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The role of space agencies in remotely sensed essential biodiversity variables

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Abstract

The Group on Earth Observations Biodiversity Observation Network (GEO BON) is developing the Essential Biodiversity Variables (EBVs) as the key variables needed, on a regular and global basis, to understand and monitor changes in the Earth's biodiversity. A subset of these EBVs can be derived from space-based remote sensing, within this paper referred to as remotely sensed EBVs (RS-EBVs). Given the global, periodic and standardized character of satellite remote sensing measures, RS-EBVs may be seen as easier to generate than non-remotely sensed EBVs, which have to be assembled from disparate and local sources of information. Particularly because they are global and periodic, RS-EBVs are of special relevance for monitoring the state of and changes to biodiversity, notably the structure and function of ecosystems. If well developed, RS-EBVs can provide key information for global biodiversity assessments as well as for national governments to meet their obligations under the Convention on Biological Diversity (CBD), in particular to formulate and implement appropriate management responses to biodiversity losses. However, the relevance and usage of globally produced RS-EBVs in wide-scale ecological modelling, such as in species distribution and abundance studies or in ecosystem integrity analyses, are still to be demonstrated, in particular when it comes to deriving biodiversity indicators for policy making and implementation. The biodiversity community at large, from those conducting scientific ecological studies to those involved in the development of remote sensing applications for biodiversity monitoring, can gain value from RS-EBVs, but doing so requires close cooperation with space agencies. Effective interaction is only likely to result if the biodiversity community understands how space agencies determine their observation and product requirements. To develop these requirements, space agencies need to precisely specify the physical measurements for their spaceflight instruments, as well as the algorithmic approaches, to generate RS-EBV products from these measurements. Here, we address the biodiversity community to discuss the role space agencies should play in the development of EBVs arising from satellite remote sensing. Importantly, we explain the necessity for translating the observational needs of the biodiversity community into specific satellite remote sensing measurement and algorithm requirements. By summarizing the prerequisite conditions that are required for obtaining a collective and strong engagement of space agencies in the co-development of RS-EBVs, we aim to facilitate collaborative efforts between the biodiversity community and the space agencies, which can ultimately contribute to a global and comprehensive biodiversity knowledge system.

Introduction

Satellite remote sensing supports the observation, understanding, monitoring and prediction of global change. The use of spaceborne remote sensing in global change studies has principally supported the observation and understanding of changes in the Earth's physical climate system, but technological and scientific advances have led to an increased ability of satellite sensors to characterize and monitor changes in other areas such as in biological systems (Turner et al. 2003; Horning et al. 2010; Pettorelli et al. 2014b).

Biodiversity has a relatively small but growing and important role in the activities of the world's space agencies. The increasing spatial, temporal and spectral resolutions of Earth Observation satellites have enhanced the ability of the remote sensing community to conduct biodiversity research in terrestrial, freshwater and marine environments, often addressing fundamental biogeographic questions about the distribution and abundance of species as well as the integrity of the ecosystems they inhabit (Rocchini et al. 2010; Pettorelli et al. 2014a; Rose et al. 2014). In doing so, satellite remote sensing has furthered our knowledge of the interconnections of biotic and abiotic phenomena, while simultaneously advancing our overall understanding of biological systems. For example, remote sensing is very useful in elucidating the larger scale environmental conditions that influence the distribution, abundance and interaction of species (Turner et al. 2003; Pettorelli et al. 2005; Elith and Leathwick 2009; Wegmann et al. 2014; Neumann et al. 2015; Jetz et al. 2016) and can contribute to the knowledge products needed to track progress towards the 2020 Aichi Biodiversity Targets of the Convention on Biological Diversity (CBD) and the 2030 Sustainable Development Goals of the United Nations (Secades et al. 2014; Brooks et al. 2015; O'Connor et al. 2015). This work requires combining biological and environmental information with ecological models. In situ and remotely sensed observations provide complementary information, which are both needed to improve the understanding of biological systems, to characterize the state of biodiversity and to assess how it is changing in space and time. Some biodiversity variables such as species population abundances are primarily collected through in situ sampling methods, while other important biodiversity parameters such as ecosystem extent and fragmentation are better retrieved from satellite observations. Work to date has demonstrated that the need for global coverage and periodic repeated measures make remote sensing a powerful tool, while still acknowledging that consistent monitoring and accurate assessment of the state of biodiversity is best based on a combination of field measurements and satellite observations.

