Satellite remote sensing of ecosystem functions: opportunities, challenges and way forward

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Satellite remote sensing of ecosystem functions: opportunities, challenges and way forward

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Abstract
Societal, economic and scientific interests in knowing where biodiversity is, how it is faring and what can be done to efficiently mitigate further biodiversity loss and the associated loss of ecosystem services are at an all-time high. So far, however, biodiversity monitoring has primarily focused on structural and compositional features of ecosystems despite growing evidence that ecosystem functions are key to elucidating the mechanisms through which biological diversity generates services to humanity. This monitoring gap can be traced to the current lack of consensus on what exactly
Introduction

Biodiversity is in crisis, as wildlife populations decline (McCauley et al. 2015; WWF Living Planet Report 2016), species extinction rates surge (Ceballos et al. 2015; Alroy 2015; Webb and Mindel 2015), and ecosystems fragment, degrade and collapse (Valiela et al. 2001; Hansen et al. 2013). To halt further depletion of the Earth’s biological diversity and avoid detrimental impacts on human well-being (Millennium Ecosystem Assessment 2005), there is an urgent need not only to improve our ability to track changes in biodiversity and the pressures affecting it (Halpern et al. 2008; Pettorelli et al. 2014), but also to further our understanding of the relationships between biodiversity and ecosystem services (Geijzendorffer and Roche 2013; Harrison et al. 2014). Key to elucidating the mechanisms through which biological diversity generates services to humans is the concept of ecosystem functions (Duncan et al. 2015).

What ecosystem functions are and how they relate to biodiversity has been subjects of debate for decades, due partly to much confusion over definitions (Paterson et al. 2012; Roe et al. 2013). Biodiversity, as defined in the seminal paper by Noss (1990), possesses three primary attributes – composition, structure, and function – which can be tracked at multiple levels of biological organization, from ecosystem to population/species and genetic. This definition, which underpins the definition adopted by the United Nations Convention on Biological Diversity (CBD), makes it clear that biodiversity is a fundamentally multidimensional concept that includes ecosystem functions (Culman et al. 2010).

Interestingly, ecosystem functions are rarely measured, particularly over large areas, with biodiversity monitoring as a whole having historically been primarily based on structural and compositional features of the observed systems, rather than functional features (Callicott et al. 1999; Magurran 2004; Schröter et al. 2016). Past attempts to measure ecosystem functions have indeed been primarily undertaken at relatively small spatial extents, and can be grouped into four broad categories, namely: (i) proxy-based monitoring based on population and species data (Drever et al. 2008; Keinke and Samways 2012), (ii) process-based monitoring (such as using primary productivity to track changes in pollination; Werling et al. 2014), (iii) proxy-based monitoring based on genetic information (such as determining functional connectivity of populations; Braunisch et al. 2010) and (iv) trait-based monitoring [assuming either that high trait or functional diversity is a proxy for good ecosystem functioning (see e.g. Moretti and Legg 2009) or that dominant trait values determine the rates of functions (see e.g. Queirós et al. 2013; Solan et al. 2004)]. Most ecosystem assessments and conservation efforts then fail to account for functions due to a perceived lack of adequate spatial data to map these features (Tulloch et al. 2016), instead relying on species and structural data as surrogates for processes.

This reliance on compositional and structural features to track changes in ecosystem functions, as well as the current inability to map multiple functions across broad scales not only hampers our ability to expand our understanding of biodiversity-ecosystem services relationships, but also hinders the development of conservation management strategies (e.g. no-net loss strategies), impairs environmental impact assessments and limits our comprehension of what sustainable development should take into consideration (Fuhlendorf et al. 2006; Kollmann et al. 2016). Ecosystem functions may indeed sometimes respond more quickly to environmental change than structural or compositional attributes (McNaughton et al. 1989; Milchunas and Lauenroth 1995), and as such, could be among the most sensitive indicators of change when monitoring ecosystems globally (Daily et al. 2009; Haines-Young et al. 2012; Koschke et al. 2012).

Despite extensive discussion of the need for coordinated monitoring of ecosystem functions (Oliver et al. 2015), the practical implementation of such an approach is still lacking. Progress to recognize and fill this biodiversity monitoring gap has, however, been made in the past 10 years. Notably, the Red List of Ecosystems assessments, which are based on a set of criteria for performing evidence-based assessments of the risk of ecosystem collapse,
explicitly refer to the monitoring of ecosystem function-
ing (Keith et al. 2015). However, assessments undertaken
thus far have highlighted the relative lack of data on
ecosystem functioning, with 50% of them not assessing
functional criteria (L. Bland, pers. comm.). In parallel to
this, the Group on Earth Observations – Biodiversity
Observation Network (GEO BON) developed a frame-
work for biodiversity monitoring based on the concept of
essential biodiversity variables (EBVs) (Pereira et al.
2013), which includes a class for ecosystem functions.
However, so far no scientific consensus has been reached
on what exactly ecosystem functions are and how to track
them at scales beyond the site level; this lack of clarity has hampered progress in terms of identifying opportuni-
ties for ecosystem function monitoring globally.

To address these gaps, we propose the adoption of a
set of definitions and typology for ecosystem functions
relevant to both terrestrial and marine ecologists, build-
ing on previous efforts to identify and monitor ecosystem
functions (Petter et al. 2012; Meyer et al. 2015). Because
satellite remote sensing is the only methodology currently
able to provide global coverage and continuous measures
across space at relatively high spatial and temporal reso-
lutions (Skidmore et al. 2015; Pettorelli et al. 2016), we
subsequently provide an up-to-date perspective on the
current and future prospects of satellite remote sensing
for monitoring ecosystem functions in both the terrestrial
and marine realms, reviewing established products, high-
lighting new developments that have the greatest poten-
tial to make a difference to practitioners and policy
makers, and discussing potential limitations. We con-
clude by stressing opportunities for the proposed moni-
toring framework to inform relevant global policy initia-
tives.

Agreeing on What Ecosystem
Functions Are

Ecosystem processes, ecosystem functions
and ecosystem services

Ecosystem functions mean different things to different
people. Multiple definitions of ecosystem functions can
indeed be found in the literature and the term is often
used synonymously with ecosystem services (Srivastava
and Vellend 2005; Lamarque et al. 2011), ecological pro-
cesses (Lawton and Brown 1993) and ecosystem processes
(Dominati et al. 2010; Mace et al. 2012; see Table 1). Yet
without agreement on what ecosystem functions are
(Table 1), progress on our ability to monitor them is
likely to be slow and erratic.

To help identify an implementable framework for the
monitoring of ecosystem functions globally, we here
suggest adopting the following definitions of ecological
processes, ecosystem processes, ecosystem functions and
ecosystem services, which are applicable across all ecologi-
cal realms and integrate these concepts into a common
framework consistent with Noss’ (1990) definition of bio-
diversity (Fig. 1). Specifically, we considered three criteria
to select appropriate definitions of these terms, namely (i)
the proposed definitions should clearly separate functional
and structural/compositional properties of ecosystems; (ii)
they should clearly distinguish between organism- and
ecosystem-level properties; and (iii) they must allow inte-
grating all concepts (i.e. ecological processes, ecosystem
processes, ecosystem functions and ecosystem services) in
a common framework.

An overview of existing definitions of ecological pro-
cesses, ecosystem processes, ecosystem functions and
ecosystem services are provided in Table 1, together with
the rationale behind retaining or rejecting a given defini-
tion. Based on this approach, we here define ecological
processes as activities that result from interactions among
organisms and between organisms and their environment,
following Martinez (1996). Examples of ecological pro-
cesses thus include competition, herbivory, carnivory and
photosynthesis. Ecosystem processes are then understood
as transfers of energy, material, or organisms among pools
in an ecosystem, following the definition introduced by
Lovett et al. (2006). Examples of ecosystem processes
include primary production, decomposition, hetero-
trophic respiration and evapotranspiration. Similarly, we
propose to adopt the definition of ecosystem functions put
forward by Lovett et al. (2006), which states that ecosystem
functions are attributes related to the performance of
an ecosystem that are the consequence of one or multiple
ecosystem processes. Specifically, we understand ecosystem
functions as the direct and indirect benefits of ecosystem processes for a range of species, including
humans. Under this definition, examples of ecosystem
functions include nutrient regulation, food production
and water supply. Ecosystem services are finally defined as
the benefits human populations derive, directly or indi-
rectly, from ecosystem functions, following the definition
introduced by Costanza et al. (1997). Examples of ecosys-
tem services include food (refers to any nutritious sub-
stance that people, and/or other species that people value,
eto maintain life and growth, such as game, fish, crop)
production, raw material production (referring here to
raw material that people use, such as skin, fuel wood,
fodder), carbon sequestration, recreational experience and
cultural services. The key distinction between ecosystem
functions and services, as noted by Petter et al. (2012), is
that functions can have both intrinsic and potential
anthropocentric values, while services are defined only in
terms of their benefits to people.
Table 1. Coexisting definitions pertinent to the concepts of ecological processes, ecosystem processes, ecosystem functions and ecosystem services.

