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Monitoring global changes in biodiversity and climate essential as ecological crisis intensifies

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ABSTRACT

The Intergovernmental Panel on Climate Change and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services have presented unequivocal evidence for human induced climate change and biodiversity decline. Transformative societal change is required in response. However, while the Global Observing System for Climate has coordinated climate observations for these assessments, there has been no equivalent actor for the biodiversity assessment. Here we argue that a central agency for coordinated biodiversity observations can lead to an improved assessment process for biodiversity status and coupled climate - biodiversity observations in areas of mutual interest such as monitoring indicators of Nature's Contributions to People. A global biodiversity observation system has already begun to evolve through bottom up development of the Essential Biodiversity Variables. We propose recommendations on how to build on this progress through definition of user requirements, observation principles, creation of a community data basis and regional actions through existing networks.

Climate change is accelerating biodiversity loss at an alarming rate (IPBES, 2019), altering the distribution of life on Earth itself (Burrows et al., 2014). Global transformative change is urgently required to tackle this existential crisis. The global assessments of the

Intergovernmental Panel on Climate Change (IPCC) and the Intergovernmental Science-

Policy Platform on Biodiversity and Ecosystem Services (IPBES) have recognised the dependencies and interactions between biodiversity loss and climate change, not least in the biosphere's role in regulating climate extremes. Both the IPCC and IPBES have called for urgent and dramatic societal action to reduce the human ecological footprint and decarbonisation of the global economy (IPBES, 2019; IPCC, 2018).

The political response has been to set climate and biodiversity targets that must be achieved if the worst impacts are to be avoided, e.g. the 2 °C target set by the 2016 Paris Agreement and the 2020 Aichi Biodiversity Targets, respectively. However, we have largely failed to meet the Aichi Targets (Tittensor et al., 2014), while all evidence suggests that the targets set out by the 2016 Paris Agreement to limit global temperature rise this century will also be challenging to meet (IPCC, 2018). It is now more important than ever to set robust climate and biodiversity targets, and to be able to monitor progress towards these targets effectively. Satellite Earth Observation (EO) can be a key tool in this endeavour because of its global coverage, rapid assessment capability and systematic observation capacity. As this perspective piece illustrates, there is as yet unrealised potential for joint EO-based observing systems to monitor biodiversity and climate change synergistically - not least through shared space-borne monitoring assets and existing in situ networks. In order to realise this potential, the biodiversity community must catch up with their climate counterparts and define what, where and when to observe from space. Only then can priorities be communicated clearly to policy makers.

This perspective is timely as biodiversity policy makers will meet next year to create new targets at the 2020 UN Conference on Biodiversity as part of a new deal for nature, while other climate policies and plans (Nationally Determined Contributions, National Adaptation Plans) offer good opportunities for integrating EO-based targets and exploring the potential for shared observing strategies.

1. Essential biodiversity and climate variables – current status

In 2013, Pereira et al. proposed a global observation system based

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on the concept of Essential Biodiversity Variables (EBVs) "by defining a minimum set of essential measurements to capture major dimensions of biodiversity change, complementary to one another and to other environmental change observation initiatives" (Pereira et al., 2013). This was partly inspired by the Essential Climate Variables (ECVs) concept (Bojinski et al., 2014), implemented through the Global Climate Observing System (GCOS). The EBVs occupy a theoretical space between primary biodiversity observations and indicators. An indicator can be a simple measure, such as a count of individuals of a species present, or the percentage coverage of forest, in an area. It can equally be a complex, composite index, combining different data to tell a story about a particular issue, e.g. as the IUCN Red List indicates species extinction rates based on population size data on, rate of decline, and area of distribution. The defining feature of an indicator, as opposed to a 'measure' or 'metric', is that the information has been interpreted. The International Bureau of Weights and Measures (BIPM, 2010) define an indicator as 'a measure, based on verifiable data that conveys information about more than just itself'. The EBV concept was therefore envisioned to forge a clearer path from primary observation to indicator by introducing global standards as to how biodiversity should be monitored and to lay the foundation for a global biodiversity observing system. The development of EBVs from a concept to practical use has seen slow but incremental progress to date, e.g. as seen by interim outputs on species populations (Jetz et al., 2019) and species traits (Kissling et al., 2018a, 2018b). There is great potential for satellite remote sensing as a monitoring tool for some of the EBVs, especially in relation to addressing progress towards the 2020 Aichi Targets (O'Connor et al., 2015).

While the ECVs were initially a good model for the development of a set of EBVs, their operationalisation has not progressed at a comparable pace, not least because of the fundamental differences in how knowledge is generated and assessed by their assessment bodies - the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and the Intergovernmental Panel on Climate Change (IPCC) (Brooks et al., 2014). While acknowledging there is a stark contrast between the predominantly physical science basis for climate assessment and the varied sources of knowledge generation for biodiversity assessment, which includes indigenous knowledge, this paper outlines that there are interdependences and interactions between these bodies of knowledge and that these can be captured most succinctly in coupled EBV and ECV strategies. Furthermore, it aims to draw on the lessons learned by the climate community in their successful development of ECVs, to inject some momentum towards the quest for operational EBVs. For completeness we also allude to the wider family of essential variables where other observation systems have started to develop around sets of core variables, for instance the Essential Ocean Variables (EOVs) (Miloslavich et al., 2018; UNESCO, 2012). A detailed overview of the use of these variables for sustainable development can be found in Reyers et al. (2017).