Remote Sensing and EBVs, a Pathway to Global Monitoring of Biodiversity

Understanding what is changing and why requires the establishment of monitoring programmes that focus on the most important observations. Harmonizing and standardizing these observations greatly eases implementation and supports regional and global assessments. The Essential Biodiversity Variables (EBVs, Pereira et al. 2013) have been conceived by the Group on Earth Observations Biodiversity Observation Network (GEO BON) with these standardized monitoring needs in mind. The EBVs represent a relatively small and manageable set of variables for which monitoring is key to capturing the major dimensions of biodiversity change. The monitoring of a limited number of essential observations on the structural, functional and compositional aspects of biodiversity is seen as the most cost-effective and efficient framework to develop a global and consistent knowledge of the changing status of biodiversity. The EBV framework has been conceptually defined to streamline the monitoring of the state of biodiversity, as well as the condition of and trends in ecosystem services provided to society, through a small number of ecologically relevant, technically feasible and economically viable variables.

Essential biodiversity variables are analogous to the Essential Climate Variables (ECVs, Bojinski et al. 2014) developed under the Global Climate Observing System (GCOS) to provide the essential observations necessary to support climate research, assessment of climate change and the development of policy responses. The GCOS programme started in 1992 with the mandate to explore a more coordinated approach to observing the Earth's climate on a global scale. In 2003, GCOS launched the ECV concept to support long-term climate monitoring. Over the past decade, the ECV concept has led to a climate monitoring system that regularly provides key information to the climate community. This result is largely due to the contribution of space agencies, which collectively responded to GCOS's need for satellite observations to monitor the ECVs.

Similarly, EBVs are being advocated by GEO BON, which was founded in 2008 as the biodiversity component of GEOSS, the Global Earth Observation System of Systems established by the Group on Earth Observations (GEO) global partnership. GEO BON's mission is to improve the acquisition, coordination and delivery of biodiversity observations in support of better decision making. With this in mind, GEO BON promotes the development of interoperable biodiversity monitoring networks to enhance our understanding of the status of and trends in biodiversity, which in turn can contribute to effective policy and management decisions on the conservation of the world's ecosystems, the biodiversity they support, and the services they provide (Scholes et al. 2008). The EBV framework is a cornerstone of the GEO BON strategy to achieve a coordinated global biodiversity monitoring system.

Since their conceptual definition in 2013 (Pereira et al. 2013), EBVs have been based upon both remotely sensed observations that can be measured continuously and globally by satellites and field observations from local sampling schemes integrated into large-scale generalizations. The subset of EBVs that can be monitored from space has been referred to as remotely sensed EBVs (RS-EBVs, Skidmore et al. 2015; Pettorelli et al. 2016b; GEO BON, 2016). Although still under development, a number of RS-EBVs on ecosystem structure (such as ecosystem extent and fragmentation, or land cover types), on ecosystem function (such as net primary productivity, land surface phenology or disturbance regimes) and on community composition have been proposed as priority RS-EBV candidates.

It is important to note that virtually all biodiversity or ecologically relevant variables provided by remote sensing require the coincident collection of precise in situ measurements on a large number of well-instrumented sites in order to calibrate and validate the retrieval algorithms of these variables. The satellite measurements must first be transformed using algorithms (step-by-step methods) or models (e.g. radiative transfer models), and always require some calibration and validation with ground-based measurements. Once the algorithms are fully calibrated and validated, remote sensing can provide global datasets on a regular and periodic basis. However, the use of satellite remote sensing in biodiversity monitoring presents a number of challenges that need to be adequately addressed. Although they provide global coverage at much higher densities than attainable with in situ observations, many satellite instruments do not provide continual global coverage due to limitations of their on-board platforms (e.g. restricted power supply for active systems, limited data storage capacities, narrow fields of view). Moreover, the availability of systematic global observations does not imply that these satellite measurements are available with the necessary spatial and temporal resolutions that allow one to adequately capture, at the correct scales, the variability in the ecosystems' structural components and processes. Remote sensing captures most biodiversity-relevant variables by proxy rather than directly. The remote sensing observations often need to be assimilated into ecological models in order to derive useful information for biodiversity understanding, management and policy. The retrievals of surface variables from satellite remote sensing observations are not error-free, as is the case with any observing system. The uncertainties of the satellite observations must be precisely estimated in order to assess their impact on the accuracy of the biodiversity and ecosystem service indicators they are to inform. These technological challenges must be addressed with adequate rigorous engineering approaches that start with well-defined and unambiguous RS-EBV observation requirements.

