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How do we want Satellite Remote Sensing to support biodiversity conservation globally?

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Summary

1. Essential Biodiversity Variable, Natural Capital, Biodiversity Indicator and Ecosystem Service are four concepts that underpin the most popular frameworks currently considered for helping to coordinate and structure biodiversity monitoring efforts worldwide. Satellite Remote Sensing (SRS) has considerable potential to inform these initiatives. To date, however, discussions on the role of SRS in supporting these frameworks have mostly evolved independently; tend to be led by different groups; sometimes target slightly different scales; and are likely to reach different audiences. Because of this, there is some confusion among environmental managers and policymakers as to what the potential of SRS is or whether there is prospect in considering and promoting the use of satellite data for biodiversity conservation.

2. Here, we provide a brief overview of the role of SRS to date in informing these frameworks. Through a case study focused on the Sahara Desert ecosystem, we also demonstrate the current potential for SRS-based methodologies to support conservation in data-deficient areas and discuss the relative applicability of SRS-based metrics to each of these frameworks.

3. The relevance and use of SRS across the four frameworks are clearly variable, due to differences and ambiguity in definitions, and due to differences in monitoring priorities. Our case study illustrates the particularly high potential for SRS approaches to provide key information relevant to the Biodiversity Indicators framework in desert ecosystems; it also identifies SRS-based metrics relevant to all frameworks.

4. Altogether, this work highlights how more dialogue is required within the biodiversity-monitoring community for SRS to reach its full potential in conservation. In particular, agreement on what is needed in priority, given the realm of what is possible, will be of paramount importance to developing SRS-based products that are used by policymakers and international conventions.

Key-words: biodiversity indicator, earth observations, ecosystem service, environmental management, essential biodiversity variable, natural capital, technology, wildlife management

Introduction

As we enter the second half of the United Nations 'Decade on diversity' (Convention on Biological Diversity 2011), studies reporting major biodiversity loss around the world continue to accumulate. The latest Living Planet report, for example, highlighted how global wildlife populations declined by 52% in the past 40 years [McLellan *et al*. 2014 (Living Planet Report 2014)]; most of the Saharan megafauna is now on the brink of extinction (Durant *et al*. 2014); only one-third of all sharks, rays and chimaeras are currently considered safe according to the International Union for the Conservation of Nature (IUCN) Red List criteria (Dulvy *et al*. 2014); over 2 million square kilometres of forests have been lost over just the past decade (2000–2012; Hansen *et al*. 2013). At the same time, evidence on the role of biodiversity in supporting ecosystem functioning is mounting (Cardinale *et al*. 2012), with studies assessing the economic costs incurred by the loss of biodiversity becoming increasingly popular (Ring *et al*. 2010; Spash 2015); efforts to understand how human-driven alterations to biodiversity impact human well-being in general, and human health in particular, are also growing (Sala, Meyerson & Parmesan 2008; Summers *et al*. 2012). Such a context has led to several high-profile political commitments to promote the conservation and sustainable use of biological diversity (Cardinale *et al*. 2012; Collen *et al*. 2013).

Societal, economic and scientific interests in knowing where biodiversity is, how biodiversity is faring and what can be done

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to efficiently mitigate further biodiversity loss are thus at an all-time high. Biodiversity is, however, a complex, multidimensional concept (Lyashevska & Farnsworth 2012) that has proven hard to track globally (Collen *et al*. 2013). Among the variety of methodologies likely to deliver global monitoring options for capturing and understanding change in biological diversity, Satellite Remote Sensing (SRS) has been highlighted as displaying considerable potential (Roughgarden, Running & Matson 1991; Gillespie *et al*. 2008; Horning *et al*. 2010). Reasons for this include the fact that SRS can (i) provide global coverage that spans multiple decades; (ii) inform on the loss of biological diversity at a wide range of scales in a consistent, borderless, repeatable and rapid manner; and (iii) support a dynamic approach to environmental and wildlife management (Pettorelli *et al*. 2014a; Turner *et al*. 2015).

There are multiple conceptual frameworks that could potentially be used to help coordinate and structure biodiversity-monitoring efforts worldwide, with the four most popular ones being based on the concepts of Essential Biodiversity Variable (Pereira *et al*. 2013), Natural Capital (see e.g. Agarwala *et al*. 2014), Biodiversity Indicator (IUCN 2015) and Ecosystem Service (Millennium Ecosystem Assessment 2005). Interestingly, SRS can inform all of these frameworks and several studies have reviewed how exactly each initiative could be supported by satellite-based information (see e.g. Strand *et al*. 2007; Ayanu *et al*. 2012; Skidmore *et al*. 2015). To date, however, discussions on the role of SRS in supporting these frameworks have mostly evolved independently (but see O'Connor *et al*. 2015 for a discussion on Earth Observation as a tool for supporting the Biodiversity Indicator and Essential Biodiversity Variable frameworks); tend to be led by different groups; sometimes target slightly different scales; and are likely to reach different audiences. Because of this, there is some confusion among environmental managers and policymakers as to what the potential of SRS to support biodiversity-monitoring efforts is, or whether there is prospect in considering and promoting the use of satellite data for biodiversity conservation (given that the conclusions relative to the role of SRS in supporting efforts to halt global biodiversity loss are intrinsically linked to the framework considered). We believe that this generated confusion is contributing to the slow integration of this type of information in decision-making processes, both nationally and globally.