There are currently 21 candidate EBVs (GEO BON, 2017), 54 ECVs (GCOS, 2016) and 31 proposed EOVs (Global Ocean Observing System, 2018). A key-word search for publications across a range of online, bibliographic databases, up to and including 2019, referring to EBVs, ECVs and EOVs, shows their different publication trajectory (see Fig. 1). Since Pereira et al. (2013), 90 peer-reviewed journal articles mentioning EBVs have been published, compared to 238 using the ECV concept since 2008. By contrast, the EOV concept has been mentioned in only 38 publications since 2011. Interestingly, the EBV concept was first described in a peer-reviewed, journal article (Pereira et al., 2013) and not as an institutional publication as was the case for ECVs (GCOS, 2003) and for EOVs (UNESCO, 2012). The first peer-reviewed publications mentioning ECVs (Govaerts et al., 2008) and EOVs (Bahamon et al., 2011) came after, or were contemporary with, their respective institutional publications. Nevertheless, the ECV concept is relatively young compared to the decades to century-scale that climate datasets

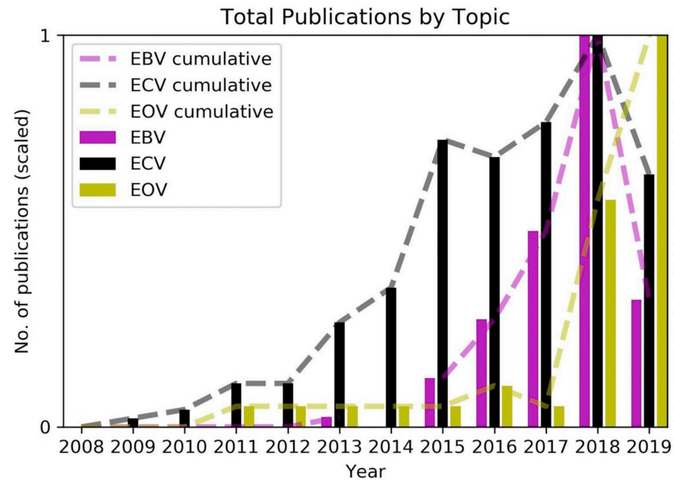

Fig. 1. The publication trajectories of the EBV, ECV and EOV concepts as illustrated by the scaled total of journal articles found in the peer viewed literature where "essential biodiversity variables", "essential climate variables" or "essential ocean variables" were mentioned in any field and for all years. Source: Web of Knowledge, as of 27th September 2019

have been recorded and used in climate science. The United Nations Framework Convention on Climate Change (UNFCCC) recognised the importance of standardised and systematic climate observations in the late 1990s and acknowledged the role of GCOS in developing, assessing and reviewing the ECVs. Although no equivalent of GCOS has been established for biodiversity, the Convention on Biodiversity Diversity (CBD) Conference of the Parties (COP) in 2012 invited GEO BON, an informal body composed of biodiversity experts supported by the Group on Earth Observations (GEO), to continue its work on the identification of Essential Biodiversity Variables and the development of associated data sets (Decision XI/3, CBD, 2012). GEO BON has been established mainly based on work by Scholes et al. (2008). There are 6 GEO BON working groups, following the EBV definitions, composed of international experts working on developing the EBVs from genetic composition to ecosystem structure (GEO BON, 2019).

By 2019, the number of EBV publications had steadily increased at a comparable rate to EOVs, even if there have been more ECV and fewer EOV papers respectively (Fig. 1). This steady uptake of the EBV concept, as reflected in the peer reviewed literature reflects an increasing interest in and demand for standardisation of biodiversity observations which is mirrored in the ocean and climate communities.

In the following sections, we discuss the interdependencies, the interactions and in some cases the coupling of the EBV and ECV concepts across 10 topics. The current lists of ECVs and EBVs are listed in Table 1. GEO BON has issued a preliminary candidate EBV list which has been used for this comparative exercise (GEO BON, 2017). The currently accepted ECVs are listed in GCOS (2016).

2. Areas of convergence and divergence for climate and biodiversity monitoring

With this comparison, we review the development of the EBVs from a new, synergistic perspective. This assessment, along lines of evidence for convergence and divergence of both concepts, might help to stimulate inter-community dialogue and discussion for both defining new EBVs and operationalising existing ones while opening up new applications in the EBV and ECV domains, not least in coupled climate-biodiversity models. In examining these lines of evidence, the differences between measurement of a biodiversity and a climate variable emerge, but so too do areas for complementarity (see Box 1).

Table 1
Current EBVs (candidates) and ECVs (GCOS-2016).