The biodiversity community has not yet precisely articulated their needs to the space agencies in order to exploit the full potential of satellite observations. The development of high-quality and reliable RS-EBVs require a precise definition of their observation requirements (e.g. temporal frequency, spatial resolution, thematic accuracy) that can then be translated by the space agencies into measurement specifications for the satellite instruments, and into algorithm specifications on how the satellite measurements are to be processed. GEO BON has started to broadly engage the biodiversity community in order to collectively prioritize the EBVs and define their observational requirements. For RS-EBVs, this requires building a close relationship with space agencies. RS-EBVs will become a reality only if the biodiversity community and space agencies unite in defining and developing the satellite observations and processing algorithms needed for continuous monitoring and production of useful information.

The Emergence of Long-Term Continuity in Satellite Missions for Biodiversity Monitoring

The importance of satellite observations for biodiversity monitoring was underscored in a recent review of the adequacy of Earth Observation approaches to monitor progress towards the 2020 Aichi Biodiversity Targets of the Convention on Biological Diversity (Secades et al. 2014). The review identified a number of obstacles that hinder greater use of satellite data in biodiversity monitoring such as restrictive data access policies, insufficient time series to capture the temporal dynamics of ecosystems at appropriate temporal and spatial scales, or uncertainties on the long-term availability of satellite observations. Although more in-depth and scientifically sound studies are needed to elaborate the use of satellite remote sensing for the production of biodiversity indicators tracking progress towards the Biodiversity Targets, the review rightfully highlighted the importance of an agreed set of minimum observation requirements and common standards from the biodiversity community to better orient and focus the contribution of the space agencies. The EBV framework (and in particular the RS-EBV subset) provides a mechanism to connect the primary remote sensing observations to high-level biodiversity and ecosystem service indicators, which ultimately should inform the scenario analyses done by biodiversity assessment bodies such as the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), and serve the development and implementation of policy instruments by the CBD (Pettorelli et al. 2016a).

During the last decade, with the political and financial support of their governments, space agencies have addressed many obstacles impeding the widespread use of satellite observations in environmental monitoring. In 2008, the US Geological Survey (USGS) made all current and past Landsat imagery available at no cost through online ordering, thus providing free access to four decades of remote sensing observations. This change to the Landsat data policy dramatically increased the use of remote sensing data by the biodiversity community (Wulder and Coops 2014), and stimulated the development of innovative research advances and novel monitoring methods such as the production of the first high-resolution global maps of forest cover change (Hansen et al. 2013). The European Copernicus initiative and its Sentinel satellites, jointly implemented by the European Commission and the European Space Agency (ESA), are also making the next decades of satellite data freely and openly available to the world, with a long-term continuity of observations. Thus, a wide array of American and European spacecraft, complemented by satellites launched by other countries, now offer an unprecedented ensemble of satellite observations with long-term continuity and a free and open data access policy, which are key for biodiversity applications. These changes enable the biodiversity community to invest more heavily in the use of remote sensing and consequently increase incentives for space agencies to engage in the development of RS-EBVs.

This new era of free and open access to global government-funded satellite data, along with assurances of continuity, permit the biodiversity and remote sensing communities to make significant progress in the regular monitoring of biodiversity from satellite observations (Turner et al. 2015). The implementation of a well-defined RS-EBV framework, like the ECV process before it, is now needed to extract the full value inherent in remote sensing data for biodiversity monitoring. RS-EBVs can serve as a bridge between the needs for essential observations from the biodiversity community and the necessity of space agencies to forecast their own activities with a coordinated set of priority requirements for global satellite monitoring.

Translating Biodiversity Observation Needs into Satellite Measurement Requirements

Space agencies are primarily engineering organizations seeking to support basic and applied scientific research. Their core business is the development of satellite missions, which involves specifying and building satellite instruments and platforms, launching them, and operating them on orbit. This requires substantial engineering and physical science expertise and an overarching emphasis on completing tasks on schedule and within budget. In keeping with this emphasis, space agencies are focused on defining the absolute requirements for a particular satellite mission, which is the minimum set of criteria that a space mission must meet to be successful and achieve its goals.

Engaging in this process requires the biodiversity community to understand the language of space agencies. To successfully communicate its observation needs, the biodiversity community must work closely with the space agencies to translate these needs into satellite measurement requirements and downstream satellite-derived products. Instrument requirements include the spatial, spectral, temporal and radiometric resolutions of the space instruments, while mission requirements include the orbit of the spacecraft carrying the instrument(s) and systems to ensure that data collected by the instrument reaches Earth in a secure and timely manner. Successful collaborations can be achieved only if the biodiversity science community works closely with the mission scientists and engineers of the space agencies. Mission scientists are responsible for ensuring that a mission fulfils its scientific objectives while mission engineers develop the satellite platform and its instrumentation. The RS-EBV satellite observational needs can be translated into requirements meaningful to space agencies through Science to Mission Requirements Traceability Matrices, which are coordinated by the mission scientists. These traceability matrices begin with the scientific objectives and work through measurement requirements to arrive at instrument and mission requirements (Table 1).