| Concept          | Definition                                                                 | Reference                  | Benefit/Drawback                                                                                                           |
|------------------|---------------------------------------------------------------------------|----------------------------|--------------------------------------------------------------------------------------------------------------------------|
| Ecological       | Activities that result from interactions among organisms and between organisms and their environment | Martinez (1996)            | This definition separates organism level processes from ecosystem level processes                                        |
| processes        | An interaction among organisms; ecological processes frequently regulate the dynamics of ecosystems and the structure and dynamics of biological communities | Mace et al. (2012)        | Incomplete: ecological processes should also include interactions between organism and their abiotic environment, since these have an important impact on organism-level attributes (such as survival) |
| Ecosystem        | Transfer of energy, material, or organisms among pools in an ecosystem     | Lovett et al. (2006)      | Clearly excludes organism-level processes; does not refer to stocks of materials                                          |
| processes        | Complex physical and biological cycles and interactions that underlie what we observe as the natural world | Brown et al. (2007)       | Vague; fails to establish the distinction between ecological and ecosystem processes                                       |
|                  | Changes in the stocks and/or flows of materials in an ecosystem, resulting from interactions among organisms and with their physical-chemical environment | Mace et al. (2012)       | Fails to establish the distinction between ecological and ecosystem processes                                             |
| Ecosystem        | Refer variously to the habitat, biological or system properties or processes of ecosystems | Costanza et al. (1997)    | Vague: fails to establish the distinction between ecosystem functions and ecosystem processes                              |
| functions        | Ecosystem processes and ecosystem stability                                | Bengtsson (1998)          | Fails to establish the distinction between ecosystem functions and ecosystem processes                                     |
|                  | Stocks of energy and materials (e.g. biomass), fluxes of energy or material processing (e.g. productivity, decomposition), and the stability of rates or stocks over time | Pacala and Kinzig (2002)  | Subsumes ecosystem structure (‘stock’) under the concept of ‘function’; fails to establish the distinction between ecosystem functions and ecosystem processes |
|                  | The capacity of natural processes and components to provide goods and services that satisfy human needs, directly or indirectly | De Groot et al. (2002)    | Fails to establish the distinction between ecosystem functions and ecosystem services                                      |
|                  | Attributes related to the performance of an ecosystem that is the consequence of one or of multiple ecosystem processes | Lovett et al. (2006)      | Explicitly relates the concept of ecosystem processes to ecosystem functions                                               |
|                  | The subset of the interactions between biophysical structures, biodiversity and ecosystem processes that underpin the capacity of an ecosystem to provide ecosystem services | Kumar (2010)              | Conflates structural and compositional attributes of biodiversity (‘stocks’) with functional aspects (‘fluxes’)           |
|                  | The ecological processes that control the fluxes of energy, nutrients and organic matter through an environment | Cardinale et al. (2012)   | Fails to establish the distinction between ecosystem processes, ecological processes and ecosystem functions             |
|                  | The energy, matter, and information fluxes linking ecosystem compartments | Meyer et al. (2015)       | Fails to establish the distinction between ecosystem processes and ecosystem functions                                      |
|                  | The biological underpinning of ecosystem services                        | Oliver et al. (2015)      | Vague; does not clearly separate function from structure                                                                   |
| Ecosystem        | The conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life | Daily (1997)              | Vague; the relationship between ecosystem functions and services is unclear                                                |
| services         | The benefits human populations derive, directly or indirectly, from ecosystem functions | Costanza et al. (1997)    | Provides a clear link to ecosystem functions                                                                               |
|                  | The benefits people derive from ecosystems                                 | Millennium Ecosystem      | Vague; the relationship between ecosystem functions and services is unclear                                                |
|                  | Ecosystem services are the aspects of the ecosystems utilized (actively or passively) to produce human well-being | Assessment (2005)         | Vague; the relationship between ecosystem functions and services is unclear                                                |
|                  | Direct and indirect contributions of ecosystems to human well-being       | Fisher et al. 2009        | Vague; the relationship between ecosystem functions and services is unclear                                                |
|                  | TEEB (2010)                                                               |                            | Vague; the relationship between ecosystem functions and services is unclear                                                |

(Continued)
Figure 1. Simplified representation of the links between ecological processes, ecosystem processes, ecosystem functions and ecosystem services. Decomposers, consumers and primary producers represent the main pools of a given ecosystem. Ecological processes mostly occur within each pool; examples of ecological processes are listed under each pool. Ecosystem processes capture the transfer of energy, material, or organisms among pools; examples of ecosystem processes appear in circles. Ecosystem functions represent attributes related to the performance of an ecosystem; they are the consequence of one or of multiple ecosystem processes. Finally, ecosystem services are those elements of ecosystem functions that benefit people.

Table 1. Continued.

| Concept                                                                 | Definition                                                                                                                                   | Reference                                      | Benefit/Drawback                                                                 |
|------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------|--------------------------------------------------------------------------------|
| Outputs of ecosystem processes that provide benefits to humans (e.g. crop and timber production) | Meyer et al. (2015) The relationship between ecosystem functions and services is unclear                                                   |                                               | Definition not as well-known as that of Costanza et al. 1997, but does not contradict it |
| Those functions and products of an ecosystem that directly or indirectly benefit humans. Often ecosystem functions are considered a service when they can be attributed an economical value | Oliver et al. (2015)                                                                                                                           |                                               |                                                                                 |

The definitions adopted for our framework appear in italic bold.
Introducing a typology of ecosystem functions

Although the concept of ecosystem function is not new (Odum 1969), only recently have attempts been made to identify and classify ecosystem functions. The first attempt to comprehensively identify and classify ecosystem functions can be traced to de Groot and colleagues in 2002; their list has been used by many as a starting point for establishing monitoring protocols for ecosystem functions and ecosystem services (see e.g. Wallace 2007; Petter et al. 2012). The main issue with this original classification is the confusion between ecosystem functions and ecosystem services, which led de Groot and colleagues to include ‘information functions’, such as aesthetic information, recreation, cultural and artistic information, spiritual and historic information, as well as science and education, in their typology of ecosystem functions. De Groot et al.’s typology was later refined by others, including Petter et al. (2012), who identified 19 terrestrial ecosystem functions. This typology is particularly relevant to developing an implementable global monitoring framework for ecosystem functions, as it was used by the authors to map these individual functions for the South East Queensland region in Australia. However, it does mention the existence of a cultural function, which reflects the interests of the authors in using ecosystem function mapping as a way to derive information about spatial variation in ecosystem services for this region. Because this cultural function was clearly based on anthropocentric values, it does not fit our definition of ecosystem functions. In the marine realm, typologies of ecosystem functions are also rarely discussed. One exception is the work by Boero and Bonsdorff (2007) who distinguished three broad groups of functions based on basic cycles of matter and energy, namely (i) extraspescific cycles (biogeochemical cycles), (ii) intraspecific cycles (life cycles and histories), and (iii) interspecific cycles (food webs). However, their definition of ecosystem functions does not distinguish between organism- and ecosystem-level processes.

We here propose a new ecosystem function typology, which broadens the definitions of the candidate functions identified by Petter and colleagues in 2012, making them relevant to all ecological realms. This new typology lines up with the widely accepted Millennium Ecosystem Assessment typology for ecosystem services (MEA 2005), thus allowing clear links between the two frameworks. Because we vetted our list against Lovett et al. (2006)’s definition of ecosystem functions (Table 2), our proposed typology excludes cultural functions (as they are ecosystem services), and thus only distinguishes 18 ecosystem functions, which are all shaped by different ecological and ecosystem processes (Table 2). These 18 functions can be broadly classified into regulating functions (which control the magnitude of ecosystem processes, such as climate regulation and biological control), provisioning functions (which provide all organisms with the resources necessary for their survival and reproduction, such as water supply and provision of food), and supporting functions (which underpin the continued functioning of the ecosystem, such as the formation and retention of soil and sediment, and pollination/larval and seed dispersal). A definition of each of these functions, as well as examples of ecological and ecosystem processes that underpin the delivery of these functions can be found in Table 2 and Figure 2.

Satellite Remote Sensing of Ecosystem Functions

Opportunities

A wealth of methods is currently available to monitor various ecosystem functions that rely on the collection of field data (Meyer et al. 2015); however, on their own, none can realistically be scaled up to reach global coverage on a regular (daily, weekly, monthly) basis. For example, Steenweg et al. (2017) suggest a framework for global monitoring of biodiversity with large-scale camera networks but major limitations include inconsistent metadata, data access, intellectual property and privacy considerations. Satellite remote sensing measurements, on the other hand, are widely accessible, and offer a relatively inexpensive and verifiable means of deriving complete spatial coverage of environmental information for large areas at different spatial and temporal resolutions in a consistent manner (Pettorelli et al. 2014), holding great potential for tracking changes in ecosystem functions (Cabello et al. 2012; Nagendra et al. 2013; Pettorelli 2013).

An agreed methodology for satellite remote sensing of ecosystem functions could offer many opportunities to advance ecology and conservation, allowing, for example, to test emerging theories and unveil the processes shaping the impacts of anthropogenic threats on biodiversity more rapidly. For example, selective defaunation of tropical forests from bushmeat hunting can lead to loss of aboveground biomass, reduced forest carbon sequestration and impacts on climate regulation (Jansen et al. 2010). Traditionally, these processes would be measured in the field (Camargo-Sanabria et al. 2015) at great expense (e.g. using plot-based tree censuses) but at scales that might not suffice to distinguish between changes in aboveground biomass and carbon storage (Harrison et al. 2013). In situations like this, the ability to track changes in these functions across broad regions using satellite data could enable more rapid detection of potential secondary
Table 2. Typology of ecosystem functions, with examples of ecological and ecosystem processes underpinning the delivery of a given function.

| Type               | Function                              | Description                                                                 | Ecological processes                                                                 | Ecosystem processes   |
|--------------------|---------------------------------------|-----------------------------------------------------------------------------|--------------------------------------------------------------------------------------|-----------------------|
| Regulating         | Gas regulation                        | Role of ecosystems in bi-geochemical cycles (such as CO₂/O₂ balance, ozone layer) | Cellular respiration<br>Coral reef calcification<br>Photosynthesis                    | Heterotrophic respiration<br>Evapotranspiration<br>Decomposition<br>Primary production<br>Decomposition |
|                    | Climate regulation                     | Influence of ecosystems on climate                                          |                                                                                      |                       |
|                    | Disturbance regulation                | Influence of ecosystem attributes on environmental disturbances            | Vegetation modulating surface resistance and infiltration<br>Wind and wave energy absorption by e.g. seagrasses and mangrove vegetation |                       |
|                    | Water regulation                       | Role of ecosystems in regulating runoff and river discharge                  | Vegetation modulating surface resistance and infiltration<br>Primary production<br>Evapotranspiration |                       |
|                    | Nutrient regulation                   | Role of ecosystems in the transport, storage and recycling of nutrients      | Herbivory<br>Predation<br>Mineralization<br>Nitrogen fixation<br>Marine bioturbation<br>Soil turnover (fossorial fauna) |                       |
| Biological control |                                       | The interactions within biotic communities that restrain the impact of outbreaks/blooms of specific populations of species on the functioning of the ecosystem, e.g. by controlling population of potential pests and disease vectors | Herbivory<br>Competition<br>Predation<br>Parasitism |                       |
| Provisioning       | Provision of food                     | Biomass that sustains living organisms. Material that can be converted to provide energy and nutrition. | Detrivory<br>Mineralization<br>Tree death<br>Coral death |                       |
|                    | Provision of raw materials            | Biomass that is used by organisms for any purpose other than food           |                                                                                      |                       |
|                    | Water supply                          | The role of ecosystems in providing water                                   | Vegetation facilitating infiltration<br>Primary production<br>Evapotranspiration<br>Primary production |                       |
|                    | Provision of shade/shelter            | Relates to vegetation/structures that ameliorates extremes in weather and climate at a local landscape/seascape scale | Tree death<br>Coral reef calcification<br>Herbivory<br>Predation<br>Competition |                       |
|                    | Pharmacological resources production  | Natural materials that are or can be used by organisms to maintain, restore or improve health | Herbivory<br>Predation<br>Competition<br>Tree death<br>Coral death |                       |
| Supporting habitats |                                       | Preservation of natural and semi-natural ecosystems as suitable living space for wild biotic communities and individual species. This function also includes the provision of suitable breeding, reproduction, nursery, refugia and corridors (connectivity). | Herbivory<br>Predation<br>Competition<br>Tree death<br>Coral death |                       |

(Continued)
effects of defaunation on tropical forest functions, allowing for more targeted field data collection and faster development and implementation of effective management actions (Osuri et al. 2016; Peres et al. 2016).