Domain (ECV)	GCOS essential climate variables
Atmospheric	Surface: Air temperature, Wind speed and direction, Water vapour, Pressure, Precipitation, Surface radiation budget
	Upper-Air: Temperature, Wind speed and direction, Water vapour, Cloud properties, Earth radiation budget, Lightning
	Composition: Carbon Dioxide (CO2), Methane (CH4), Other long-lived greenhouse gases (GHGs), Ozone, Aerosol, Precursors for aerosol and ozone.
Oceanic	Physics: Temperature: Sea surface and Subsurface, Salinity: Sea Surface and Subsurface, Currents, Surface Currents, Sea Level, Sea State, Sea Ice, Ocean Surface Stress, Ocean Surface heat Flux
	Biogeochemistry: Inorganic Carbon, Oxygen, Nutrients, Transient Tracers, Nitrous Oxide (N2O), Ocean Colour
	Biology/ecosystems: Plankton, Marine habitat properties
Terrestrial	Hydrology: River discharge, Groundwater, Lakes, Soil Moisture
	Cryosphere: Snow, Glaciers, Ice sheets and Ice shelves, Permafrost
	Biosphere: Albedo, Land cover, Fraction of absorbed photosynthetically active radiation, Leaf area index, Above-ground biomass, Soil carbon, Fire, Land Surface Temperature
	Human use of natural resources: Water use, GHG fluxes
Class (EBV)	GEO BON Essential Biodiversity Variables (candidates)
Genetic Composition	Co-ancestry, Allelic diversity, Population genetic differentiation, Breed and variety diversity
Species populations	Phenology, Natal dispersal distance, Body mass, Migratory behaviour, Demographic traits, Physiological traits
Community composition	Species richness, Species interactions
Ecosystem function	Net primary productivity, Secondary productivity, Nutrient retention, Disturbance regime
Ecosystem structure	Habitat structure, Ecosystem extent and fragmentation, Ecosystem composition by functional type

2.1. ECVs are partitioned by physical realm, EBVs are grouped according to biological organization

ECVs are partitioned by the physical realms of the Earth system: “atmosphere”, “land” and “ocean”. In contrast EBVs are organised along different levels of biological organization: genes, species, populations, and ecosystems. While this is conceptually useful, there are aspects of diversity which overlap between these categories, e.g. plant

Box 1
Synergies between ECVs and EBVs for tracking nature's contributions to people.

Nature's contributions to people (NCP), embodying both the intrinsic value of nature and the services rendered by nature to humanity (Díaz et al., 2018), are in serious decline (IPBES, 2019). The assessments that have led to this conclusion have centred on knowledge of biodiversity, human culture but also climate. Therefore, NCPs are dependent on interactions between climate and the living world. To illustrate how NCPs can be the nexus of ECV and EBV collaboration, we have taken four of the NCP indicators, used by IPBES, and identified ECVs and candidate EBVs which have potential to inform those indicators in future assessments (Table 2).

Table 2 lists potential examples of input variables to NCPs – land cover, Above-Ground Biomass (AGB), Leaf Area Index (LAI) and Fire:

- Land cover is a central component of habitat and therefore to track habitat creation and maintenance.
- AGB has a demonstrable relationship with regulation of climate, as biomass is positively correlated with higher carbon but also higher species richness, especially in tropical forests (Strassburg et al., 2010).
- LAI is major structural component of vegetation and therefore a determinant of habitat suitability for a range of pollinators in an agricultural context.
- Wild fires shapes terrestrial ecosystems while human induced fires increasingly threaten them (Pausas and Keeley, 2009)

We have mapped the most relevant candidate EBV to each NCP indicator. Arguably there are missing variables in the list, e.g. to calculate the indicator “Extent of natural habitat in agricultural areas” in addition to the EBV “habitat structure” and LAI, such as vertical structural elements - height of tree canopy and number of leaf strata. Similarly net primary productivity requires respiration rates in addition to AGB. Nevertheless, coupling EBVs and ECVs in this way can highlight potential opportunities for downstream indicators of relevance for policy making.

Table 2 Essential variables that can benefit both scientific communities, framed in terms of nature's contributions to people.

Nature's Contribution to People	Current indicator	Input Variable	Description	ECV	EBV (candidate)
Habitat creation and maintenance	Extent of suitable habitat; Biodiversity intactness	Land cover	Biophysical Earth surface cover which can support habitat	✓	Ecosystem extent and fragmentation
Regulation of climate	Prevented emissions and uptake of greenhouse gases by ecosystems	Above Ground Biomass	Quantity of terrestrial organic matter for carbon uptake and storage	✓	Net primary productivity
Pollination and dispersal of seeds and other propagules	Pollinator diversity; Extent of natural habitat in agricultural areas	Leaf Area Index	Leaf canopy density and distribution to identify natural from agricultural vegetation	✓	Habitat structure
Regulation of hazards and extreme events	Ability of ecosystems to absorb and buffer hazards	Fire	The ability of ecosystems to absorb fire determines their resilience	✓	Disturbance regime (an indirect measure of the impact of fire)

However, there are currently no shared variables among EBVs and ECVs, in contrast to 14 common EOVs and ECVs, as illustrated in Fig. 2. Yet within the EBVs themselves there are dimensions of biological organization, as illustrated, for example, when five of the 22 candidate EBVs are projected along five dimensions, or “states” of biological diversity – genetic, phylogenetic, species, functional and ecosystem diversity (Fig. 3). This illustration of a theoretical EBV “feature space” derives from the authors' estimation of the theoretical position of the 5 selected EBVs along the “state” or “target” dimension of biological diversity. The extent of overlap illustrates not only semantic issues in EBV definitions but could lead to issues of data redundancy when observing them in practice.