To help demonstrate the full potential of SRS in supporting biodiversity-monitoring efforts, we (a) define what Essential Biodiversity Variables, the Natural Capital, Biodiversity Indicators and Ecosystem Services are; (b) provide an overview of (i) how each framework can support biodiversity conservation efforts and (ii) how SRS is currently being used to support the implementation of these frameworks; and (c) use the example of the Sahara desert ecosystem to illustrate the similarities and differences that exist between these frameworks when it comes to using SRS products to inform conservation in data-deficient regions. We conclude this work by proposing possible ways forward to better integrate SRS-related discussions connected to these initiatives, for the benefit of biodiversity conservation.

The current state of play

EXISTING OPPORTUNITIES FOR SRS TO SUPPORT NATIONAL AND GLOBAL BIODIVERSITY-MONITORING EFFORTS

SRS and essential biodiversity variables (EBVs)

EBVs are currently defined as measurements required for the study, reporting, and management of biodiversity change (Pereira *et al*. 2013). They are expected to possess a set of characteristics, which include (i) being sensitive to change over time; (ii) being focused on the 'state' of biodiversity [as per the 'Pressure–State–Response' framework from the Convention on Biological Diversity (CBD)]; and (iii) being defined at a level of specificity intermediate between that of low-level (primary) observations and high-level indicators of biodiversity change. Importantly, EBVs are expected to be scalable, technically feasible and economically viable for global implementation (Pereira *et al*. 2013). Six classes of EBVs are distinguished, namely genetic composition, species populations, species traits, community composition, ecosystem structure and ecosystem functions. To date, progress on the EBV agenda has been coordinated by the Group on Earth Observation – Biodiversity Observation Network (GEO BON), which represents the biodiversity component of GEOSS, the Global Earth Observation System of Systems.

The identification of EBVs and their monitoring is directly relevant to efforts to gather information about the state of biodiversity. SRS has been expected from the start to partially contribute to EBV monitoring (Pereira *et al*. 2013) and recently, 10 variables that capture biodiversity change on the ground and can be monitored from space were identified as potential EBVs (Skidmore *et al*. 2015). These are: species traits (leaf nitrogen and chlorophyll content, specific leaf area), species populations (occurrence), ecosystem structure (distribution, fragmentation and heterogeneity, land cover, vegetation height) and ecosystem function (productivity, vegetation phenology, inundation and fire occurrence). These remotely sensed EBVs were identified as critical to develop indicators for monitoring progress towards Aichi targets 5, 7, 9, 14 and 15 (Skidmore *et al*. 2015). Discussions to agree on a definite list of EBVs that can be tracked from space are ongoing.

SRS and biodiversity indicators

Biodiversity Indicators are defined by the IUCN as statistical measures of biodiversity that help scientists, managers and politicians understand the condition of biodiversity and the factors that affect it (IUCN 2015). The Biodiversity Indicators Partnership, mandated by the CBD, is the global initiative in charge of promoting and coordinating the development and delivery of Biodiversity Indicators in support of the CBD, several Multilateral Environmental Agreements, the International Platform on Biodiversity and Ecosystem Services, national and regional governments and a range of other sectors (Biodiversity Indicators Partnership 2015a). A main difference between EBVs and biodiversity indicators is that EBVs have been conceptualized as state variables containing the information needed for the generation of biodiversity indicators that focus on the state of biodiversity (Pereira *et al.* 2013). Unlike EBVs, Biodiversity Indicators can also cover information about pressures to biodiversity, as well as society's response to changes in pressures or state. For example, the indicators used to assess progress towards the 2010 Biodiversity Target included trends in mangrove extent, the waterbird population status index and the living planet index, as well as nitrogen deposition rate and the extent of Protected Area coverage (Butchart *et al.* 2010).

