 1: Earth observation data generated by NASA's fleet of Earth-observation satellites and Google Earth Engine (GEE) were used to map Liberia's land cover. Specifically, a binary classification approach was adopted where each land cover class was mapped individually using Landsat imagery and various auxiliary geographical information. The approach allowed for achievement of more than 85% accuracy for 10 land cover classes across Liberia (de Sousa et al. 2020).

- Step 2: Generalized Dissimilarity Modeling (GDM) (Ferrier et al. 2007) was used to model biotic dissimilarity of plant species using point occurrence plant species data obtained from the Botanical Information and Ecology Network (BIEN) global plant dataset (Enquist et al. 2016) and a set of environmental variables (e.g., soil type, bioclimatic, and topographic variables). The GDM approach is particularly effective for ecosystem classification, since it can differentiate ecosystem types that are often challenging to detect with earth observation data alone. In total, 57,452 observations for 4,166 unique plant species and 10 uncorrelated environmental variables were used as GDM inputs. The GDM outputs were classified into several broad plant biome types ranging from tropical lowland, premontane to montane biomes.

- Step 3: The two results were combined using a simple spatial overlay technique to produce the final map that shows the extent of 22 resulting ecosystem classes that were identified, with few exceptions, *a priori* by local experts (below is the resulting map for 2015). Based on this map, a time series of maps that shows annual changes in the extent of these ecosystems from 2000-2021 was also produced using the GEE-implemented LandTrendr change detection algorithm (Kennedy et al. 2018; de Sousa et al. 2023).



The approach offers a robust, easy-to-implement and repeatable methodology for ecosystem extent mapping at national and sub-national scales which is highly suitable for, e.g., ecosystem accounting following the System of Environmental Economic Accounting—Ecosystem Accounting standard (United Nations et al. 2021). In addition to Liberia, to test the method across the widest range of ecosystems possible, the approach was also successfully piloted in Gabon and Botswana. The partners concur that with slight modifications this methodology is likely to be replicable in other regions around the world. For more details about the approach contact Miroslav Honzák (mhonzak@asu.edu).

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Appendix 2: Characteristics of ecosystems commonly measured using Earth observations from space

Ecosystem Characteristic	Example Products	Typical Data Source	Monitoring Time Scale (temporal resolution)	Spatial Detail (m)	Example Citation
Land Cover	Land cover thematic classes	Optical Satellite data. Landsat / Sentinel-2 / MODIS / VIIRS Sentinel-3 / PROBA-V	Annual	100m; 30m 10m (from 2024) 300m (from 1992-2015) 100m (from 2015-2019)	Buchhorn et al., 2020; de Sousa et al. 2020; 2023 CCI Land Cover Copernicus Global Land Cover
Vegetation Height	Vegetation height	GEDI	One- off - Limited Monitoring capacity	1000m 50cm	Dubayah et al. 2020
Vegetation Cover	Canopy and vegetation cover	MODIS	Annual One- off - Limited Monitoring capacity	250m 1m	
Terrain Elevation, Slope, Aspect	DEM	ASTER / SRTM TanDEM-X ALOS World 3D	One Off	25 - 30m 50cm	Copernicus GLO-30
Leaf Area Index (LAI)	LAI	MODIS Sentinel-3 / PROBA-V GCOM-C/SGLI	Monthly every 5 days	250m 300m 1km	Myneni et al. 2015 Copernicus
Phenology Dynamics	Land surface phenology Vegetation indices	Landsat / Sentinel 2 and 3/ MODIS	Daily - 8 day	30 - 250m 300m	Huete and Justice, 1999. Copernicus

Snow Cover	Snow cover	Landsat / Sentinel 2/ MODIS	Daily - 8 day	30 - 250m	CCI Snow
Biomass	Biomass	GEDI ICESat2 ALOS-2 / Sentinel-1	One Off Annual series (2010, 2017, 2018, 2019, 2020)	1000m 100m 30m	Spawn et al. 2020 CCI Biomass
Chlorophyll	Chlorophyll content	MODIS GCOM-C/SGLI	8 day	250m	Xu et al. 2022
Leaf Traits (Nitrogen content, carotenoid content, etc)	Traits	Satellite or Airborne hyperspectral	Limited Monitoring capacity	3 - 30m	Dechant et al
fAPAR	fAPAR	MODIS Landsat Sentinel-3 GCOM-C/SGLI	8 day within 5 days	15 m to 500 m 300m	Zhu et al. 2013. Han Ma 2022. Copernicus
`Productivity	GPP, NPP	MODIS	8 day	500 m	Running and Zhao , 2019
Fluorescence	SIF	OCO-3 GOSAT/GOSAT-2	Limited	More than 1 km	Joiner et al. 2023
Deforestation and degradation	Deforestation extent/intensity	MODIS / Landsat; Sentinel-2	Annual	30 m to 250 m	Global Forest Watch
Wetland extent and change	Wetland inundation extent and duration	L-band SAR (ALOS-2, ALOS-4, NISAR)	Monthly or better	10-50 m	Rosenqvist et al. 2020. Chapman et al. 2015