Space Agencies' Role in RS-EBV Development

Space agencies have, as part of their mission, the mandate to promote space-based research as well as to develop satellite applications. The emergence of ensured observation continuity by spaceborne missions such as the Sentinels or the Landsat series has allowed the opening of a new domain of activities in the Earth Observation programmes of the space agencies. Continuity of observations over the long term has promoted an increasing attention by the space agencies and by the remote sensing community to advance the development of sustainable satellite applications for societal benefit. This enhanced applications emphasis has been facilitated by the emergence of collaborative community efforts, like the intergovernmental Group on Earth Observations (GEO), that promote

Table 1. One of the ‘Science to Mission Requirements Traceability Matrices’ used to develop the concept for a NASA HyspIRI mission. HyspIRI stands for Hyperspectral Infrared Imager and is a potential NASA mission that will study the world’s ecosystems and also provide critical information on natural hazards. The mission will include two instruments mounted on a satellite in Low Earth Orbit: an imaging spectrometer measuring from the visible to short wave infrared (VSWIR: 380–2500 nm) in 10 nm contiguous bands and a multispectral imager measuring from 3 to 12 um in the mid and thermal infrared (TIR). The table provides the traceability between science objectives and instrument and mission requirements related to Ecosystem Function and Diversity.

Science objectives	Measurement objectives	Measurement requirements	Instrument requirements	Other requirements
Ecosystem Function and Diversity				
Detect changes in the regional and global extent of terrestrial plant functional types and aquatic phytoplankton functional types	*Terrestrial:* Dominant terrestrial plant functional type fractions: e.g. tree, shrub, herbaceous, cryptogam Thick/thin leaves broad/needle leaves Deciduous/evergreen Nitrogen fixer/non-fixer; C3/C4 physiology *Aquatic:* (a) Dominant aquatic functional types: e.g. phytoplankton (diatoms, dinoflagellates, coccolithophores, N-fixers), kelp, seagrass, mangroves, *Spartina*, etc. (b) Aquatic constituents (phytoplankton, sediment, CDOM, benthos)	Plant functional type fraction uncertainty: ±10% Annual products of ≤ monthly Observations Sampling 100,000 m^2 patches Regionally important plant functional types 380–2500 nm reflectance, High dynamic range (dark aquatic targets near bright surfaces) Global coverage: Full spatial resolution for shallow water <50 m deep and coarse resolution (~1 km) imagery for deeper water	Imaging spectrometer signal to noise ratio (SNR): 600 = visible to near infrared (VNIR) and 300 = shortwave infrared (SWIR) (zenith angle=23.5°, 25% reflectance) >95% absolute radiometric calibration >98% on-orbit relative reflectance ≤60 m pixels SNR: violet/blue/green: 400:1, yellow/orange/red: 300:1 wavelength >900 nm: >100:1 14-bit digitization >99.5% radiometric calibration relative stability Rapid (<2 pixel) bright target recovery (no significant ringing)	Surface reflectance for solar zenith angles ≤70° Monthly lunar calibration manoeuvres Design for daily solar calibration ~840 Mbps raw data rate Regional algorithm development Terra-like sun-synchronous repeat-track low Earth orbit Local equatorial crossing time 10:30 AM to 11:30 AM Reversible high resolution data calibration High throughput on-board processing for spatial aggregation of open ocean data.
Detect changes in spatial extent of certain diagnostic species	Diagnostic species/taxa *Terrestrial:* pine, juniper, larch, Cecropia *Aquatic:* seagrass, live coral, Trichodesmium, diatoms, dinoflagellates	Regional coverage with annual products	>95% cross-track uniformity and spectral uniformity	Data corrected for atmosphere and observed geometry
Detect changes in global extent of ecosystems	Refined ecosystem types: *Terrestrial:* grasslands, shrublands, broadleaf evergreen forests, needleleaf evergreen woodlands, etc. *Aquatic:* a) shallow/clear water: tropical coral reefs, macroalgal beds, sediments b) shallow/turbid: estuaries, river plumes, harmful and benign algal blooms c) lakes	Classification accuracy ≥90% Annual products of ≤ monthly observations	High-fidelity imaging spectrometer: 0.38–2.5 micrometers ≤10 nm resolution >99% linearity (2 to 98% saturation) Polarization sensitivity <2% No significant cross-talk between bands, stray light or ghosting (<0.2% ocean top of atmosphere)	Landsat-like sun synchronous repeat-track orbit Local equatorial crossing time 10:00 AM to 11:00 AM Rigorous calibration/validation programme Pointing strategy to avoid sunglint pattern and hot spot

access to better coordinated, comprehensive and sustained Earth observation data and information for the benefit of society. In turn, GEO has also helped align space agency applications programmes to the observation needs of its member communities.