Global biodiversity indicators are identified on the premises that they carry key information for assessing progress towards the targets set by the CBD. Very few of the global indicators used to assess progress towards the 2010 Biodiversity Target relied on, or could be derived from, satellite information (Butchart *et al.* 2010). The only exceptions to this were the indicators capturing change in the extent of specific ecosystems, namely forests, mangroves and seagrasses. To date, the only new global indicator derived from satellite information that is being considered by the Biodiversity Indicators Partnership is forest fragmentation (Biodiversity Indicators Partnership 2015b).

SRS and ecosystem services

Ecosystem services are the (actual or perceived) benefits derived by humans from the world's ecosystems (Millennium Ecosystem Assessment 2005), comprising provisioning (e.g. food, fuel and fibre production), regulating (e.g. air cleansing, water quality, storm/flood protection, carbon storage), supporting (e.g. soil formation, primary production) and cultural services (e.g. recreation, tourism; Millennium Ecosystem Assessment 2005). The recent creation of the International Platform on Biodiversity and Ecosystem Services (IPBES) heralds a central stage for assessment of the state of knowledge, science and policy on ecosystem services (Díaz *et al.* 2015; www.ipbes.net), now necessitating a wealth of status and trend monitoring for ecosystem services (Geijzendorffer & Roche 2013). Monitoring of reliable ecosystem services indicators is also essential for progress towards Aichi targets 11 and 14.

National, regional and global mapping of services' proxies enables assessment of the state of supply of ecosystem services to human societies, as well as human demand for those services (Ayanu *et al.* 2012), and, consequently, monitoring of ecosystem services provides information relevant to biodiversity monitoring in two ways. First, supply of many provisioning services (e.g. food and fuel production) is associated with low biodiversity and delivery of multiple regulating, supporting and cultural services (Maes *et al.* 2012). Accordingly, monitoring of the extent and distribution of, for example, cropland or timber plantations enables mapping of trade-offs between such provisioning services and biodiversity conservation priorities (Naidoo *et al.* 2008; Bowman *et al.* 2011; Maes *et al.* 2012). Monitoring through time further enables information on human pressures to be gathered through changes to the distribution and intensity of demand, as well as to the relative magnitude and distribution of supply of different services across landscapes (e.g. amount of land under agricultural crop production; Ellis & Ramankutty 2008; Phalan *et al.* 2014). Second, biodiversity both supports and directly delivers many ecosystem services through space and time (Cardinale *et al.* 2012; Mace, Norris & Fitter 2012); for example, being associated with areas of high net primary productivity (Hooper *et al.* 2012), or providing in itself key cultural ecosystem service benefits (Bowman *et al.* 2011; Mace, Norris & Fitter 2012; Maes *et al.* 2012). Importantly, it is the functional traits of organisms and communities that drive key ecosystem functions underpinning ecosystem services delivery (Díaz *et al.* 2007). Many key plant traits for ecosystem functioning can be monitored with SRS – for example, leaf chemical traits and specific leaf area, vegetation height (Feld *et al.* 2009).

SRS can be employed to create direct proxies of supply, or to produce land cover classifications from which supply can be inferred or modelled, for a multitude of provisioning and regulating services, as well as for human demand (Ayanu *et al.* 2012). Unlike previously discussed frameworks (Biodiversity Indicators and EBVs), however, a comprehensive set of ecosystem services indicators is still lacking (Layke *et al.* 2012; Tallis *et al.* 2012), even for well-studied and readily measurable regulating services (Egoh *et al.* 2012; Geijzendorffer & Roche 2013). The GEO BON Ecosystem Service Working Group recently outlined a conceptual framework for monitoring trends in ecosystem services globally, based on numerical modelling combining SRS, field-based and national statistics data (Tallis *et al.* 2012). However, this framework is currently unable to support monitoring of many important regulating and cultural ecosystem services (Tallis *et al.* 2012). The current and potential role of SRS for ecosystem services supply monitoring is hindered by the same problems that have constrained development of standard indicators: (1) complexity in ecosystem services definitions and avoidance of 'double counting' (Fisher & Turner 2008; Mace, Norris & Fitter 2012; Geijzendorffer & Roche 2013); (2) differences in spatial scales of delivery to different stakeholders (Layke *et al.* 2012; Tallis *et al.* 2012); (3) differences between types of services according to linkages to underlying ecosystem functions, which impact the applicability of broad proxies to their monitoring (Mace, Norris & Fitter 2012; Geijzendorffer & Roche 2013; Duncan, Thompson & Pettorelli 2015).