As with most conceptual frameworks that inform our understanding of the natural world (Stephens et al. 2015), ecosystem functions ultimately relate to entities that can be hard to measure directly and are the result of multiple ecosystem processes (Table 2; Fig. 2). Hence, the monitoring a given ecosystem function will mostly depend on the tracking of many relevant indicators. Table 3 provides a non-exhaustive list of open-access satellite remote sensing products that could contribute to the dynamic, global monitoring of ecosystem functions: as one can see, a range of ecosystem function indicators is already well supported by existing products (Table 3). In addition, upcoming satellite missions will increase the level of detail and accuracy with which we can map ecosystem functions, as well as opening new monitoring opportunities (Table 4). The Sentinel missions in particular could become a game changer for comprehensive global ecosystem function monitoring, since they (i) carry a range of sensors relevant to land, ocean and atmospheric monitoring; (ii) provide the only global, open-access radar imagery (Sentinel 1); (iii) allow gathering data at both high temporal (5 days) and spatial resolutions (5–10 m). Future spaceborne hyperspectral sensor missions (such as the Environmental Mapping and Analysis Program (EnMAP), the Hyperspectral Infrared Imager (HyspIRI), and the Hyperspectral Precursor of the Application Mission (PRISMA – Italian Space Agency) could moreover provide unprecedented opportunities to characterize surface chemistry and structure in great detail (Chambers et al. 2007). Data collected by these missions could indeed expand ecosystem monitoring capacity significantly, especially with regard to carbon and water vapour flux modelling (Fuentes et al. 2006), chemical composition of foliage (Schlerf et al. 2010), early detection of defoliators (Fassnacht et al. 2014), accurate mapping of burned areas (Veraverbeke et al. 2014), permafrost monitoring (Buchhorn et al. 2013) and measurements of ecosystem methane emissions (Thompson et al. 2015), complementing the monitoring capacity of existing sensors (Guanter et al. 2015). Monitoring of biomass (Hyde et al. 2007; Nelson et al. 2007) and canopy structure (Vierling et al. 2008; Lefsky 2010; Enßle et al. 2014) are also likely to be facilitated by the availability of global LiDAR data from spaceborne missions (e.g. ICESat-2 and GEDI; Patterson and Healey 2015; Brown et al. 2016). Beyond new satellite missions, advances in data processing are also likely to expand ecosystem function monitoring capacities. For instance, image fusion techniques allow combining imagery with high spatial, low temporal...
resolution (e.g. Landsat) and imagery with low spatial, high temporal resolution (e.g. MODIS) into time series with high spatial, high temporal resolution (Gao et al. 2006; Schmidt et al. 2015), which could support a better characterization of vegetation phenology.

**Limitations**

Monitoring ecosystem functions, using satellite data or ground-based information, first necessitates agreement on what ecosystem functions are, but also on what ecosystems are and where their boundaries lie (Likens 1992). Such difficulties are not limited to ecosystems, with similar discussions arising when considering populations or species (see e.g. Mallet 1995; Berryman 2002). The Red List of Ecosystems offers a comprehensive framework for defining and monitoring ecosystems (Bland et al. 2016), and as such could be used as a reference point for agreeing on where boundaries should be set. Doing so would allow complementarity and effectiveness in efforts to monitor, and report on, the state of ecosystems globally.

As demonstrated in Table 3, monitoring ecosystem function then involves making a number of choices in terms of which indicators and which proxies to consider; these choices may all have implications for the reliability of the inferred trends. Satellite remote sensing is moreover associated with intrinsic limitations, which have been discussed at length (see e.g. Petorelli 2013; Petorelli et al. 2014, 2016); one can thus expect data product characteristics (spatial, temporal, spectral resolutions) to influence mapping accuracy and monitoring opportunities for certain ecosystem functions in certain environments. Integrated use of multiple remote sensing sources and increased remote sensing capacity can help overcome many of these known challenges, as long as data and product requirements are clearly identified: the prioritization of new satellite missions associated with freely accessible data for scientific use might indeed be facilitated by the formulation of clear, consensual demands from ecosystem researchers (Paganini et al. 2016).

Discussions around the monitoring of ecosystem functions will need to involve clarity on which processes are being monitored for each considered ecosystem function; what the reliability and sensitivity of each considered proxy are; what aggregation method is being used (if any) to integrate the collated information relating to the ecosystem processes that shape a given ecosystem function; and how the choices made affect decision-making robustness in a given context (Stephens et al. 2015). Remote sensing proxies will often need to be combined with field measurements to accurately represent the desired ecosystem function (e.g. Tong et al. 2004). Indeed, joint analysis of satellite data with *in situ* measurements, or process measurements in the lab, may be essential steps to the refinement and increased capacity and utility of satellite-based indicators for ecosystem function monitoring (Racault et al. 2014). This is likely to be a non-trivial task, particularly in highly dynamic
### Table 3. Non-exhaustive list of freely available, global satellite remote sensing data products that open opportunities for the dynamic monitoring of ecosystem functions.

| Function                          | Indicator                        | Proxy                                                                 | Satellite (sensor)            | SRS data product                          | Examples                                                                 |
|-----------------------------------|----------------------------------|----------------------------------------------------------------------|-------------------------------|-------------------------------------------|-------------------------------------------------------------------------|
| **Gas regulation**                | Gas concentrations               | Total ozone burden                                                   | Terra/Aqua (MODIS)            | MODIS Atmospheric Profile product         | Spichtinger et al. (2001) used GOME-derived nitrogen oxide concentration to map emissions from boreal forest fires. |
|                                   |                                  |                                                                     | Nimbus-7/Meteor-3/Earth Probe | Total Ozone Mapping Spectrometer (TOMS) (1978-2006) | Ribeiro et al. (2016) used the Aqua (AIRS) Methane product to link methane concentrations over the Amazon to wetness and biomass burning. |
|                                   |                                  |                                                                    | Sentinel-5P (TROPOMI)         | O₂ tropospheric profile                   |                                                                         |
|                                   |                                  |                                                                    | Aqua (AIRS)                   | Methane product                           |                                                                         |
| **Emissions of gases by ecosystems** | Total methane burden             |                                                                     | Multiple, including POES (AVHRR), Terra/Aqua (MODIS), TRMM (CERES) | NOAA AOML Surface O₂ Flux maps (1982–2009) |                                                                         |
|                                   | Air-sea CO₂ flux                 |                                                                     |                                |                                            |                                                                         |
| **Climate regulation**            | Temperature regulation           | Land and sea surface temperature                                     | Terra/Aqua (MODIS)            | MODIS Land Surface Temperature and Emissivity | Jin and Dickinson (2010) used Terra (MODIS) data to derive land skin temperature and investigate its relationship with local surface albedo and vegetation, among other parameters. |
|                                   |                                  |                                                                    | POES (AVHRR)                  | MODIS Sea Surface Temperature             |                                                                         |
|                                   |                                  |                                                                    | Sentinel 3 (SLSTR)            | NOAA Coral Reef Watch Sea Surface Temperature |                                                                         |
| **Precipitation regulation**      | Rainfall                         |                                                                     | TRMM (PR, TMI, VIIRS, CERES)  | TRMM precipitation estimates (1998–2015)   |                                                                         |
|                                   |                                  |                                                                    | TRMM (PR, TMI, VIIRS, CERES)  | CHIRPS                                    |                                                                         |
|                                   |                                  |                                                                    | TRMM (PR, TMI, VIIRS, CERES)  | GPCP                                      |                                                                         |
| **Evapotranspiration**            |                                  |                                                                    | Terra/Aqua (MODIS)            | MODIS evapotranspiration                   |                                                                         |
|                                   |                                  |                                                                    | Landsat (TM, ETM+, OLI/IRS)   | Landsat evapotranspiration                 |                                                                         |
| **Cloud cover**                   |                                  |                                                                    | Terra/Aqua (MODIS)            | MODIS Cloud Cover                         |                                                                         |
|                                   |                                  |                                                                    | CloudSat (CALIPSO)            | CALIPSO Cloud Cover (2006-2011)            |                                                                         |
| **Ocean carbon cycle regulation** | Coral reef calcification         |                                                                     | Merged MERIS, Aqua-MODIS, SeaWIFS and VIIRS data | ESA Ocean Colour CCI product               |                                                                         |
|                                   |                                  |                                                                    |                                |                                            |                                                                         |
| **Disturbance regulation**        | Fire occurrence                  | Fire hotspots                                                       | Terra/Aqua (MODIS)            | MODIS FIRMS                                | Hantson et al. (2015) used the MODIS Burned Area product to investigate what drives the distribution of fire extent worldwide. |
|                                   | Extent of fire damages            | Extent of burned area                                               | Terra/Aqua (MODIS)            | MODIS Burned Area Product                  |                                                                         |
|                                   |                                  |                                                                    | SPOT (HRV, HRVIR, HRG)        | SPOT VGT Burned Area                       |                                                                         |
| **Flood occurrence**              | Standing water                   |                                                                     | Terra/Aqua (MODIS)            | NRT Global Flood Mapping                   | NOAA CRW products were used to monitor the Great Barrier Reef during the 2002 bleaching event (Liu et al. 2003). |
|                                   |                                  |                                                                    | TRMM (CERES)                  | Global Flood Monitoring System             |                                                                         |
|                                   |                                  |                                                                    | DMS (SSM/I), ERS-1, POES (AVHRR) | Global Inundation Extent from Multi-Satellites (1993–2007) |                                                                         |
| **Drought occurrence**            | Standardized precipitation index (SPI) | Water-content in standing vegetation                           | TRMM (PR, TMI, VIIRS, CERES)  | Satellite-Based Global Drought Climate Data Record | Harvey et al. (2015) used MERIS data to monitor chlorophyll-a concentration in coastal waters. |
|                                   |                                  |                                                                    |                                | Vegetation Optical Depth from VUA-NASA Land Parameter Retrieval Model |                                                                         |
|                                   |                                  |                                                                    | Nimbus-7 (SMMR), DMS (SSM/I), TRMM (TMI) |                                            |                                                                         |