Since space agencies are predominantly engineering agencies, it is primarily their research and development programmes that support the development of new satellite applications, thereby responding to both scientific and societal objectives. Consequently, the main role space agencies can play to support community efforts to establish operational monitoring programmes is through engineering activities such as the detailed specification of RS-EBV data products, the development of the associated retrieval algorithms, and the demonstration of the scientific and technological readiness of the RS-EBV measurement techniques. The Scientific Readiness Level (SRL) of research addresses the critical assessment of the level of scientific maturity and associated risk to achieve the scientific objectives of the RS-EBVs. The Technological Readiness Level (TRL) of production systems includes the critical assessment of the adequacy of the retrieval algorithms and processing systems for future wide-scale production of the RS-EBVs.

The space agencies can benefit from scientific networks that address the knowledge gaps in biodiversity monitoring. The Future Earth core projects and their activities, such as the cluster on “Global Biodiversity Monitoring, Prediction and Reporting” are some of the key scientific networks that the space agencies should liaise with, especially when it comes to bringing together the biodiversity, remote sensing and modeling communities to jointly conduct research activities.

The Committee on Earth Observation Satellites, the Collaborative Platform for Space Agencies to Engage in RS-EBV Development

Space agencies have agency-specific approaches to setting requirements, different mechanisms for receiving funding for their programmes, and varied priorities for mission and applications development. Consequently, achieving an integrated response across space agencies to developing RS-EBVs is challenging, even with a clear articulation of remote sensing needs. Nonetheless, there is a mechanism to achieve collective engagement across space agencies: the Committee on Earth Observation Satellites (CEOS).

CEOS is the main coordination body for civilian space agencies engaged in remote sensing. It is the mechanism by which space agencies share information, coordinate activities and set priorities. Its principal mandate is to optimize the collective benefits of satellite remote sensing by coordinating the planning and tasking of satellite missions, by establishing best practices for product development and validation, and by developing compatible data products, applications and policies. CEOS is also the focal point for international user communities to interact with civilian space agencies – and this is where the role of CEOS is essential for RS-EBV development. CEOS has a close relationship with GEO and acts as its space-based remote sensing arm, with a particular relevance to its global monitoring programmes. In 2006, CEOS responded to the GCOS implementation plan at the request of the United Nations Framework Convention on Climate Change (UNFCCC) and provided a collective response from the space agencies to the systematic observation requirements for satellite-based products for climate (GCOS, 2004, 2006; CEOS, 2006). That said, while CEOS is key for coordinating the work of numerous space agencies, ultimately each organization has its own programmes and sets its own priorities. So, engaging with CEOS for RS-EBVs would still need to be followed up by individual decisions of key CEOS member agencies regarding the orientation of their Earth Observation programmes towards RS-EBV development. Nonetheless, CEOS is the entry point for presenting the remote sensing needs of the biodiversity community to the space agencies as a whole.

Biodiversity already has a presence in CEOS through its activity on Remote Sensing for Biodiversity and Conservation, which includes biodiversity researchers and conservation practitioners that use remote sensing. The aim of this group is to identify remote sensing needs and shortcomings for biodiversity and conservation, to improve coordination between the space-based remote sensing and biodiversity communities, and facilitate access to remote sensing data and software for biodiversity and conservation activities. Another CEOS group with an important role in the engineering of the RS-EBVs is the CEOS Working Group on Calibration and Validation (WGCV) and its Land Product Validation (LPV) subgroup. Their mandate is to develop best practice approaches to satellite-derived product development and validation, such as the ‘Validation Good Practices for the Global Leaf Area Index Product’ by Fernandes et al. (2014). While the CEOS biodiversity activity is key to engage and convene the remote sensing experts in biodiversity to review the satellite observation requirements for RS-EBVs, the CEOS WGCV and its LPV subgroup have a vital role to play for ensuring the development of high-quality RS-EBV data products.