SRS and natural capital accounting

Following the recommendations from the Natural Capital Committee, Natural Capital is defined here as '*the elements of nature that directly and indirectly produce value or benefits to people, including ecosystems, species, freshwater, land, minerals, the air and oceans, as well as natural processes and functions*' (Natural Capital Committee 2014). In simple terms, this capital represents the stock of nature (which may be organized into classes called assets) that has the power of producing goods (or utilities) that support human societies. Eleven types of Natural

Capital assets have so far been distinguished: species (including genetic variation), ecological communities, soils, freshwaters, land, minerals, the atmosphere, subsoil assets, coasts, oceans, as well as the natural processes and functions that underpin their operation. Likewise, major classes of benefits include food, fibre, energy, freshwater, aesthetics, recreation, clean air, wildlife, hazard protection and equable climate (Mace *et al.* 2015). The ecosystem services framework is intimately linked to the Natural Capital framework: Natural Capital stocks is what underpins the delivery of ecosystem services.

Natural Capital accounting exercises, which are currently being considered for implementation mainly at the national scale, can be expected to provide some levels of information on the state of biodiversity, given that many of the asset types are direct components of biodiversity (i.e. species, ecological communities) and that habitat monitoring has been advocated as a way to link Natural Capital assets to benefits (with some of these habitat types actually representing ecosystems; Mace *et al.* 2015). Discussions on ways to monitor our Natural Capital are yet very young, as the scientific community is only starting to agree on what the assets are. It is clear, however, that the potential for SRS to play a key role in the monitoring of Natural Capital assets is high, as SRS can, for example, be used to track changes in the distribution (and sometimes the condition) of woodlands (Hansen *et al.* 2013), urban areas (Taubenböck *et al.* 2012), wetlands (McDonald *et al.* 2011), lakes (Verpoorter *et al.* 2014), dunes (Hermas, Leprince & El-Magd 2012), estuaries (Cui & Li 2011), coastal lagoons (Camacho-Valdez *et al.* 2014), grasslands (Buck *et al.* 2015) and bogs (Cole, McMorrow & Evans 2014). In some cases, SRS can also help assess the distribution and abundance of specific species (see e.g. Fretwell *et al.* 2012; Fretwell, Staniland & Forcada 2014).

CASE STUDY: THE SAHARA DESERT ECOSYSTEM

To help demonstrate the full potential of SRS in supporting biodiversity-monitoring efforts, we illustrate here the similarities and differences that exist between the essential biodiversity variable, biodiversity indicator, ecosystem services and natural capital frameworks when it comes to using SRS products to inform conservation on the ground. We do so using the Sahara as a case study, an ecosystem that is host to unique biodiversity and supports the livelihoods of 6% of the world's population (Mortimore *et al.* 2009). Projected to be among the areas with the fastest climate change velocity (Loarie *et al.* 2009; IPCC 2013), combined with multiple ongoing anthropogenic pressures upon its function (Brito *et al.* 2014), the Sahara's future appears bleak. It is indeed an ecosystem that has undergone, and continues to undergo, substantial changes to its biodiversity, due to these multiple climatic and anthropogenic factors (Durant *et al.* 2014). SRS is being pushed as a possible method for systematically monitoring ecosystems globally (Skidmore *et al.* 2015), and the Sahara makes for an interesting case study due to its relatively low productivity (Durant *et al.* 2012); low cloud cover that really bolsters remote-sensing capabilities (less cloud cover means greater data availability for trend and change analysis; Wylie *et al.* 2005) and remoteness, making it a region mostly dependable upon remote-sensing techniques for monitoring and understanding changes in biodiversity levels. Current SRS capabilities mean that most metrics are centred on vegetation, although these are only applicable to portions of the Sahara. Other metrics such as inundation zones (seasonally inundated riverbeds and pools) are of great importance in drylands, with biodiversity highly adapted to exploit short periodic supplies of water. Permanently inundated zones such as mountain rock pools are key biodiversity hotspots (Vale, Pimm & Brito 2015). Fire dynamics also play an important role in the functioning of desert ecosystems: fires indeed promote productivity, yet increased fire occurrence and/or intensity due to anthropogenic activity or the introduction of flammable plant species can seriously alter ecosystem functions (Bowman *et al.* 2011).

We collected and processed all openly available satellite-derived data for variables relevant to arid ecosystems and sensitive to change (i.e. we only considered temporally variable metrics), and conducted basic linear trend analysis (Pettorelli *et al.* 2012); we then allocated these metrics based on their relevance to the aforementioned frameworks (details in Table 1). The Saharan region was defined by excluding any land where rainfall was above 250 mm isohyet (following the approach detailed in Durant *et al.* 2014). For each metric (see Table 1), the entire archive of all tiles within the Saharan boundary was downloaded using Wget (GNU Wget, 2015), projected (WGS 84), cropped, and merged using the Geospatial Data Abstraction Library (GDAL) extension in R (Bivand, Keitt & Rowlingson 2013; R, 2015). To conduct our linear trend analyses, the slope coefficient of the relationship between each variable as a function of the year was extracted for each pixel for the available time series, to establish any negative or positive changes within each variable in space (Pettorelli *et al.* 2012). Linear trends were calculated across the available time-series data for all metrics on yearly-summed (Normalized Difference Vegetation Index & Fire) and -averaged (Land Surface Temperature; LST; Aerosol Optical Depth; AOD; GRACE Equivalent Water Thickness; EWT) data using the 'raster' package (Hijmans 2013) in R. To facilitate the visual display of the data, metrics were plotted using values within the 1% and 99% quantiles. Any values outside this interval were brought back to the 1% or 99% values, depending on whether extreme low or extreme high values were considered.