(Continued)
Table 3. Continued.

| Function                  | Indicator                          | Proxy                                      | Satellite (sensor)                       | SRS data product                          | Examples                                                                 |
|---------------------------|------------------------------------|--------------------------------------------|------------------------------------------|-------------------------------------------|--------------------------------------------------------------------------|
| Defoliator outbreaks      | Changes in maximum NDVI            | POES (AVHRR)                              | Terra/Aqua (MODIS)                       | GIMMS NDVI (1981–2011)                    | Spruce et al. (2011) used MODIS NDVI time series to map defoliation by European gypsy moth Lymantria dispar in North America. |
| Coral bleaching           | Sea surface temperature            | POES (AVHRR)                              | Terra/Aqua (MODIS)                       | MODIS NDVI                                |                                                                          |
|                           | Hotspots of sea surface temperature| POES (AVHRR)                              | Terra/Aqua (MODIS)                       | NOAA Coral Reef Watch products            |                                                                          |
|                           | Degree Heating Weeks               | POES (AVHRR)                              | Terra/Aqua (MODIS)                       | NOAA Coral Reef Watch products            |                                                                          |
|                           | Bleaching Alert Areas              | POES (AVHRR)                              | Terra/Aqua (MODIS)                       | NOAA Coral Reef Watch products            |                                                                          |
| Eutrophication of water bodies | Ocean Colour   | POES (AVHRR)                              | Terra/Aqua (MODIS)                       | Ocean colour (total suspended matter) data from MERIS, MODIS and SeaWiFS |                                                                          |
|                           |                                    | ENVISAT (MERIS)                           | Terra/Aqua (MODIS)                       |                                            |                                                                          |
|                           |                                    | Terra/Aqua (MODIS)                        | Orb-View-2 (SeaWiFS)                     |                                            |                                                                          |
|                           |                                    | Sentinel 3 (OLCI)                         |                                          |                                            |                                                                          |
| Water regulation          | Inland water dynamic               | Change in water stage                     | Sentinel 3 (SRAL)                        | Sentinel 3 altimetry (lakes level)        |                                                                          |
|                           |                                    | Water body distribution                   | Terra/Aqua (MODIS)                       | MODIS Water Mask                         |                                                                          |
|                           |                                    |                                          | Landsat (TM, ETM+)                       | Global Surface Water (1984–2015)          |                                                                          |
| Soil/Sediment retention  | Sediment plumes                    | Turbidity                                 | ENVISAT (MERIS)                          | Ocean colour (total suspended matter) data from MERIS, MODIS and SeaWiFS | Valente and da Silva (2009) used an MODIS Ocean Colour product to monitor a turbid plume in an estuary. |
|                           |                                    |                                          | Terra/Aqua (MODIS)                       |                                            |                                                                          |
|                           |                                    |                                          | Orb-View-2 (SeaWiFS)                     |                                            |                                                                          |
|                           |                                    |                                          | Sentinel 3 (OLCI)                        |                                            |                                                                          |
| Nutrient regulation       | Nutrient availability              | Suspended sediment                         | Many, including ENVISAT (MERIS), Terra/Aqua (MODIS), Orb-View-2 (SeaWiFS), VIIRS | Suspended sediment concentration         | Huang et al. (2014) used Landsat and MODIS data to characterize eutrophication in response to land use change in a lake's catchment. |
|                           |                                    | Algal bloom                               |                                           |                                            |                                                                          |
| Pollination               | Vegetation phenology               | Chlorophyll-α concentration               | Many, including MODIS, MERIS, VIIRS, GOCI, SeaWiFS, CZCS | Chlorophyll-α product from NASA Ocean Color project | Schulp and Alkemade (2011) mapped pollination efficiency using the GLOBCOVER land cover product. |
|                           |                                    | Temporal dynamics of seasonal changes in vegetation indices | Terra/Aqua (MODIS)                       | MODIS NDVI                                |                                                                          |
|                           |                                    | SRS-based primary productivity estimates | Terra/Aqua (MODIS)                       | AVHRR NDVI3 g (1981–2011)                 |                                                                          |
|                           |                                    |                                          | Metop (AVHRR)                            | MODIS EVI                                 |                                                                          |
| Biological control        | Defoliator control                 | Changes in maximum NDVI                   | Terra/Aqua (MODIS)                       | MODIS NDVI                                |                                                                          |
| Function                          | Indicator        | Proxy                                | Satellite (sensor)                          | SRS data product                                      | Examples                                                                 |
|----------------------------------|------------------|--------------------------------------|--------------------------------------------|-------------------------------------------------------|--------------------------------------------------------------------------|
| Barrier effect of vegetation     | Vegetation barriers | Forest cover | Landsat (TM, ETM+, OLI) | Landsat Global Forest Cover Change (2000–2012) | Carniello et al. (2014) used Landsat-derived maps of benthic vegetation to account for their barrier effect in a model of coastal sediment dynamics. |
|                                  |                  | Tree cover                             | Terra/Aqua (MODIS)                         | MODIS Land Cover Type                                 |                                                                          |
|                                  |                  |                                      | Landsat (TM, ETM+, OLI)                    | MODIS Vegetation Continuous Fields (2000–2013)        |                                                                          |
|                                  |                  |                                      | Terra/Aqua (MODIS)                         | Landsat Tree Cover Continuous Fields (2000 & 2005)    |                                                                          |
|                                  |                  |                                      | Landsat (TM, ETM+, OLI)                    | MODIS Land Cover Type                                 |                                                                          |
|                                  |                  |                                      | Land cover                                | MODIS Vegetation Continuous Fields (2000–2014)        |                                                                          |
|                                  |                  |                                      | Terra/Aqua (MODIS)                         | MODIS Land Cover Type                                 |                                                                          |
|                                  |                  |                                      | Terra/Aqua (MODIS)                         | MODIS Vegetation Continuous Fields (2000–2013)        |                                                                          |
|                                  |                  |                                      | Terra/Aqua (MODIS)                         | Landsat Tree Cover Continuous Fields (2000 & 2005)    |                                                                          |
| Air quality                      | Aerosol particles | Terra (MODIS)                          | Aerosol Optical Thickness                  |                                                        |                                                                          |
|                                  |                  |                                      | CALIPSO (CALIOP/IIR/WFC)                  | CALIPSO All-Sky Aerosol Extinction product            |                                                                          |
|                                  | Nitrogen dioxide | Metop (GOME)                           | GOME or SCIAMACY Nitrogen Dioxide          |                                                        |                                                                          |
|                                  | Sulfur dioxide   | Aura (OMI)                             | OMI/Aura sulfur dioxide abundance          |                                                        |                                                                          |
| Wind speed                       |                  |                                      | OMI/Aura                                   |                                                        |                                                                          |
| Supporting habitats              | Habitat extent   | Land cover                             | ESA global land cover maps for 2000, 2005 and 2010 (MERIS and SPOT) | Harwood et al. (2016) improved habitat condition assessments across Australia using two land cover products (based on AVHRR and MODIS). |
|                                  |                  |                                      | Terra/Aqua (MODIS)                         | MODIS Land Cover Type                                 |                                                                          |
|                                  |                  | Forest cover                           | Landsat (TM, ETM+, OLI)                    | Landsat Global Forest Cover Change (2000–2014)        |                                                                          |
|                                  |                  |                                      | Terra/Aqua (MODIS)                         | MODIS Land Cover Type                                 |                                                                          |
|                                  |                  | Tree cover                             | Terra/Aqua (MODIS)                         | MODIS Vegetation Continuous Fields (2000–2013)        |                                                                          |
|                                  |                  |                                      | Terra/Aqua (MODIS)                         | Landsat Tree Cover Continuous Fields (2000 & 2005)    |                                                                          |
|                                  |                  |                                      | Landsat (TM, ETM+, OLI)                    | MODIS Water Mask                                      |                                                                          |
| Water body distribution          |                  |                                      | Terra/Aqua (MODIS)                         |                                                        |                                                                          |
| Inland water dynamic Sea ice     |                  |                                      | Land cover                                |                                                        |                                                                          |
|                                  |                  | Sea ice                               | Global Surface Water (1984–2015)          |                                                        |                                                                          |
|                                  |                  |                                      | nimbus-7 (SMMR)                            | Sea Ice Concentration (from Nimbus-7 and DMSP)         |                                                                          |
|                                  |                  |                                      | DMSP (SSMI, SSMIS)                         | GRACE Monthly surface mass changes                    |                                                                          |
|                                  |                  |                                      | GRACE (KBR)                                |                                                        |                                                                          |
|                                  |                  |                                      | Cryostat (SIRAL)                           | Cryostat ice thickness                                |                                                                          |
|                                  |                  |                                      | Terra (ASTER)                              |                                                        |                                                                          |
| Glaciers                         |                  |                                      | GLIMS                                      |                                                        |                                                                          |
| Habitat quality                  | Salinity         | SMOS (Miras)                           | SMOS salinity                              |                                                        |                                                                          |
|                                  |                  | SAC-D (Aquarius)                       | Aquarius sea surface salinity (2011–2015)   |                                                        |                                                                          |