GEO BON, the Importance of a Collective Voice

GEO BON, in its leadership role of facilitating the development of EBVs, is the key organization that can channel the satellite observation requirements for remotely sensed EBVs from the biodiversity community to the space agencies. The overall process envisioned is depicted in Fig. 1. Having a unique body such as GEO BON that communicates on behalf of the whole biodiversity community makes the work of space agencies much easier. Rather than having a complex dialogue with hundreds of different biodiversity and conservation actors, GEO BON can provide, with the RS-EBVs, a coordinated set of satellite

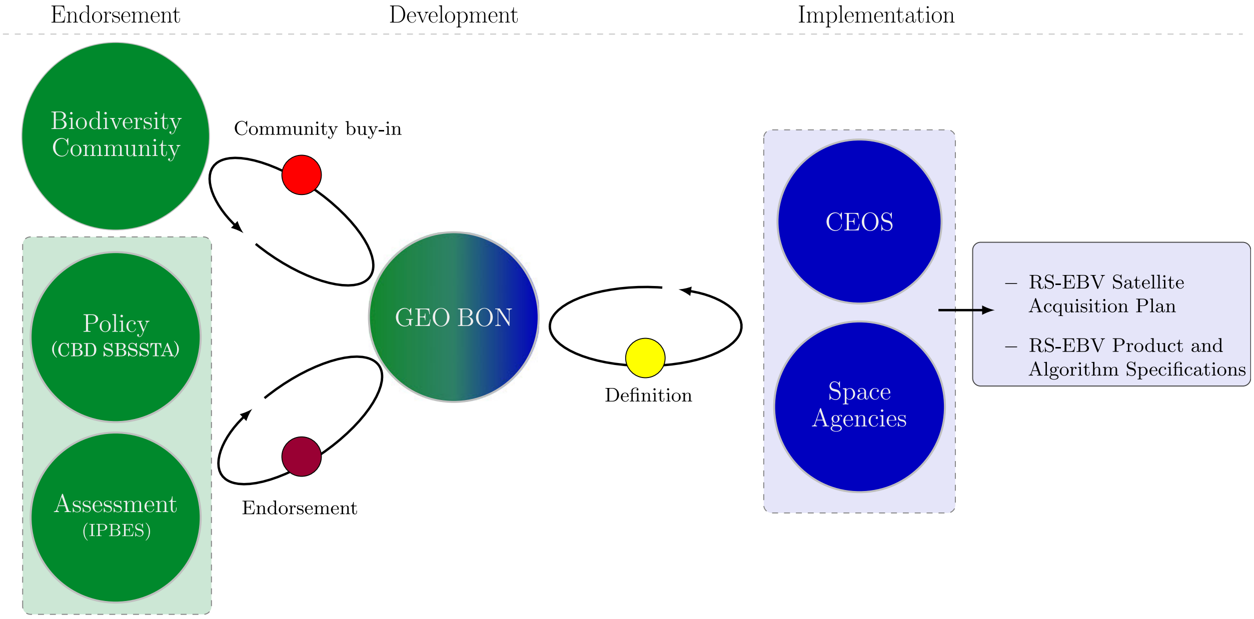

Figure 1. Outline of the overall process by which remotely sensed Essential Biodiversity Variables should be developed and matured.

observation needs to space agencies. This is similar to the mechanism that the climate community uses with the Global Climate Observing System (GCOS) to promote the development of ECVs.

GEO BON must ensure community recognition of all EBVs much like GCOS accomplished with ECVs. For RS-EBVs, this implies that GEO BON must not only engage the biodiversity and remote sensing communities openly and widely in the RS-EBV development, but also seek RS-EBV endorsement by a recognized institution. That endorsement is key to the engagement of space agencies. The best placed authority for that endorsement is the CBD Subsidiary Body on Scientific, Technical and Technological Advice (SBSTTA). Its mandate is to provide scientific and technical evaluation of CBD's implementation and to advise on scientific programmes and international cooperation in research and development. By recognizing the importance of EBVs – including the RS-EBVs subset – the CBD SBSTTA should request GEO BON to coordinate and space agencies to support the development of remotely sensed EBVs for an effective global biodiversity observing system. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) is another important authority that has a vital role to play in RS-EBV endorsement. IPBES needs global observations for its scientific assessments of the state of biodiversity and has the mandate to prioritize information for policy decisions and catalyze efforts to collect the necessary observations to generate new knowledge.

Endorsement of EBVs – including RS-EBVs – by the CBD SBSTTA, as well as an expression of their usefulness from IPBES, will provide strong justification for space agency engagement in RS-EBV development and should lead to increased allocation of resources for this effort by space agencies (individually and through CEOS).

Challenges and the Road Ahead

In order to gain the full support of the space agencies, including the space agencies that have not been involved in the initial EBV conceptual activities, the biodiversity community and remote sensing experts must together complete the list of RS-EBVs and especially their prioritization and the assessment of their scientific and technological readiness.