Interesting results include the visualization of the Sahara/Sahel greening, which is captured by the positive trend in the Integrated Normalized Difference Vegetation Index (I-NDVI; Fig. 1). This greening was recently attributed to increasing rainfall (Brandt *et al.* 2015), and this hypothesis is supported by the positive trend in Equivalent Water Thickness (EWT) reported for this region. EWT captures changes in both surface and groundwater, and so decreasing trends in EWT in the north-east part of the Sahara associated with higher Land Surface Temperature (LST) and higher Aerosol Optical Depth (AOD) could indicate a possible desertification. Higher temperatures along with land use change are thought to lead to greater dust emissions (Field *et al.* 2009), a likely scenario in

Table 1. Processed variables for the Sahara case study, along with corresponding information on data/sensor used, spatial/temporal resolution, source time span, and the information it could capture in relation to the Biodiversity Indicators (BI), Essential Biodiversity Variables (EBVs), Ecosystem Services (ES) and Natural Capital (NC) frameworks. The MODIS AQUA-derived vegetation products were chosen over TERRA due to sensor breakdown within relative bands on this sensor, causing slight inaccuracies (Tian *et al*. 2015). In this table, NPP stands for net Primary productivity; LST for Land Surface Temperature; NL for Night Light; EWT for Equivalent Water Thickness; AOD for Aerosol Optical Depth

Variable	Data	Spatial & temporal resolution	Source	Time span	Proxy and framework
NPP	MODIS aqua NDVI composite	16 Days, 1 km	http://e4ftl01.cr.usgs.gov/	2002–2014	Primary productivity as an ecosystem function (BI & EBV); fodder production (ES); grassland/scrubland cover (NC)
LST	MODIS Terra surface temperature	8 Days, 1 km	http://e4ftl01.cr.usgs.gov/	2000–2014	Trend in desertification (BI)
Fire	MODIS Terra thermal anomalies + fire	8 Days, 1 km	http://e4ftl01.cr.usgs.gov/	2000–2014	Trend in fire occurrence (BI); changes in ecosystem function (EBV)
EWT	JPL GRACE equivalent water thickness	Monthly, 111 km	ftp://podaac-ftp.jpl.nasa.gov/	2002–2014	Water availability (BI); fresh groundwater availability (ES); total freshwater availability (NC)
AOD	AATSR AOD(550 nm) composite	Monthly, 100 km	http://www.icare.univ-lille1.fr/drupal/archive/?dir = CCI-Aerosols/	2002–2012	Atmospheric dust content as a proxy for erosion (BI)

this region, considering the increase in dry farming and irrigation in Northern Sahara as a whole (Darkoh 2003). Increased aerosol has the potential to suppress precipitation (Rosenfeld, Rudich & Lahav 2001; Bowman *et al*. 2011), further amplifying desertification. High yearly fire counts are clear along the Sahara/Sahel border with Lake Chad being a particular hotspot, as well as high counts along the Nile. Human-induced fires and the introduction of flammable plant species can substantially alter the functioning of an arid ecosystem (Bowman *et al*. 2011); such processes may well be occurring within areas such as the Nile (Fig. 1), where human presence is high.

Our case study also reveals that, although all metrics considered can ultimately potentially inform the Biodiversity Indicator framework, very few global variables sensitive to change are currently applicable to Natural Capital, ecosystem services and EBV monitoring. Such a difference in SRS potential to support the four frameworks considered could ultimately be driven by the biodiversity indicator framework being associated with the broadest monitoring scope. The poor availability of global, time-sensitive products to monitor the state of biodiversity is one reason for the recent emergence of the EBV framework: this poor availability is still a reality, as illustrated here by the low number of SRS-based metrics relevant to Natural Capital, ecosystem services and EBV monitoring (which all heavily rely on information about the state of biodiversity). Admittedly, we only considered SRS-based global variables sensitive to change, and it might well be that such a choice artificially restricted the number of SRS-based products considered in our study case. At the same time, being sensitive to change is a key requirement for any variable to inform a given monitoring endeavour; likewise, accessibility is of paramount importance for managers and policymakers to be able to capitalize on SRS-based products. Interestingly, we were unable to find any ecosystem-wide SRS-based product, which was relevant to one of our four frameworks, sensitive to change and freely accessible to feed into our comparative approach. As previously mentioned, arid ecosystems are in an ideal situation to be the first ecosystems to reap the benefits of SRS-based monitoring, especially so when it comes to new technologically advanced sensors (e.g. hyperspectral sensors, very high-resolution imagery), the use of which is frequently hindered by low revisit times and cloud cover. However, much needs to be done for these threatened ecosystems to fully benefit from SRS technology. Of particular interest to these ecosystems is the potential opportunity to monitor species distribution from space, as feasibility in these areas should be particularly high. But the key priority is the sustainable production of SRS-based products relevant to biodiversity monitoring: there are indeed many available static products that could be relevant to one or more of our frameworks, should they be produced on a continuous basis. Should this happen, this type of contribution could make a real difference to conservation efforts on the ground.