(Continued)
| Function          | Indicator                      | Proxy                          | Satellite (sensor)                          | SRS data product                                      | Examples                                                                 |
|-------------------|--------------------------------|--------------------------------|---------------------------------------------|-------------------------------------------------------|-------------------------------------------------------------------------|
| Sediment formation| Deposition                     | Surface particle size distribution | Terra (ASTER)                              | MODIS Sea Surface temperature                        | Villar et al. (2013) used MODIS surface reflectance data to predict sedimentation rates in a river |
| Food              | Production of vegetal biomass  | SRS-based primary productivity estimates | Terra/Aqua (MODIS)                          | MODIS Gross Primary Production/Net Primary Production | Malmstrom et al. (2009) used Landsat-derived biomass estimates to investigate effects of different grassland restoration treatments on forage availability |
|                   |                                |                                | Soil moisture                                | MODIS Chlorophyll α                                   |                                                                         |
|                   |                                |                                | Multiple, including ERS-1/2, Metop, DMSP/SSMI, TRMM/TMI | MODIS Soil Moisture                                   |                                                                         |
|                   |                                |                                | Vegetation indices                           | MODIS FAPAR                                            |                                                                         |
|                   |                                |                                | Terra/Aqua (MODIS), Terra/Aqua (MODIS), Terra/Aqua (MODIS) | MODIS LAI                                              |                                                                         |
|                   |                                |                                | Terra/Aqua (MODIS)                            | MODIS Chlorophyll α                                   |                                                                         |
|                   |                                |                                | Terra/Aqua (MODIS)                            | MODIS Land Cover                                       |                                                                         |
|                   |                                |                                | Terra/Aqua (MODIS)                            | MODIS Sea Surface temperature                         |                                                                         |
| Raw materials     | Wood and NTFP                  | Tree cover                      | Terra/Aqua (MODIS)                           | MODIS Vegetation Continuous Fields (2000-2013)       | Cudahy et al. (2016) used ASTER to map mineral composition of vegetation-free surfaces across Australia |
|                   |                                |                                | Landsat (TM, ETM+, OLI)                      | Landsat Tree Cover Continuous Fields (2000 & 2005)    |                                                                         |
| Water supply      | Water availability             | Evapotranspiration              | Terra/Aqua (MODIS)                           | MODIS evapotranspiration                              | Senay et al. (2013) used ASTER surface reflectance to map water holes in semi-arid rangelands and then used satellite-derived precipitation and digital elevation to monitor their water levels |
|                   |                                |                                | Landsat (TM, ETM+, OLI/TIRS)                 | Landsat evapotranspiration                            |                                                                         |
|                   |                                |                                | Many, including Terra/Aqua (MODIS), TRMM (CERES), DMSP (SSMI) | Evapotranspiration data from the Global Land Evaporation Amsterdam Model (GLEAM) |                                                                         |
|                   |                                |                                | Terra/Aqua (MODIS)                            | MODIS Snow Cover                                       |                                                                         |
|                   |                                |                                | Snow cover                                   |                                                        |                                                                         |
| Function                  | Indicator                      | Proxy                  | Satellite (sensor)       | SRS data product                                      | Examples                                                                 |
|---------------------------|--------------------------------|------------------------|--------------------------|-------------------------------------------------------|---------------------------------------------------------------------------|
| Provision of shade and shelter | Extent to which vegetation shades the ground | Tree cover             | Terra/Aqua (MODIS)       | MODIS Vegetation Continuous Fields (2000-2013)       | Huang et al. (2016) produced a MODIS snow cover product to estimate spatio-temporal changes in snow cover across China |
|                           |                                |                        | Landsat (TM, ETM+, OLI)  | Landsat Tree Cover Continuous Fields (2000 & 2005)    | Guzy et al. (2015) use LiDAR to estimate the effect of riparian vegetation cover on urban stream shade and stream restoration potential |
| Pharmacological resources | Availability of plants          | Plant canopy           | Terra/Aqua (MODIS)       | MODIS Leaf Area Index                                 | No example found for this particular function                              |
|                           |                                |                        | Terra/Aqua (MODIS)       | MODIS Gross Primary Production/Net Primary Production |                                                                           |

Most are currently routinely produced; discontinued products (based on existing sensors) were included too, when they could conceivably contribute to elaborating a monitoring scheme for a given function (since routine production could be resumed). In such cases, the time period for which they are available was stated.

AIRS, Atmospheric Infrared Sounder; AOML, Atlantic Oceanographic and Meteorological Laboratory; ASTER SWIR and TIR, Advanced Spaceborne Thermal Emission and Reflection Radiometer Short Wave Infrared and Thermal Infrared; AVHRR, Advanced Very High Resolution Radiometer; AVISO, Archiving, Validation and Interpretation of Satellite Oceanographic data; CALIOP, Cloud-Aerosol Lidar with Orthogonal Polarization; CALIPSO, Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation; CCl, Climate Change Initiative; CERES, Clouds and the Earth's Radiant Energy System; CHIRPS, Climate Hazards Group Infrared Precipitation with Station data; CZCS, Coastal Zone Color Scanner; DMSP, Defense Meteorological Satellite Platform; ENVISAT, Environmental Satellite; ERS, European Remote Sensing Satellites; ESA, European Space Agency; ETM+, Enhanced Thematic Mapper Plus; EVI, Enhanced vegetation index; FAPAR, Fraction of absorbed Photosynthetic Active Radiation; FIRMS, Fire Information for Resource Management System; GIMMS, Global Modeling and Mapping Studies; GLIMS, Global Land Ice Measurements from Space; GOCI, Geostationary Ocean Color Imager; GOME, Global Ozone Monitoring Experiment; GPCP, Global Precipitation Climatology Project; GRACE, Gravity Recovery And Climate Experiment; GFSC, Goddard Space Flight Center; HRG, High Resolution Geometric; HRVR, High Resolution Visible; IIR, Infrared Imaging Radiometer; KBR, K-Band Ranging System; LAI, Leaf Area Index; MERIS, Medium Resolution Imaging Spectrometer; MIRAS, Microwave Imaging Radiometer with Aperture Synthesis; MODIS, Moderate Resolution Imaging Spectroradiometer; NASA, National Aeronautics and Space Administration; NDVI, Normalized Difference Vegetation Index; NFTP, Non-Timber Forest Product; NOAA, National Oceanic and Atmospheric Administration; NRT, Near Real Time; OLCI, Ocean and Land Colour Instrument; OLI, Operational Land Imager; POES, Polar Operational Environmental Satellites; PR, Precipitation Radar; SAC-D, Satelite de Aplicaciones Cientificas; SCIAMACHY, Scanning Imaging Absorption Spectrometer for Atmospheric Cartography; SeaWiFS, Sea-viewing Wide Field-of-view Sensor; SIRAL, Synthetic Aperture Interferometric Radar Altimeter; SMAP, Soil Moisture Active Passive; SMMR, Scanning Multichannel Microwave Radiometer; SMOS, Soil Moisture and Ocean Salinity; SPOT, Satellite Pour l’Observation de la Terre; SSMI, Special Sensor Microwave Imager; SSMIS, Special Sensor Microwave Imager Sounder; TIRS, Thermal Infrared Sensor; TM, Thematic Mapper; TRMM Microwave Imager; TROPOMI, Tropospheric Monitoring Instrument; OMI, Ozone Monitoring Instrument; TRMM, Tropical Rainfall Measuring Mission; VGT, Vegetation; VIRR, Visible Infrared Imaging Radiometer Suite; VIRS, Visible and Infrared Scanner; VUA, VU University Amsterdam; WFC, Wide Field Camera.
Table 4. Non-exhaustive list of potential future satellite remote sensing data products that could expand ecosystem function monitoring capacity.

| Function | Indicator | Proxy | Satellite (sensor) | SRS data product |
|----------|-----------|-------|--------------------|------------------|
| Gas regulation | Emissions of gases by ecosystems | Emissions from fire | HyspIRI (VSWIR/TIR) | HyspIRI fire emissions |
| Climate regulation | Precipitation regulation | Evapotranspiration | HyspIRI (VSWIR/TIR) | HyspIRI evapotranspiration |
| | Ocean carbon cycle regulation | Oceanic particulate organic carbon stock | Aqua (MODIS) | Potential future product |
| | | Oceanic biological carbon stock | ESA-CCI | Potential future product |
| | | Ocean acidification | NOAA | Potential future product |
| Disturbance regulation | Fire occurrence | Fire hotspots | HyspIRI (VSWIR/TIR) | HyspIRI fuel status |
| | | Fire temperature | Sentinel 3 (SLSTR) | Sentinel 3 Fire temperature |
| | Extent of fire damages | Extent of burned area | Proba V (Vegetation) | Proba V Burned Area |
| | | | HyspIRI (VSWIR/TIR) | HyspIRI biomass burning |
| | | | Sentinel 2, Sentinel 3 (OLCI, SLSTR) | Sentinel 2 and 3 Burnt Area |
| Flood occurrence | Standing water | Terra/Aqua (MODIS) | MODIS daily surface water extent (using the Open Water Likelihood algorithm) |
| Defoliator outbreaks | Changes in maximum NDVI | Proba V (Vegetation) | Proba V NDVI |
| Coral bleaching | Status of coral reefs | HyspIRI (VSWIR/TIR) | HyspIRI global composition and status of coral reefs and coastal habitats |
| Eutrophication of water bodies | Chlorophyll-α concentration | Sentinel 3 (OLCI) | Ocean chlorophyll |
| Water regulation | Inland water dynamic | Change in surface water extent | Terra/Aqua (MODIS) | MODIS daily surface water extent (using the Open Water Likelihood algorithm) |
| Nutrient regulation | Nutrient availability | Change in water stage | TRMM (PR, TMI, VIRS, CERES) | Water stage (Puri et al. 2011) |
| Waste treatment and assimilation | Presence of waste products in the soil | Soil nitrogen/presence of heavy metals | Landsat (TM) | Ocean chlorophyll |
| | | | | Soil nitrogen/heavy metals derived from surface reflectance (Peng et al. 2016) |
| Pollination | Vegetation phenology | Timing and magnitude of seasonal changes in Normalized Difference Vegetation Index (NDVI) | Proba V (Vegetation) | Proba V NDVI |
| | | | Landsat (TM, ETM+, OLI) | NDVI derived from Landsat surface reflectance product alone or derived from MODIS-Landsat fused time series (Hilker et al. 2009; Walker et al. 2012) |
| | | | Terra/Aqua (MODIS) | MODIS Visible atmospherically resistant index (VARI) |
| | | | | EnMAP terrestrial phenology |
| | | | | FLEX photosynthetic activity |
| Production of biomass | SRS-based estimates of primary productivity | Timing and magnitude of other vegetation indices | Sentinel 2 (MSI) | FLEX primary productivity |
| | | | Terra/Aqua (MODIS) | Proba V vegetation productivity index |
| | | | | EnMAP vegetation productivity index |
| | | | | SPOT VGT or Proba V Dry Matter Productivity product |