GEO BON is well suited to lead the community engagement and EBV endorsement, as well as to supervise the technical development of EBVs (including the subset of RS-EBVs). Effectively communicating with CEOS will require discipline within the biodiversity community to speak with a united voice about the satellite observation requirements for RS-EBVs. A united voice is only possible once the list of RS-EBVs achieves broad acceptance. So, obtaining community buy-in is a key first step. One way to solidify RS-EBV acceptance is through expert workshops followed by open and transparent review processes, where the biodiversity community can refine, prioritize and vet the list of RS-EBVs, clearly justifying the importance of each variable for biodiversity policy and management purposes. Therefore, the community will need, during this prioritization process, to carefully consider how each RS-EBV will be used in practical cases, such as in global and regional biodiversity assessments, or in National Biodiversity Strategies and Action Plans (NBSAPs). This would demonstrate how RS-EBVs are valuable for monitoring biodiversity status and change, and ultimately for providing societal benefits.

Next, the community must detail the observational requirements for each RS-EBV through a requirements traceability framework. Broad community buy-in through open reviews is essential throughout this process since it underpins the strength of the requirement for space agencies to address the associated observation needs. In parallel, GEO BON should seek official endorsement of the EBV framework (including the RS-EBVs subset) by an authority such as the CBD SBSTTA.

Once the list of RS-EBVs is refined, prioritized and reviewed by an open consultation process, endorsed by an authority such as the CBD, and the corresponding satellite observation requirements are well specified, then the conditions will be met to fully engage CEOS and the space agencies in RS-EBV development towards dedicated programmatic instruments and financial commitments. However, space agencies should play a role in the initial and conceptual phase of RS-EBV development by using their existing funded research and development programmes to support RS-EBV refinement, specification and demonstration.

This is an excellent time to significantly advance the monitoring of biodiversity by space agencies. With the emergence of satellite missions with ensured observational continuity and free and open data policies, space agencies will provide, over the long term, a unique means to monitor, understand, and predict the status of and trends in biodiversity. This capability is matched by rising awareness within space agencies of the importance of biodiversity research, coupled with a growing remote sensing biodiversity research and applications community that can synthesize and articulate the satellite observation requirements in a way that resonates with space agencies. Thus, all of the key pieces are in place for implementing RS-EBVs and advancing the monitoring of biodiversity by space agencies. What remains is to knit these pieces together and move forward with the RS-EBV refinement, development and implementation.

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Conflict of Interest

None declared.

References

Bojinski, S., M. Verstraete, T. C. Peterson, C. Richter, A. Simmons, and M. Zemp. 2014. The concept of Essential Climate Variables in support of climate research, applications, and policy. *Bull. Am. Meteorol. Soc.* **95**, 1431–1443.

Brooks, T. M., S. H. M. Butchart, N. A. Cox, M. Heath, C. Hilton-Taylor, M. Hoffmann, et al. 2015. Harnessing biodiversity and conservation knowledge products to track the Aichi Targets and Sustainable Development Goals. *Biodiversity* **16**, 157–174. doi:10.1080/14888386.2015.1075903.

CEOS 2006. Satellite Observation of the Climate System: The Committee on Earth Observation Satellites (CEOS) Response to the Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC, October 2006.

Elith, J., and J. R. Leathwick. 2009. Species distribution models: ecological explanation and prediction across space and time. *Annu. Rev. Ecol. Evol. Syst.* **40**, 677–697.

Fernandes, R., S. Plummer, J. Nightingale, F. Baret, F Camacho, H. Fag, et al. 2014. Global leaf area index product, validation good practices, Version 2.0. Pp. 76 *in* G. Schaepman-Strub, M. Román, J. Nickeson, eds. *Best practice for satellite-derived land product validation*. Land Product Validation Subgroup (WGCV/CEOS), doi:10.5067/doc/ceoswgcv/lpv/lai.002

GCOS 2004. Implementation Plan for the Global Observing System for Climate in support of the UNFCCC, GCOS-92 (WMO/TD No.1219).

GCOS 2006. Systematic Observation Requirements for Satellite-based Products for Climate: Supplemental details to the satellite-based component of the Implementation Plan for the Global Observing System for Climate in support of the UNFCCC, GCOS-107 (WMO/TD No.1338).

GEO BON 2016. Remote Sensing of Essential Biodiversity Variables, information document of the CBD Subsidiary Body on Implementation (SBI-01), UNEP/CBD/SBI/1/INF/49.

Hansen, M. C., P. V. Potapov, R. Moore, M. Hancher, S. A. Turubanova, A. Tyukavina, et al. 2013. High-resolution global maps of 21st-century forest cover change. *Science* **342**, 850–853.

Horning, N., J. A. Robinson, E. J. Sterling, W. Turner, S. Spector 2010. *Techniques in Ecology & Conservation*. Pp.1–467. Oxford University Press, UK. ISBN: 978-0-19-921994-0 (hc); 978-0-19-921995-7 (pb).