Moving forward

At least four frameworks are currently being discussed as a way to help stop further loss of biodiversity, with each of these frameworks highlighting a relatively different set of variables that need to be monitored for natural resources to ultimately be managed more sustainably. As demonstrated by our case

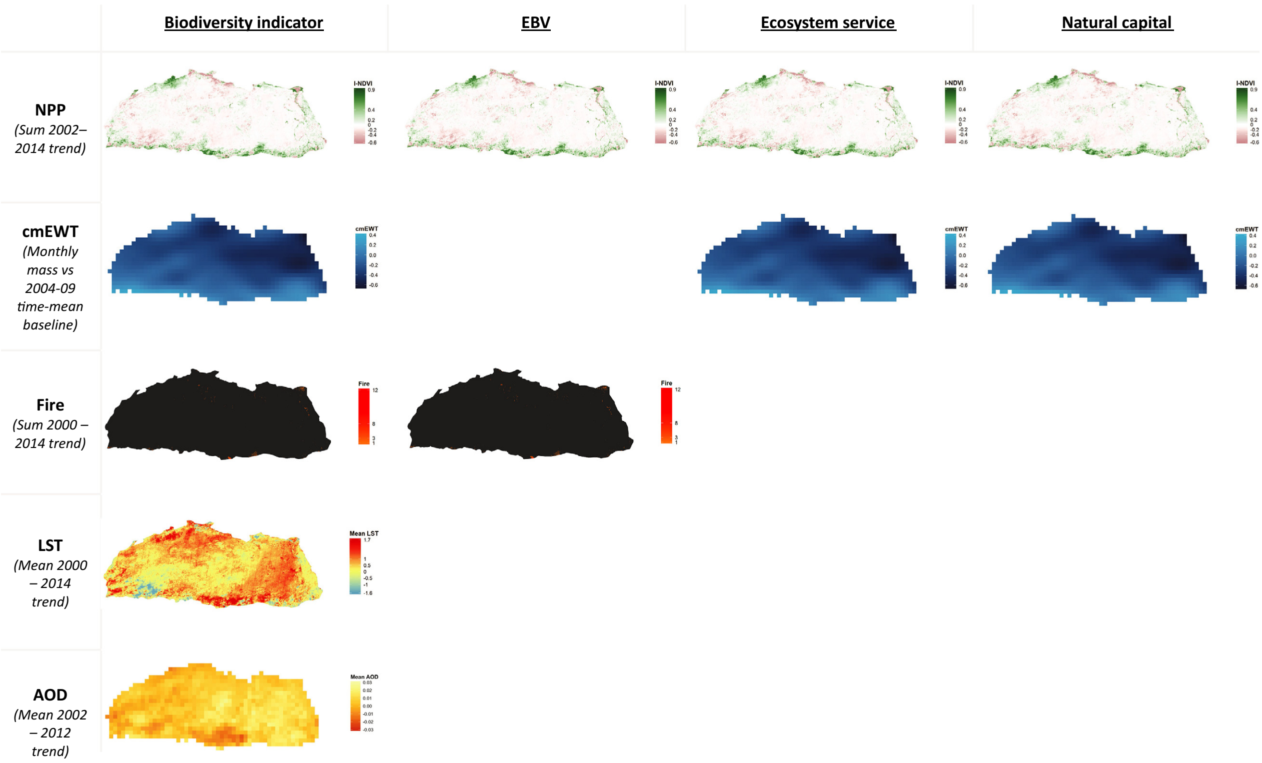

Fig. 1. SRS-based metrics relevant to biodiversity monitoring for the Saharan ecosystem. Metrics' relevance for each of the four frameworks considered in this article (namely those based on the concept of Essential Biodiversity Variables (EBV); Natural Capital; Biodiversity Indicators; and Ecosystem Services) is detailed. Relevance here is different from actual designation, and it is important to note that (a) none of the variables listed as relevant to the biodiversity indicator framework has been listed as global indicators by the Biodiversity Indicators Partnership (BIP 2015) and (b) there is no agreed list of EBVs. Fire is considered as a potential EBV, given its association with ecosystem function. In this figure, NPP stands for Net Primary productivity; LST for Land Surface Temperature; EWT for Equivalent Water Thickness; AOD for Aerosol Optical Depth; I-NDVI for Integrated Normalized Difference vegetation Index (Pettorelli 2013). Pixel values within each map (see legends within the figure) refer to the slope coefficient of the linear trend of each variable across the available time series for that given pixel (see far left-hand panel).

study and broadly supported by a quick review of freely available global SRS products relevant to the four frameworks considered (Table 2), the way SRS can support the implementation of each of these frameworks is variable, with the Biodiversity Indicator framework associated with the broadest scope (Fig. 1), given its established nature, clear protocols, defined aims as well as its interest in gathering information on pressures, state and response. Clearly, information on land cover distribution will be of value to all these frameworks (Table 2), but not systematically in the same format, as EBV initiatives might be concerned with ecosystem distribution, while Natural Capital accounting exercises might be concerned with habitat distribution and Biodiversity Indicator groups with anthropogenic developments such as the road network expansion. In most cases, however, the set of raw SRS measurements and global products required to support the implementation of these frameworks is likely to be different.

ESTABLISHING PRIORITIES

The number of global products that could be generated from raw SRS measurements to inform the four frameworks considered is quite high (e.g. at a recent workshop discussing potential EBVs that could be monitored from space, over 25 variables were identified as potential priorities (with 10 of them ending up being the ones listed in Skidmore *et al.* 2015); NP, *pers. comm.*), and their simultaneous development unlikely to be achievable and sustainable due to financial and logistical constraints. So which SRS-based products should be prioritized? So far, this question (when being asked) is mostly being discussed within each framework, yet these discussions also need to happen across frameworks, given, for example, that not all of them consider pressures to biodiversity as part of their monitoring needs. Identifying priorities for global product development based on SRS data and relevant to biodiversity conservation is urgently needed for the potential of SRS information to support conservation to be reached, and this discussion requires all segments of the relevant scientific community to be consulted and engaged. Reaching a consensus on monitoring priorities could help prevent space agencies and product developers feeling highly confused as to what the needs of the biodiversity community as a whole are.