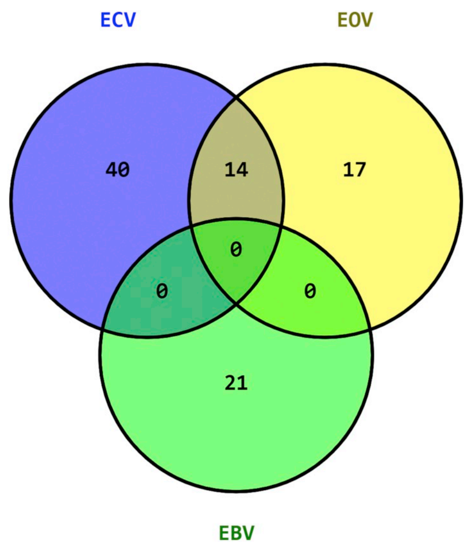

Fig. 2. Actual overlap in EBV, EOV and ECV as they are currently defined – more coordinated effort is needed to find common variables between biodiversity, ocean and climate, as has been done between the climate and ocean community, as 14 ECVs are also EOVs.

species traits like phenology will also serve a function (productivity), provide a structure (flower or leaf) and can respond to genetic diversity within the same species (Doi et al., 2010; Yamasaki et al., 2017). In addition, in the context of satellite remote sensing, the term 'land surface phenology' is generally used (Garonna et al., 2018).Therefore, phenology could be observed from a functional, structural or genetic perspective, at least for plant species. It is important to disaggregate these dependencies between the EBV classes, both from a methodological and scientific viewpoint even if from an ontological point of view, the categorisation is logical. The physical partition of ECVs along Earth's major realms provides clearer boundary conditions for the ECV domains yet even those boundaries can be blurred: GCOS considers closing the carbon budget, energy balance and water cycle as major targets which require observations and estimates of fluxes across physical domains; it also has accepted heat flux over the oceans as an ECV (GCOS, 2016). There are also interdependences between the ECV and EBVs in coupled Earth System models – aspects of ecosystem function have been shown to both be dependent on and alter atmospheric composition, e.g. through gaseous exchange in net primary productivity of plants (Smith et al., 2019).

2.2. ECVs and EBVs are both intended for multi-scale assessments of change, however datasets are compiled differently

ECVs were developed to provide the empirical evidence needed to understand and predict the evolution of climate, to guide mitigation and adaption measures, to assess risks and enable attribution of climate events to underlying causes, and to underpin climate services (WMO, 2018). They are multi-purpose but are designed to evaluate the climate system from a global point of view where the requirements are most firmly defined, even if ECV datasets can underpin regional or local climate analysis. In contrast, biodiversity observations tend to be locally representative, suggesting that aggregation of multiple local observations at regional and global scales, combined with modelling, is needed to achieve EBV datasets with global coverage, as has been proposed for a global EBV dataset on species populations (Jetz et al., 2019). This difference in approaches reflects the original user demand. The IPCC recognised the need to simulate future global climate change scenarios based on socioeconomic pathways from the early 1990's. ECVs evolved with the demand for global climate models to inform the IPCC assessments. The history of global biodiversity modelling is younger and global models of biodiversity status and changes are still in their infancy (Kim et al., 2018). Pettorelli et al. (2016) suggested that the users of EBVs could be scientists working to understand changes in biodiversity on behalf of the CBD and IPBES. However, more clarification is needed on who the users are – a starting point to define their requirements.

2.3. ECVs constitute physical, chemical or biological variables that encompass some EBVs yet areas for combined use remain unexplored

There should be much to gain from coupled - or at least coordinated - biodiversity-climate monitoring yet to date there has been little combined efforts to link the observational needs of both communities (see Box 1 for suggested synergies). This might be due to their level of maturity - the ECVs have a longer history and are therefore more mature both in terms of time series records and technical implementation but could be driven by lack of formalised and mandated knowledge exchange structures. Nevertheless, some of the current ECVs (see Table 1) are important for biodiversity research and assessment of biosphere change, such as Leaf area index (LAI), fraction of absorbed photosynthetically active radiation (FAPAR), land-cover, biomass (Turner et al., 2003) or ECVs describing ocean life such as plankton, nutrients and ocean colour (GCOS, 2016). Indeed, the EBVs should be ecosystem agnostic and therefore describe all biodiversity whether in the terrestrial, marine or freshwater realms. Currently, land use change, attributed to agriculture, is one of the main drivers of biodiversity changes (Maxwell et al., 2016), while, the contribution of land use change to the global carbon budget and thus global climate change remains significant (Le Quéré et al., 2018). The complex interaction between biodiversity, land use and climate change is therefore just one area of research where EBV-ECV integration could benefit. As stated in the most recent GCOS Implementation Plan (GCOS, 2016): "Climate observations are also useful for the United Nations Convention to Combat Desertification (UNCCD), the Convention on Biological Diversity (CBD), other Multilateral Environmental Agreements (MEA), Agenda 2030 and its [Sustainable Development Goals] SDGs". Perhaps the lack of integration of ECVs into biodiversity monitoring schemes to date has stemmed from the EBV definition as a "biological" state variable which excludes physio-chemical variables that can contribute to explaining differences in biodiversity distributions. However, ECVs are already observed in-situ in international networks with an ecological focus, such as FLUXNET (Lawrence Berkeley National Laboratory, U, 2019) and the International Long Term Ecological Research Network (ILTER). There are also many observations of ecosystems, physical properties and fluxes which influence climate undertaken in these networks of terrestrial monitoring sites (Schimel et al., 2019).