(Continued)
| Function | Indicator | Proxy | Satellite (sensor) | SRS data product |
|----------|-----------|-------|-------------------|-----------------|
| Biological control | Defoliator control | Changes in maximum NDVI | Proba V (Vegetation) | Proba V NDVI |
| | | | Landsat (TM, ETM+, OLI) Terra/Aqua (MODIS) | NDVI derived from Landsat surface reflectance product alone or derived from MODIS-Landsat fused time series (Hilker et al. 2009; Walker et al. 2012) |
| | | | Sentinel 2 (MSI) | NDVI derived from Sentinel 2 |
| | | | Defoliator presence | EnMAP or HyspIRI Infestation Identification |
| Harmful algal bloom control | Harmful algal bloom extent | Harmful algal bloom extent | EnVISAT (MERIS) Terra/Aqua (MODIS) | Harmful algal blooms derived from ocean colour (total suspended matter) data from MERIS, MODIS and SeaWIFS (Kurekin et al. 2014) |
| Barrier effect | Vegetation barriers | Tree cover | Proba V (Vegetation) | Proba V Fraction of green vegetation Cover |
| of vegetation | Air quality | Aerosol particles | HyspIRI (VSWIR/TIR) | HyspIRI carbon and dust on snow/ice |
| Supporting habitats | Habitat extent | Land cover | Sentinel 1 (SAR), Sentinel 2 (MSI), Sentinel 3 (OLCI & SLSTR) | Sentinel Land cover |
| | | | Tree Cover | Proba V Fraction of green vegetation Cover |
| | | | Vertical vegetation structure | LiDAR vertical structure |
| | | | Water body distribution | Proba V Water Bodies product |
| | | | Sea ice | EnVISAT ice thickness |
| | | | Glaciers | IceSat-2 ice thickness |
| | | | Sentinel 2 (MSI) | Sentinel-2 Glacier area, LSSIA and snowline |
| | | | Sentinel 1 (SAR) | Sentinel-1 glacier surface topography |
| | | | Snow Cover | Snow Cover Area Global |
| | | | Albedo | Surface albedo |
| | | | Proba V (Vegetation) | Surface albedo |
| Habitat quality | | Primary productivity | EnMAP (VNIR/SWIR) | EnMAP terrestrial and aquatic phenology |
| | | Vegetation condition | Proba V (Vegetation) | Proba V vegetation condition index |
| | | Vegetation indices | Proba V (Vegetation) | Proba V FPAR |
| | | | Proba V (Vegetation) | Proba V LAI |
| | | | Proba V (Vegetation) | Sentinel 2 and 3 Chlorophyll and Leaf Area Index (LAI) |
| Food | Production of vegetal biomass | Biomass | Sentinel 1 (SAR) | Sentinel 1 biomass |
| | | | Proba V (Vegetation) | Proba V Fraction of green vegetation cover |
| | | | Proba V (Vegetation) | Proba V surface mineral resources |
| Raw materials | Wood and NTFP | Tree cover | HyspIRI (VSWIR/TIR) | HyspIRI evapotranspiration |
| | | | Proba V (Vegetation) | Proba V Water Bodies product |
| | Mineral resources | | | |
| Water supply | Water provision | Evapotranspiration | HyspIRI (VSWIR/TIR) | |
| | | | Water body distribution | |
| | | | Proba V (Vegetation) | |

(Continued)
areas such as coastal waters and the seabed (Tilstone et al. 2017). Remote sensing products are moreover unlikely to fill all of the needs of conservation decision-makers, scientific research, and environmental assessment focused on tracking or improving ecosystem function, because these needs are defined at different spatial and temporal extents and resolutions, and come with differences in expectations. Given that most data collected to track ecosystem functions will be surrogates (whether it be remotely-sensed, gathered through on-ground monitoring programs, or a combination of both), assessing and acknowledging the expected benefits and limitations of the measured quantity, in terms of accuracy, representativeness, cost, and sensitivity will ultimately be key (Lindentmayer et al. 2015).

The list of satellite remote sensing products relevant to monitoring ecosystem function is likely to change rapidly as efforts to integrate ecosystem function in ecosystem assessments increase, knowledge and technology advances, and costs of data access and processing diminish. Consequently, product users could struggle to maintain an up-to-date knowledge of available data and tools, and decide on how to best derive trends from datasets generated by sensors covering different periods and that have different specifications. To improve on the use of satellite remote sensing data to monitor ecosystem functions, and fully capitalize on current and future opportunities, will require the sharing of information between data providers, ecologists, ecosystem modellers and remote sensing experts interested in ecosystem function monitoring. For this to happen, a clear and common platform for discussion and communication of data products urgently needs to be identified, with well-defined terminology, conceptual translation across disciplines, provision for data sharing and version controls, and communication of the development and capabilities of relevant new technologies. To make such a platform a reality requires identifying who will take responsibility for (i) developing the platform; (ii) updating the information provided on a regular basis, (iii) managing and optimizing engagement with potential users and (iv) securing its viability in the long term. It also requires consistent and continuing funding being allocated to the development and maintenance of such a platform. Such interdisciplinary communication actions may benefit from lessons learned through similar efforts across these communities, e.g. ecosystem model development (Queirós et al. 2015).

The use of satellite remote sensing data to monitor ecosystem functions necessitates practical and/or theoretical training, particularly related to ecology and the geophysical sciences, as well as knowledge in remote sensing; yet few ecologists and conservation biologists typically

| Table 4. Continued. |
|---------------------|
| Function | Indicator | Proxy | SRS data product |
| Water quality | Water quality, EnMAP SRS-based estimates of water quality | EnMAP (VNIR/SWIR) | EnMAP water quality and availability |
| Shade and shelter | Shade and shelter, Proba V Fraction of green vegetation Cover | Proba V (Vegetation) | Proba V Fraction of green vegetation Cover |
| Provision of shade and shelter | Provision of shade and shelter, Sentinel 2 (MSI) | Sentinel 2 (MSI) | Sentinel 2 Leaf Area Index |
| ASAR, Advanced Synthetic Aperture Radar; ATLAS, Advanced Topographic Laser Altimeter System; CCI, Climate Change Initiative; CERES, Clouds and the Earth’s Radiant Energy System; EnMAP, Environmental Mapping and Analysis Program; ENVISAT, Environment Dynamics, Investigation; EOM, European Space Agency; ETM+, Enhanced Thematic Mapper Plus; FLEX, Fluorescence Explorer; FLORIS, FLuORescence Imaging Spectrometer; GEDI, Global Ecosystem Dynamics Investigation; HRR, High Resolution Radiometer; HRG, High Resolution Geometric; HRV, High Resolution Visible; MODIS, Moderate Resolution Imaging Spectroradiometer; OLI, Operational Land Imager; PR, Precipitation Radar; SAR, Synthetic Aperture Radar; SeaWiFS, Sea-viewing Wide Field-of-view Sensor; SLSTR, Sea and Land Surface Temperature Radiometer; SSM/I, Special Sensor Microwave Imager; SVNIR, Visible and Near Infrared; VGT, Vegetation; PRT, VSWIR, Visible and Short Wave Infrared; VHR, High Resolution Radiometer; VHR, Visible and Short Wave Infrared; VNR, Visible and Near Infrared. |

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receive this type of training (Cabello et al. 2012; Pettorelli et al. 2014). Conceptual models of ecosystem functions are a possible nexus of ecosystem process and remote sensing expertise (see Fig. 2), similar to and/or informed by the conceptual ecosystem models developed as part of Red List of Ecosystems assessments (Bland et al. 2016). Potential differences in the conceptual understanding of causality in the drivers of ecosystem processes across disciplines may in this way become apparent, and clarity of understanding promoted across different foci of expertise. By making the variables underpinning ecosystem functions and the relationships between them explicit, such models can help identify a minimum set of agreed variables needed to monitor a given ecosystem function. Opportunities for monitoring these variables via remote sensing could then be systematically identified, focussing on user needs, and gaps in monitoring capacity prioritized. Ultimately, without common references and definitions, and centralized, jointly developed platforms such as these, rapid advances are unlikely.

**Policy Implications**

In 2011, parties of the CBD adopted a strategic plan for the period until 2020 based on 20 targets of which two address the conservation (Target 11) and restoration (Target 15) of ecosystems services, whose monitoring partially relies on ecosystem function monitoring (Fig. 1). Currently, very little information on the state of ecosystem functions and services is available from the Biodiversity Indicators Partnership, a global initiative to promote and coordinate the development and delivery of biodiversity indicators for use by the CBD and other biodiversity-related conventions, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, the Sustainable Development Goals and national and regional agencies. While satellite remote sensing could help track progress towards the CBD targets on ecosystems services (Secades et al. 2014), considerations have so far been limited to carbon and water-based ecosystem services. Satellite applications to the monitoring of ecosystem function and services are also exceptionally well placed to support the achievement of Target 14. A of the United Nations Sustainable Development Goal 14, aimed at the development of research capacity and transfer of marine technology in support of ocean health and the development of nations reliant on living marine resources. But achievement of the aims of the Sustainability Agenda under the United Nations system are currently heavily focused on regional cooperation for data acquisition in support of development policies, and improving access to technology by developing nations.

Focusing on the use of satellite remote sensing to monitor ecosystem functions and deconstructing these into ecological and ecosystem processes should help identify the processes to be monitored and greatly ease the design of the more complex models required to assess the societal benefits underpinned by biodiversity. There is a growing push towards use of ecosystem accounting in policy development and economic analysis from the United Nations Statistical Commission. Similarly, the European Union’s first priority objective of the 7th Environment Action Programme to 2020 is to protect, conserve and enhance the Union’s natural capital, further highlighting the need to integrate economic indicators with environmental and social indicators, including by means of natural capital accounting (European Commission 2017). This accounting approach would measure changes in the stock of natural capital at a variety of scales and integrate the value of ecosystem services into accounting and reporting systems at the European Union and national levels. It should be seen as a tool supporting the mainstreaming of biodiversity in economic decision-making.