Identifying a clear and inclusive hub for promoting dialogue across all actors engaged with the development of various conceptual frameworks is key for agreeing on monitoring priorities when it comes to biodiversity conservation. For these discussions to eventually translate into actions, this hub needs to be well connected to decision mak-

Table 2. Non-exhaustive list of potential SRS-based variables that could fit the requirements of the Biodiversity Indicator framework, Essential Biodiversity Variable framework, Ecosystem Services framework and Natural Capital framework. All of the SRS products below share common characteristics, namely these are all (1) global products, (2) sensitive to change over time (i.e. all static measures were not considered) and (3) freely available

Biodiversity indicator framework	Essential biodiversity variable framework	Ecosystem services framework	Natural capital framework
Land surface temperature (desertification)	Forest cover/Land cover (ecosystem distribution)	Land cover (carbon stock mapping)	Land cover (spatial distribution of certain assets, such as wetlands, grasslands)
Equivalent water thickness (water availability)	Phytoplankton distribution	Normalized difference vegetation index (fuelwood availability)	Normalized difference vegetation index (woody biomass)
Aerosol optical depth (erosion)	Leaf area index/fraction of absorbed photosynthetically active radiation (ecosystem function)	Net primary productivity (fodder production)	Leaf area index/fraction of absorbed photosynthetically active radiation (index of certain assets' quality)
Inundation (anthropogenic pressure)	Inundation (ecosystem function)	Forest cover (storm protection; heatwave protection; erosion prevention)	
Fire (anthropogenic pressure)	Fire (ecosystem function)	Equivalent water thickness (water availability)	
Night light (urbanization)	Net primary productivity (ecosystem function)	Chlorophyll *a* (water quality)	
Land cover (as a proxy for ecosystem distribution and land use)			
Net primary productivity (ecosystem function)			

ers. Given its broad scope and clear mandate, the Biodiversity Indicator framework set by the CBD and implemented by the Biodiversity Indicators Partnership is potentially well suited to facilitate the identification of monitoring priorities: ecosystem services monitoring is indeed already required to identify ecosystems that provide essential services, and therefore key for progress towards Aichi target 14; EBVs have then been expected from the start to represent the foundations of future Biodiversity Indicators (Pereira *et al.* 2013). Another option could be the setting up of an interdisciplinary biodiversity-monitoring task force within the IPBES to assist IPBES in '*identifying and prioritizing key scientific information needed for policymakers at appropriate scales*' (IPBES, 2015). The development of the Essential Climate Variable framework by the Global Climate Observing System could offer an example of how priority could be assessed (see e.g. Bojinski *et al.* 2014); to facilitate discussions, such a prioritization approach could be undertaken for each framework first.