2.4. ECVs describe distinct, physical states; EBVs include state, process and proxy variables

An ECV is a physical, chemical or biological variable or a group of linked variables that critically contributes to the characterization of Earth's climate (WMO, 2018). They are characterised by physical properties that are measurable, also known as observables. For instance, the physical properties of the atmosphere and ocean can be described by fluid dynamics, e.g. the Navier–Stokes equations for viscous flow(Salby, 1996). These properties have typical correlation lengths and analytical relationships which allow the measurement to be approximated within acceptable bounds of uncertainty, e.g. to fill gaps in fields of measurement such as of surface air pressure. On the terrestrial side, land and vegetation dynamics can to some extent be approximated analytically; but real vegetation dynamics is governed by individual (species) and collective (ecosystem) dynamics which complicate such analytical relationships and requires broader knowledge of species interactions (Smith et al., 2002). Furthermore, uncertainty and bias in biological field records compound the issue of accuracy, e.g. in

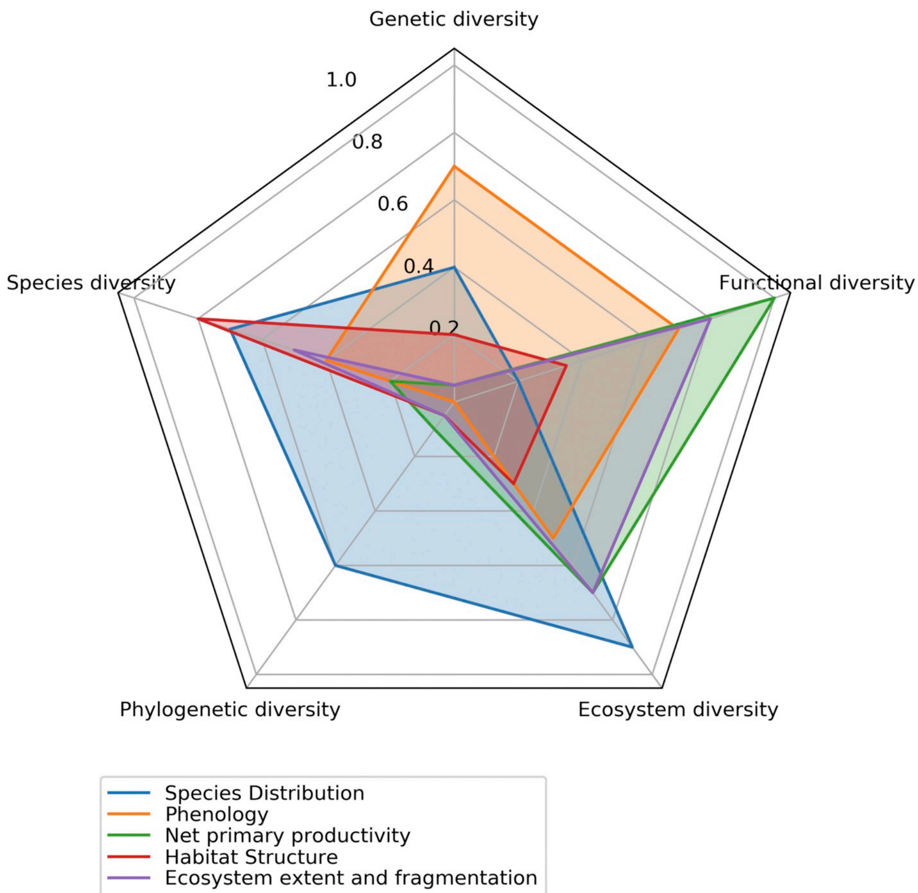

Fig. 3. A theoretical EBV multidimensional feature space. Spokes of the plot represent key dimensions of biological diversity scaled from 0 to 1. Five example EBVs are plotted on the feature space using estimated values of the EBV (between 0 and 1) on each dimension. There are considerable overlaps in the resulting feature space, suggesting that there will be redundancy when observing them in practice.

over or under estimating species occurrences (Rocchini et al., 2017). Although there are a very large number of non-biological variables that can cause changes in biodiversity such as precipitation or surface temperature changes, biodiversity should be described in terms of evolution along different lines of biological organization: genes, species, populations, and ecosystems. These different elements do not scale linearly with each other, neither in space nor time, e.g. there will not be the same amount of genetic material, species and population per unit area of ecosystem in the boreal, compared to the tropical zone, nor can the rate of change of genetic or species diversity per unit area of forest be yet approximated accurately through physical, analytical relationships since so many unknowns are at play, e.g. physical ecosystem disturbances. However, with further research the correct analytical measure may be found for biodiversity.