An integrated system for natural capital and ecosystem services accounting is currently in development by the European Union (DG ENV 2015) to explicitly account for the range of ecosystem services and demonstrate in monetary terms the benefits of investing in nature and the sustainable management of resources, allowing assessment of benefits beyond growth of domestic product. Such an integrated accounting system is designed as a shared platform of linked data sets and tools for covering georeferenced information on ecosystems and their services. It will allow assessment of ecosystems’ economic importance and value, which can be linked to standard national accounts. It includes layers of data based on (i) earth observation (e.g. land cover), (ii) statistical collections including physical data about human activities (e.g. land use, industrial use), biomass production, water use and availability, (iii) environmental monitoring data including data reported under relevant legislation and (iv) models that quantify ecosystem services such as water, air and soil regulation, pollination, carbon release and sequestration. Here again, providing a clear way for satellite remote sensing to help characterize ecosystem functions would not only allow identification and design of the products that would fit such a system, but the approach itself would greatly ease the identification of the different variables required by the platform when providing quantitative assessments with documented uncertainties.

**Conclusions**

With a policy agenda increasingly focused on ecosystem service provision (Perrings et al. 2010), understanding the
ecology of ecosystem functioning and its implications for the delivery of ecosystem services has never been more important. This contribution both provides a theoretical framework that articulates clear monitoring aims and delivers a list of globally available, standardized remote sensing data sets that relates to ecosystem function monitoring. The structured approach we propose here is particularly important given the ongoing evolution of remote sensing technologies and data availability, and can help progress multiple initiatives (such as the EBV process or the integrated system for natural capital and ecosystem services accounting) aimed at improving global biodiversity monitoring and supporting global conservation targets. This contribution is also intended to catalyse a much needed discussion on how best to capitalize on current and future opportunities associated with satellite remote sensing for monitoring ecosystem functions.

References

Alroy, J. 2015. Current extinction rates of reptiles and amphibians. Proc. Natl Acad. Sci. 112, 13003–13008.

Bengtsson, J. 1998. Which species? What kind of diversity? Which ecosystem function? Some problems in studies of relations between biodiversity and ecosystem function. Appl. Ecol. 10, 191–199.

Berryman, A. A. 2002. Population: a central concept for ecology? Oikos 97, 439–442.

Bland, L. M., D. A. Keith, R. M. Miller, N. J. Murray, and J. Berryman, A. A. 2002. Population: a central concept for ecology? Oikos 97, 439–442.

Bland, L. M., D. A. Keith, R. M. Miller, N. J. Murray, and J. P. Rodriguez, eds. 2016. Guidelines for the application of IUCN Red List of Ecosystems Categories and Criteria, Version 1.0. Pp. ix + 94. IUCN, Gland, Switzerland.

Boero, F., and E. Bonsdorff. 2007. A conceptual framework for marine biodiversity and ecosystem functioning. Mar. Ecol. 28, 134–145.

Braunisch, V., G. Segelbacher, and A. H. Hirzel. 2010. Modelling functional land-scape connectivity from genetic population structure: a new spatially explicit approach. Mol. Ecol. 19, 3664–3678.

Brown, T. C., J. C. Bergstrom, and J. B. Loomis. 2007. Defining, valuing and providing ecosystem goods and services. Nat. Res. J. 47, 329–376.

Brown, M. E., S. D. Arias, T. Neumann, M. F. Jasinski, P. Posey, G. Babonis, et al. 2016. Applications for ICESat-2 data: from NASA’s early adopter program. IEEE Geosci. Remote Sens. Mag. 4, 24–37.

Buchhorn, M., D. A. Walker, B. Heim, M. K. Raynolds, H. E. Epstein, and M. Schwieder. 2013. Ground-based hyperspectral characterization of Alaska tundra vegetation along environmental gradients. Remote Sens. 5, 3971–4005.

Cabello, J., N. Fernandez, D. Alcaraz-Segura, C. Oyonarte, G. Pineiro, A. Altesor, et al. 2012. The ecosystem functioning dimension in conservation: insights from remote sensing. Biodivers. Conserv. 21, 3287–3305.

Callicott, J. B., L. B. Crowder, and K. Mumford. 1999. Current normative concepts in conservation. Conserv. Biol. 13, 22–35.

Camargo-Sanabria, A. A., E. Mendoza, R. Guevara, M. Martínez-Ramos, and R. Dirzo. 2015. Experimental defaunation of terrestrial mammalian herbivores alters tropical rainforest understorey diversity. Proc. R. Soc. Lond. B Biol. Sci. 282, 20142580.

Cardinale, B. J., J. E. Duffy, A. Gonzalez, D. U. Hooper, C. Perrings, P. Venail, et al. 2012. Biodiversity loss and its impact on humanity. Nature 486, 59–67.

Carniello, L., S. Silvestri, M. Marani, A. D’Alpaos, V. Volpe, and A. Defina. 2014. Sediment dynamics in shallow tidal basins: in situ observations, satellite retrievals, and numerical modeling in the Venice Lagoon. J. Geophys. Res., series F 119, 802–815.

Ceballos, G., P. R. Ehrlich, A. D. Barnosky, A. García, R. M. Pringle, and T. M. Palmer. 2015. Accelerated modern human–induced species losses: entering the sixth mass extinction. Sci. Adv. 1, e1400253.

Chambers, J. Q., G. P. Asner, D. C. Morton, L. O. Anderson, S. S. Saatchi, F. D. Espírito-Santo, et al. 2007. Regional ecosystem structure and function: ecological insights from remote sensing of tropical forests. Trends Ecol. Evol. 22, 414–423.

Costanza, R., R. d’Arge, R. de Groot, S. Farber, M. Grasso, B. Hannon, et al. 1997. The value of the world’s ecosystem services and natural capital. Nature 387, 253–260.

Cudaby, T., M. Caccetta, M. Thomas, R. Hewson, M. Abrams, M. Kato, et al. 2016. Satellite-derived mineral mapping and monitoring of weathering, deposition and erosion. Sci. Rep. 6, 23702.

Culman, S. W., A. Young-Mathews, A. D. Hollander, H. Ferris, S. Sánchez-Moreno, A. T. O’Geen, et al. 2010. Biodiversity is associated with indicators of soil ecosystem functions over a landscape gradient of agricultural intensification. Landscape Ecol. 25, 1333–1348.

Daily, G. C. 1997. Nature’s services: societal dependence on natural ecosystems. Island, Washington, DC.

Daily, G. C., S. Polasky, J. Goldstein, P. M. Kareiva, H. A. Mooney, L. Pechar, et al. 2009. Ecosystem services in decision making: time to deliver. Front. Ecol. Environ. 7, 21–28.

De Groot, R. S., M. A. Wilson, and R. M. J. Boumans. 2002. A framework for the classification, description and valuation of ecosystem functions, goods and services. Ecol. Econ. 41, 393–408.

DG ENV. 2015. http://ted.europa.eu/udl?uri=TED:NOTICE:64198-2015:TEXT:EN:HTML accessed 27/3/2017.

Dominati, E., M. Patterson, and A. Mackay. 2010. Which ecosystem function? Some problems in studies of ecology? Oikos 97, 439–442.

González, B., J. T. Ricketts, and H. Hough-Goldstein. 2007. The value of the world’s ecosystem services and natural capital. Nature 387, 253–260.
Duncan, C., J. R. Thompson, and N. Pettorelli. 2015. The quest for a mechanistic understanding of biodiversity-ecosystem services relationships. *Proc. R. Soc. B* 282, 20151348.

Enßle, F., J. Heinzel, and B. Koch. 2014. Accuracy of vegetation height and terrain elevation derived from ICESat/GLAS in forested areas. *Int. J. Appl. Earth Obs. Geoinf.* 31, 37–44.

European Commission. 2017. http://ec.europa.eu/environment/nature/capital_accounting/index_en.htm. Accessed 28/3/2017.

Fassnacht, F. E., H. Latifi, A. Ghosh, P. K. Joshi, and B. Koch. 2014. Assessing the potential of hyperspectral imagery to map bark beetle-induced tree mortality. *Remote Sens. Environ.* 140, 533–548.

Fisher, B., R. K. Turner, and P. Morling. 2009. Defining and classifying ecosystem services for decision making. *Ecol. Econ.* 68, 643–653.

Fuentes, D. A., J. A. Gamon, Y. Cheng, H. C. Claudio, H. L. Qiu, Z. Mao, et al. 2006. Mapping carbon and water vapor fluxes in a chaparral ecosystem using vegetation indices derived from AVIRIS. *Remote Sens. Environ.* 103(3), 312–323.

Fuhlendorf, S. D., W. C. Harrell, D. M. Engle, R. G. Hamilton, C. A. Davis, and D. M. Leslie. 2006. Should heterogeneity be the basis for conservation? Grassland bird response to fire and grazing. *Ecol. Appl.* 16, 1706–1716.

Gao, F., J. Masek, M. Schwaller, and F. Hall. 2006. On the blending of the Landsat and MODIS surface reflectance: predicting daily Landsat surface reflectance. *IEEE Trans. Geosci. Remote Sens.* 44, 2207–2218.

Geijzendorffer, I. R., and P. K. Roche. 2013. Can biodiversity monitoring schemes provide indicators for ecosystem services? *Ecol. Ind.* 33, 148–157.

Guanter, L., H. Kaufmann, K. Segl, S. Chabrillat, S. Förster, C. Rogass, et al. 2015. The EnMAP spaceborne imaging spectroscopy mission for Earth Observation. *Remote Sens. 7*, 8830–8857.

Guzy, M., K. Richardson, and J. G. Lambrinos. 2015. A tool for assisting municipalities in developing riparian shade inventories. *Urban For. Urban Green.* 14, 345–353.

Haines-Young, R., M. Potschin, and F. Kienast. 2012. Indicators of ecosystem service potential at European scales: mapping marginal changes and trade-offs. *Ecol. Ind.* 21, 39–53.

Halpern, B. S., S. Walbridge, K. A. Selkoe, C. V. Kappel, F. Micheli, C. D’Agrosa, et al. 2008. A global map of human impact on marine ecosystems. *Science* 319, 948–952.

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.

Hanson, S., S. Pueyo, and E. Chuvieco. 2015. Global fire size distribution is driven by human impact and climate. *Glob. Ecol. Biogeogr.* 24, 77–86.

Harrison, R. D., S. Tan, J. B. Plotkin, F. Slik, M. Detto, T. Brenes, et al. 2013. Consequences of defaunation for a tropical tree community. *Ecol. Lett.* 16, 687–694.

Harrison, P. A., P. M. Berry, G. Simpson, J. R. Haslett, M. Blicharska, M. Bucur, et al. 2014. Linkages between biodiversity attributes and ecosystem services: a systematic review. *Ecosyst. Serv.* 9, 191–203.