COORDINATING EFFORTS

Monitoring priorities are likely to be dynamic. Prioritization of SRS information will rely on costs and implementation status, and these characteristics will continue to change over time: for example, monitoring vegetation height worldwide on a regular basis is currently not feasible at reasonable costs, due to the lack of appropriate sensor onboard active satellite (see e.g. Fatoyinbo Agueh & Simard 2013). However, LiDAR sensors are expected to be launched soon, and the collected data will drastically alter LiDAR cost estimates. Therefore, the generation of a priority list is only a first step towards transitioning from a system where data products are developed *ad hoc* to a system where products are developed based on a clear vision of what these should be.

For SRS to achieve its potential to support biodiversity-monitoring efforts worldwide, a clear and common platform for data providers, ecologists and SRS scientists to interact and share ideas also needs to be identified, and used to coordinate action in the long run. There is indeed little doubt that the establishment of clear monitoring priorities for biodiversity conservation worldwide will stimulate innovation and global product development; such a platform would allow scientists and space agencies to not only push more effectively for new technologies and sensors to be developed and implemented but also to make a better use of existing data and product metrics. This would also encourage data providers to work more in unison to ensure that an agreed, accessible and updated data portal exists for all potential stakeholders to use.

There are several entities that could host and promote these required interdisciplinary discussions, such as the Group on Earth Observations Biodiversity Observation Network (GEO BON) or the group on Remote Sensing for Biodiversity within CEOS (www.remote-sensing-biodiversity.org) who are already trying to bridge the communication gaps between the remote-sensing and biodiversity-monitoring communities.

THINKING ABOUT LONGEVITY

SRS potential to support biodiversity-monitoring needs is ultimately heavily reliant upon access to open-source data and methodologies that have longevity (Pettorelli 2013; Pettorelli *et al*. 2014a; Turner *et al*. 2015). Data archives such as the Landsat one have facilitated the development of highly sophisticated SRS-based biodiversity-monitoring products (Skidmore *et al*. 2015); these developments have been made possible by the archives becoming open access (Wulder *et al*. 2012). Likewise, open-source software solutions are of paramount importance to facilitating the development of methodologies accessible to all, independently of financial means. The combination of freely accessible data and open-source software provides an opportunity to derive products that are standardized, transparent and cost effective, enhancing the prospects for these data sets to be maintained in the long term.

An ongoing issue is the production of SRS-based data sets that are ultimately not maintained through time. This may be due to the lack of incentive to produce and maintain publicly available products within the scientific community. This may also be due to the drive for scientists to continuously improve techniques and algorithms to process SRS images, sometimes at the cost of producing global products that are ultimately comparable through time (O'Connor *et al*. 2015). Sensors, algorithms and accuracy can always be improved, but constant changes in methodologies hamper our ability to capitalize on the years of data captured so far. There is a trade-off between optimizing the accuracy and optimizing the usefulness of SRS data for biodiversity monitoring at the global scale; decisions about which levels of inaccuracy are acceptable may need to be made for SRS data to reach their full potential.

Conclusions

Much has been written about the needs for more dialogue and collaboration between the biodiversity-monitoring community and the remote-sensing community, for SRS to become a tool of choice in conservation (Pettorelli, Safi & Turner 2014b; Pettorelli *et al*. 2014c; O'Connor *et al*. 2015); this work aims to highlight that more dialogue is also required within the biodiversity-monitoring community for this to happen. Agreement on what is needed as a priority, given the realm of what is possible, is of paramount importance to developing SRS-based products that are used by policymakers and international conventions: such an agreement will require efforts to be made for the full spectrum of stakeholders to feel engaged and wanting to work in unison. Institutional leadership will be critical for these efforts to be coordinated and delivered upon: there are several organizations that are in a good position to fulfil this role, but the place remains so far vacant.

Data accessibility

GRACE Monthly Land Mass Data were accessed at ftp://podaac-ftp.jpl.nasa.gov/allData/tellus/L3/land_mass/. All MODIS data sets (Fire, NPP, Day time LST) were downloaded from http://e4ftl01.cr.usgs.gov/. The aerosol data (AATSR_SU/4·1) were accessed through http://www.icare.univ-lille1.fr/drupal/archive/?dir = CCI-Aerosols/.

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