2.5. ECVs are described as simple or compound variables, while EBVs may be multidimensional

The set of ECVs are defined in a manner that they can be measured in unambiguous terms. For instance, sea surface temperature is a relatively simple, absolute, unambiguous measurement (measurement method not withstanding) while for compound variables such as glaciers and ice caps, changes in glacier length, area, volume, and mass are the key, single variables that constitute the parent ECV (Bojinski et al., 2014). The EBVs and in particular the EBV classes mostly have a "living" dimension and are described as multidimensional complexes, not as simple variables, with the exception of species richness (number of species per unit area) or net primary productivity (mass per unit area per unit time interval). On the other hand, the EBV candidate phenology would for instance describe a time-dependent process consisting of phenological events per year and one single event cannot be isolated without tracking the time-dependent process. Genetic diversity is similarly a complex of many different measurable quantities but is neither bounded nor constrained by what can be measured along one dimension of change e.g. genetic diversity of a population versus that of an individual.

2.6. ECVs have established measuring methods, EBVs lack measurement standards

ECVs were based on a long history of climate records, for instance, through meteorological observations underpinned by standardised monitoring protocols maintained by the World Meteorological Organization (WMO). With the ECV-initiative these efforts were intensified and expanded to many other observation systems outside classical meteorology. The ECV concept is founded on three elements (Bojinski et al., 2014): (i) quantitative user requirements for observations (measurand, resolution in time and space, uncertainty etc.), (ii) observing principles and standards, and (iii) guidelines for dataset generation. These are recognised and maintained by the climate community for most ECVs. Currently candidate EBVs are not founded on such a pathway from requirement to observation to dataset generation. However, measurement and metadata standards do exist, especially for species distribution and abundance data (e.g. Simple Darwin Core, Darwin Core 'event' and Humboldt Core). Nevertheless, there are broader standards for all ecological data such as the Ecological Metadata Language (EML) which describes a dataset's spatial, temporal and taxonomic coverage (Kissling et al., 2018a, 2018b). Adopting such a standard would make EBV datasets "discoverable" and open up the possibility of global EBV dataset inventories which must be the starting point for a coordinated observing system. The status quo – of amassing biodiversity observations without being able to access them centrally or via a distributed network, using a common protocol and standard, risks an uncoordinated use of such observations. The climate community adopted a standardised Climate Data Record (CDR) definition for each ECV which should be stable and include a characterization of uncertainty (statistical, systematic, etc.). Collaboration of the climate community with the metrology community, guided internationally by the BIPM (BIPM, 2019), has helped establish standards for ensuring traceability of measurements, and for describing and calculating uncertainty in CDRs (BIPM, 2010). CDRs are used in modelling, attribution, projection, prediction, trend assessment, and data assimilation. Validation of the ECV data sets and assessment of different datasets describing the same ECV with the corresponding scientific users is a core element of ECV development and operationalisation in order to understand uncertainties in climate predictions. EBVs have not yet an equivalent standard for the CDR aside from the stated need for the "primary observations" to supply the EBVs, however since its inception in 1993 the International Long-term Ecological Research Network (ILTER) could play such a role. The primary role of ILTER to elucidate the mechanism of response of ecosystem structure, function, and services in response to a wide range of environmental forcing using long-term, place-based research. Space agencies also have a role to play in providing long-term, continuous observations of relevance to EBVs as outlined by Skidmore et al. (2015).

2.7. The selection of ECVs is grounded in user needs, primarily climate modellers, while EBVs have been selected based on expert knowledge

The concept of 'Essential Climate Variables' was introduced in the 2003 Second Adequacy Report to the UNFCCC (GCOS, 2003), in order to ensure that the needs of the UNFCCC and the IPCC for systematic climate observations were addressed. Furthermore, it was stressed that these variables should be global in coverage and of sufficient quality for climate analyses while being feasible (i.e., measurement methods are mature and datasets exist) and cost effective. In contrast the conception and definition of EBVs was through an initial expert workshop, organised in 2012 by GEO BON, as a response to the lack of coordination and interoperability between biodiversity measures such as those mentioned above (point 6). The purpose of said workshop was to provide guidance on key observations of biodiversity change that can be efficiently monitored. The concept has subsequently been progressed through the peer reviewed literature, and while a strategy document has been issued (GEO BON, 2017), there has been no definitive list of EBVs which allows a coordinated response, e.g. from civilian space agencies via the Committee on Earth Observation Satellites (CEOS). The driver of such a coordinated effort should come from the CBD Subsidiary Body on Scientific, Technical and Technological Advice (SBSTTA), IPBES and other science-policy platforms, policy frameworks and action plans so that the development of EBVs can be thoroughly justified for use at the science-policy interface.