Jetz, W., J. Cavender-Bares, R. Pavlick, D. Schimel, F. W. Davis, G. P. Asner, et al. 2016. Monitoring plant functional diversity from space. *Nature Plants* **2**, 16024. doi:10.1038/NPLANTS.2016.24.

Neumann, W., S. Martinuzzi, A. B. Estes, A. M. Pidgeon, H. Dettki, G. Ericsson, et al. 2015. Opportunities for the application of advanced remotely-sensed data in ecological studies of terrestrial animal movement. *Movement Ecology* **3**, 8.

O'Connor, B., C. Secades, J. Penner, R. Sonnenschein, A. Skidmore, N. D. Burgess, et al. 2015. Earth observation as a tool for tracking progress towards the Aichi Biodiversity Targets. *Remote Sens. Ecol. Conserv.* **1**, 19–28.

Pereira, H. M., S. Ferrier, M. Walters, G. N. Geller, R. H. G. Jongman, R. J. Scholes, et al. 2013. Essential biodiversity variables. *Science* **339**, 277–278.

Pettorelli, N., J. O. Vik, A. Mysterud, J. M. Gaillard, C. J. Tucker, and N. C. Stenseth. 2005. Using the satellite-derived NDVI to assess ecological responses to environmental change, Trends Ecol. *Evol.* **20**, 503–510. doi:10.1016/j.tree.2005.05.011.

Pettorelli, N., W. F. Laurance, T. G. O'Brien, M. Wegmann, H. Nagendra, and W. Turner. 2014a. Satellite remote sensing for applied ecologists: opportunities and challenges. *J. Appl. Ecol.* **51**, 839–848.

Pettorelli, N., K. Safi, and W. Turner. 2014b. Satellite remote sensing, biodiversity research and conservation of the future. *Phil. Trans. R. Soc. B* **369**, 20130190. doi:10.1098/rstb.2013.0190.

Pettorelli, N., H. J. F. Owen, and C. Duncan. 2016a. How do we want Satellite Remote Sensing to support biodiversity conservation globally. *Methods Ecol. Evol.* **7**, 656–665. doi:10.1111/2041-210X.1254.

Pettorelli, N., M. Wegmann, A. Skidmore, S. Mücher, et al. 2016b. Framing the concept of satellite remote sensing essential biodiversity variables: challenges and future directions. *Remote Sens. Ecol. Conserv.*, **2**, 122–131.

Rocchini, D., N. Balkenhol, G. A. Carter, G. M. Foodye, T. W. Gillespie, K. S. He, et al. 2010. Remotely sensed spectral heterogeneity as a proxy of species diversity: recent advances and open challenges. *Ecol. Inform.* **5**, 318–329.

Rose, R. A., D. Byler, J. R. Eastman, E. Fleishman, G. Geller, S. Goetz, et al. 2014. Ten ways remote sensing can contribute to conservation. *Conserv. Biol.*, **29**, 350–359.

Scholes, R. J., G. M. Mace, W. Turner, G. N. Geller, N. Jürgens, A. Larigauderie, et al. 2008. Toward a Global Biodiversity Observing System. *Science* **321**, 1044–1045.

Secades, C., B. O'Connor, C. Brown, and M. Walpole. 2014. Earth Observation for Biodiversity Monitoring: a Review of Current Approaches and Future Opportunities for Tracking Progress Towards the Aichi Biodiversity Targets. *Secretariat of the Conv. Biolog. Divers.* CBD Technical Series No **72**, 1–188.

Skidmore, A. K., N. Pettorelli, N. C. Coops, G. N. Geller, M. Hansen, R. Lucas, et al. 2015. Agree on biodiversity metrics to track from space. *Nature* **523**, 403–405.

Turner, W., S. Spector, N. Gardiner, M. Fladeland, E. Sterling, and M. Steininger. 2003. Remote sensing for biodiversity science and conservation. *Trends Ecol. Evol.* **18**, 306–314.

Turner, W., C. Rondinini, N. Pettorelli, B. Mora, A. K. Leidner, Z. Szantoi, et al. 2015. Free and open-access satellite data are key to biodiversity conservation. *Biol. Conserv.* **182**, 173–176. doi:10.1016/j.biocon.2014.11.048.

Wegmann, M., L. Santini, B. Leutner, K. Safi, D. Rocchini, M. Bevanda, et al. 2014. Role of African protected areas in maintaining connectivity for large mammals. *Philos. Trans. R. Soc. Lond. B: Biol. Sci.* **369**, 20130193.

Wulder, M. A., and N. C. Coops. 2014. Make Earth observations open access. *Nature* **513**, 30–31. doi:10.1038/513030a.