2.8. Space-based observations play a role in ECV and EBV data continuity

The necessity for monitoring on a global scale implies a regular and cost efficient observing system yet we argue that resources should be focused (initially) on biodiversity hotspot areas (Myers et al., 2000) with a view to scaling up later, e.g. as has been done with the Hot Spot Land Cover Change Explorer of the Copernicus Global Land Service (Copernicus Global Land Service, 2019). Satellite remote sensing has already been shown to identify regional cluster of high vegetation productivity which can be linked to hotspots of species richness, at least for amphibians and mammals (Coops et al., 2018). Earth Observation (EO) satellites are the only platforms capable of providing continuous, consistent datasets with global coverage. The production of ECVs therefore relies strongly on EO data and time series thereof: the EO-based contribution is significant for measuring more than half of the ECVs. Based on satellite-specific, quantitative requirements (GCOS, 2011), many satellite agencies around the world launched major programmes to generate satellite-based climate data records. Nevertheless, without in-situ validation the uncertainty in EO data would be difficult to quantify. In addition, EO data are approximations of the processes observed on the ground, and some processes might not be observable (yet) from space (e.g. genetic signatures; Cavender-Bares et al., 2016). Therefore, a strong integration and a physical basis for joint analysis of in-situ and EO data sets is needed. Within the biodiversity community, the integration of multi-scale observations is challenging as small-scale variability is highly relevant for biodiversity monitoring and scaling effects are important. Furthermore, integrating in-situ observations on a species level, and remote sensing observations on a community level, is still challenging. Nevertheless, with an ever increasing amount of higher resolution EO data available, such as from Landsat, Sentinel-2 or through the CEOS Analysis Ready Data for Land Initiative (CEOS, 2019), approaching plant species- scale, this gap is becoming smaller.

2.9. There is a steadily evolving set of 'essential' variables but the process for nominating and selecting EBVs and ECVs differs

One of the main criteria for defining the ECV is the "feasibility" and "cost effectiveness" of observing them (GCOS, 2016). As technology and scientific understanding continually evolves, the catalogue of ECVs can be changed and extended. Likewise, the EBVs are not static and will change in respond to user demand. However, their definition and prioritization is under ongoing discussion (Turak et al., 2017; Vihervaara et al., 2017). Furthermore, there appears to be divergence in how the EBV datasets should be procured or produced, collated, curated, and disseminated with a variety of data portals currently serving EBV-relevant information to the user community. This divergence among experts across biodiversity relevant domains must be overcome if a centralised biodiversity observation system is to be realised. A first step to achieve this goal is the launch of the GEO BON EBV portal, currently under development, containing a growing repository of datasets for some EBVs.

2.10. Measuring EBVs should be prioritized using a dimensional analysis; ECVs inherently describe different spatio-temporal dimensions of the climate system

The aim of the EBV concept to capture the "major dimensions of biodiversity change", as illustrated in Fig. 3 (above), infers a sense of order or priority in EBV definition in that higher dimensions should be more important in terms of explaining variance, than lower ones. For ECVs, this is implicit as the climate system can be described by larger-scale (e.g. global albedo) and smaller-scale (e.g. lake extent) variables. Depending on the application of ECV datasets, this helps to prioritise observations. Yet, the EBVs have no concept of dimensionality or priority as currently defined, with all classes and their EBV candidates being defined at the same level, i.e. all appear to be equally important. Yet, some EBVs should be prioritized, at least for the sake of resource allocation. This raises the prospect of a true dimensionality analysis of the current EBV candidates, in order to define priorities within the current EBV list. For example, how much of terrestrial plant diversity can be described by chlorophyll content versus ecosystem extent and fragmentation? Currently of all the EBVs candidates, some variables may be more important than others in explaining global biodiversity change.

3. Summary and conclusion

We have outlined ten lines of evidence to examine dependencies, synergies but also key differences between EBVs and ECVs in order to demonstrate that there can be greater cooperation between climate and biodiversity scientists which can lead to synergistic efforts to develop a global observation system for biodiversity. Additionally, the inclusion of biodiversity as a key component of the climate system is key to linking concepts of ECVs and EBVs in a more holistic fashion, finally improving representation of Earth system function. However, fundamental differences between EBV and ECV definition, not least the physical basis for ECVs, need to be acknowledged when defining the minimum requirements for overlapping variables in these different domains. Yet, with further scientific research there are multiple benefits to coupling some ECVs and EBVs in assessments of environmental change, not least in their potential contribution to indicators of nature's vital goods and services to people. Specifically, we foresee three mutual benefits for both communities in closer cooperation:

- Improved Earth System models where specific attributes of biological diversity such as tree height or ocean colour can be linked to improved quantification of radiative transfer, required for increasingly sophisticated Earth System models
- Efficient and cost effective observation networks at the national or regional level pooling human and financial resources for joint biodiversity and climate observations
- Political potency of a joint agenda will generate greater impact and increase pressure for political action to tackle climate change and biodiversity decline

In order to realise these benefits and initiate concrete action we propose the following recommendations:

3.1. Refinement of the EBV approach through observing system principles and standards

The ten basic monitoring principles for observing climate, issued by GCOS, after adoption by the UNFCCC in 2003, serve as a basis for a similar set of standards for observing biodiversity. However, the GCOS standards are largely concerned with physical observations, their observing systems, instruments, operations and associated errors in contrast to the wider knowledge base for assessments of biodiversity status – such as species conservation, indigenous knowledge and other observations gleaned from museum repositories, citizen science networks and genetic libraries. Despite this heterogeneity in sources of observations, general principles of the GCOS standards still apply – focusing priority on additional observations in data poor regions or to fill significant gaps in critical observations. Furthermore, as a first principle, GCOS recognised the need to assess the impact of any new observations systems or changes to existing ones before implementing them – an issue that can impact the interpretability of any observational record including those of biological diversity. Principles governing observations of terrestrial and oceanic biodiversity from satellites, in situ networks, or citizen science should focus on a common metadata definition, a common monitoring and reporting format, digitization of paper records and federation of existing but disparate databases as well as guidelines for dataset generation: data availability and policy, format, representation (i.e. raw vs. derived vs. indices), metadata, curation and archiving through recognised data centres. Without such measures observations will not be "discoverable" to prospective users. International and interdisciplinary scientific networks who coordinate specialist biological observations such as those of the International Geosphere-Biosphere Programme, herbariums and museums, assessors of species conservations status of the International Union for Conservation of Nature's (IUCN) Red List, other in-situ monitoring networks and databases (e.g. the TRY plant trait database) should be included in the establishment of monitoring principles.

3.2. Apply the concept of science traceability to move from user requirements to indicator production, overseen by a joint working group of biodiversity and climate experts

The mode of transition from concept to definition and implementation of the EBVs in an operational observing system is still largely undefined. The global climate observing system, that partly inspired the EBV concept, initially coordinated efforts to document user requirements for the ECVs, which necessitated a definition of who the users are – an issue for EBVs that still needs clarification. To date the bottom-up evolution of EBVs has suggested a scientific user base, but this will need elucidation to determine who uses observations of biodiversity variables and derivative indicators, for what purpose, and where the biggest gaps are in data availability – spatial, temporal, taxonomic, ecoregion representativity etc. Firstly, this information should be extracted from 'anchor' users such as scientists involved in the IPBES assessments, national authorities, taxonomists and species experts of the IUCN, other research organisations and non-governmental organisations (NGOs) involved in biodiversity and ecosystem science & conservation as well as the UN Environment and its affiliated partners. Second is the requirement to produce a traceability matrix of science requirements to engineering specifications, finally allowing engineers to build instruments and observation networks to serve the goal to measure EBV's (and hence biodiversity) on the ground and from space. Even though 'biodiversity can never be fully captured by a single number' (Purvis and Hector, 2000), a science traceability matrix would strongly support the prioritization of EBVs.

Thirdly, we recommend that a funded and resourced forum be set up that would allow regular and organised exchanges between these prospective users of EBVs and their counterparts in the ECV communities. This forum dialogue will be a first step from which a roadmap to coordinated observations could be developed. In addition, we recommend that initial efforts should focus on the overlapping variables required by both communities, such as land cover in the terrestrial domain and marine habitat properties in the marine domain. We propose that a dedicated working group, composed of experts from GCOS, GEOBON, IPCC and IPBES should be established and core funded to facilitate this forum with a funded secretariat. This would set in motion the synergies required and lead to the roadmap towards formalising these coordinated efforts, without the danger of losing sight (c.f., NEON, Skidmore et al., 2015).

3.3. Focus efforts initially on biodiversity hotspots of change, deduced from trend analysis

Decadal time series are needed to assess Earth system change. However, to effectively detect change, (temporal) 'oversampling' is required to distinguish variability and trend and effectively allocate change to a true trend. Once areas of true, or 'hotspots', of change have been identified, they would be the focus of intensified efforts where it is most needed. These geographically-focused efforts would initially consist of an adaptation of the GCOS principles for climate monitoring to biodiversity and the clear definition of user requirements for EBVs. As alluded to in point 8, there are hotspots of biodiversity change which are undergoing rapid biodiversity decline and which can be identified by satellite remote sensing. We recommend that a series of regional workshops should be initiated with regional partners and invited climate and biodiversity experts to examine issues around user definitions, monitoring principles and standards in areas of global biodiversity importance. Potential regional partners who could initiate such focal networks for coordinated biodiversity-climate observations are the National Commission for the Knowledge and Use of Biodiversity in Mexico (CONABIO), Alexander von Humboldt Biological Resources Research Institute of Colombia or the South African National Biodiversity Institute. The repositories of expertise, knowledge and capacity building that these institutes house are also important for South-South cooperation in the area of climate –biodiversity interactions and initiating a response to global ecological crisis at the regional level which can spur action elsewhere. These recommendations could form the basis for the terms of reference of a joint IPCC-IPBES-GCOS-GEOBON working group which could be later developed through said workshops.

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