Harvey, E. T., S. Kratzler, and P. Philipson. 2015. Satellite-based water quality monitoring for improved spatial and temporal retrieval of chlorophyll-a in coastal waters. *Remote Sens. Environ.* 158, 417–430.

Harwood, T. D., R. J. Donohue, K. J. Williams, S. Ferrier, T. R. McVicar, G. Newell, et al. 2016. Habitat Condition Assessment System: a new way to assess the condition of natural habitats for terrestrial biodiversity across whole regions using remote sensing data. *Methods Ecol. Evol.* 7, 1050–1059.

Hilker, T., M. A. Wulder, N. C. Coops, N. Seitz, J. C. White, F. Gao, et al. 2009. Generation of dense time series synthetic Landsat data through data blending with MODIS using a spatial and temporal adaptive reflectance fusion model. *Remote Sens. Environ.* 113, 1988–1999.

Huang, C., X. Wang, H. Yang, Y. Li, Y. Wang, X. Chen, et al. 2014. Satellite data regarding the eutrophication response to human activities in the plateau lake Dianchi in China from 1974 to 2009. *Sci. Total Environ.* 485, 1–11.

Huang, X., J. Deng, X. Ma, Y. Wang, Q. Feng, X. Hao, et al. 2016. Spatiotemporal dynamics of snow cover based on multi-source remote sensing data in China. *Cryosphere* 10, 2453.

Hyde, P., R. Nelson, D. Kimes, and E. Levine. 2007. Exploring LiDAR–RaDAR synergy—predicting aboveground biomass in a southwestern ponderosa pine forest using LiDAR, SAR and InSAR. *Remote Sens. Environ.* 106, 28–38.

Jansen, P. A., H. C. Muller-Landau, and S. J. Wright. 2010. Bushmeat hunting and climate: an indirect link. *Science* 327, 30.

Jin, M., and R. E. Dickinson. 2010. Land surface skin temperature climatology: benefitting from the strengths of satellite observations. *Environ. Res. Lett.* 5, 044004.

Kehinde, T., and M. J. Samways. 2012. Endemic pollinator diversity is driven by human impact and climate. *Ecol. Biogeogr.* 21, 850–853.
assessment of ecosystem services provision to support landscape planning. Ecol. Ind. 21, 54–66.
Kumar, P. 2010. The economics of ecosystems and biodiversity: ecological and economic foundations. Earthscan, London and Washington DC.
Kurekin, A. A., P. I. Miller, and H. J. Van der Woerd. 2014. Satellite discrimination of Karenia mikimotoi and Phaeocystis harmful algal blooms in European coastal waters: merged classification of ocean colour data. Harmful Algae 31, 163–176.
Lamarque, P., F. Quetier, and S. Lavorel. 2011. The diversity of the ecosystem services concept and its implications for their assessment and management. C.R. Biol. 334, 441–449.
Lawton, J. H., and V. K. Brown. 1993. Redundancy in ecosystems. Pp. 255–270 in E. D. Schulze and H. A. Mooney, eds. Biodiversity and ecosystem function. Springer, New York.
Lefsky, M. A. 2010. A global forest canopy height map from the Moderate Resolution Imaging Spectroradiometer and the Geoscience Laser Altimeter System. Geophys. Res. Lett. 37, L15401.
Likens, G. E. 1992. The ecosystem approach: its use and abuse. Ecology Institute, Oldendorf, Luhe.
Lindenmayer, D., J. Pierson, P. Barton, M. Beger, C. Branquinho, A. Calhoun, et al. 2015. A new framework for selecting environmental surrogates. Sci. Total Environ. 538, 1029–1038.
Liu, G., A. E. Strong, and W. Skirving. 2003. Remote sensing of sea surface temperatures during 2002 Barrier Reef coral bleaching. Eos. 84, 137–141.
Lovett, G. M., C. G. Jones, M. G. Turner, and K. C. Weathers. 2006. Ecosystem function in heterogeneous landscapes. Pp. 1–4 in G. M. Lovett, C. G. Jones, M. G. Turner and K. C. Weathers, eds. Ecosystem function in heterogeneous landscapes. Springer, New York.
Mace, G. M., K. Norris, and A. H. Fitter. 2012. Biodiversity and ecosystem services: a multi-layered relationship. Trends Ecol. Evol. 27, 19–26.
Magurran, A. 2004. Measuring biological diversity. Blackwell, Oxford.
Mallet, J. 1995. A species definition for the modern synthesis. Trends Ecol. Evol. 10, 294–299.
Malmström, C. M., H. S. Butterfield, C. Barber, B. Dieter, R. Harrison, J. Qi, et al. 2009. Using remote sensing to evaluate the influence of grassland restoration activities on ecosystem forage provisioning services. Restor. Ecol. 17, 526–538.
Martinez, N. D. 1996. Defining and measuring functional aspects of biodiversity. Pp. 114–148 in K. J. Gaston, ed. Biodiversity: a biology of numbers and difference. Blackwell Science, Oxford.
McCauley, D. J., M. L. Pinsky, S. R. Palumbi, J. A. Estes, F. H. Joyce, and R. R. Warner. 2015. Marine defaunation: animal loss in the global ocean. Science 347, 1255641–1255641.
McNaughton, S. J., M. Oesterheld, D. A. Frank, and K. J. Williams. 1989. Ecosystem-level patterns of primary productivity and herbivory in terrestrial habitats. Nature 341, 142–144.
Meyer, S. T., C. Koch, and W. W. Weisser. 2015. Towards a standardized Rapid Ecosystem Function Assessment (REFA). Trends Ecol. Evol. 30, 390–397.
Milchunas, D. T., and W. K. Lauenroth. 1995. Inertia in plant community structure: state changes after cessation of nutrient-enrichment stress. Ecol. Appl. 5, 452–458.
Millennium Ecosystem Assessment. 2005. Ecosystems and human well-being: biodiversity synthesis. World Resources Institute, Washington, DC.
Moretti, M., and C. Legg. 2009. Combining plant and animal traits to assess community functional responses to disturbance. Ecography 32, 299–309.
Nagendra, H., R. Lucas, J. P. Honrado, R. H. Jongman, C. Tarantino, M. Adamo, et al. 2013. Remote sensing for conservation monitoring: assessing protected areas, habitat extent, habitat condition, species diversity and threats. Ecol. Ind. 33, 45–59.
Nelson, R. F., P. Hyde, P. Johnson, B. Emsiiee, M. L. Imhoff, R. Campbell, et al. 2007. Investigating RaDAR–LiDAR synergy in a North Carolina pine forest. Remote Sens. Environ. 110, 98–108.
Noss, R. F. 1990. Indicators for monitoring biodiversity: a hierarchical approach. Conserv. Biol. 4, 355–364.
Odum, E. P. 1969. The strategy of ecosystem development: an understanding of ecological succession provides a basis for resolving man’s conflict with nature. Science 164, 262–270.
Oliver, T. H., M. S. Heard, N. J. B. Isaac, D. B. Roy, D. Procter, F. Eigenbrod, et al. 2015. Biodiversity and resilience of ecosystem functions. Trends Ecol. Evol. 30, 673–684.
Osuri, A. M., J. Ratnam, V. Varma, P. Alvarez-Loayza, J. H. Astaiza, M. Bradford, et al. 2016. Contrasting effects of defaunation on aboveground carbon storage across the global tropics. Nat. Commun. 7, 11351.
Pacala, S., and A. P. Kinzig. 2002. Introduction to theory and the common ecosystem model. Pp. 169–174 in A. P. Kinzig, S. W. Pacala and D. Tilman, eds. Functional consequences of biodiversity: empirical progress and theoretical extensions. Princeton Univ. Press, Princeton, NJ.
Paganini, M., A. K. Leidner, G. Geller, W. Turner, and M. Wegmann. 2016. The role of space agencies in remotely sensed essential biodiversity variables. Remote Sens. Ecol. Conserv. 2, 132–140.
Paterson, D. M., E. C. Defew, and J. Jabour. 2012. Ecosystem function and co-evolution of terminology in marine science and management. Pp. 24–33 in M. Solan, R. J. Aspden and D. M. Paterson, eds. Marine biodiversity and ecosystem functioning, 1st ed.. Oxford University Press, Oxford.
Patterson, P. L., and S. Healey. 2015. Global ecosystem dynamics investigation (GEDI) LiDAR sampling strategy. P.
Satellite Remote Sensing of Ecosystem Functions

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245 in S. M. Stanton, G. A. Christensen, eds. *Pushing boundaries: new directions in inventory techniques and applications: Forest Inventory and Analysis (FIA) symposium 2015*. 2015 December 8–10; Portland, Oregon. Gen. Tech. Rep. PNW-GTR-931. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.

Peng, Y., R. B. Kheir, K. Adhikari, R. Malinowski, M. B. Greve, M. Knadel, et al. 2016. Digital mapping of toxic metals in Qatari soils using remote sensing and ancillary data. *Remote Sens.* 8, 1003.

Peres, C. A., T. Emilio, J. Schietti, S. J. Desmoulière, and T. Levi. 2016. Dispersal limitation induces long-term biomass collapse in overhunted Amazonian forests. *Proc. Natl Acad. Sci.* 113, 892–897.

Perrings, C., S. Naem, F. Ahrestani, D. E. Bunker, P. Burkill, G. Canziani, et al. 2010. Ecosystem services for 2020. *Science* 330, 323–324.

Petter, M., S. Mooney, S. M. Maynard, A. Davidson, M. Cox, and I. Horosak. 2012. A methodology to map ecosystem functions to support ecosystem services assessments. *Ecol. Soc.* 18:31. http://dx.doi.org/https://doi.org/10.5751/ES-05260-180131.

Pettorelli, N. 2013. *The normalized difference vegetation index*. Oxford University Press, Oxford.

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

Pettorelli, N., M. Wegmann, A. Skidmore, S. Mührer, T. P. Dawson, M. Fernandez, et al. 2016. Framing the concept of Satellite Remote Sensing Essential Biodiversity variables: challenges and future directions. *Remote Sens. Ecol. Conserv.* 2, 122–131.

Puri, S., H. Stephen, and S. Ahmad. 2011. Relating TRMM precipitation radar backscatter to water stage in wetlands. *J. Hydrol.* 401, 240–249.

Queirós, A. M., S. N. Birchenuough, J. Bremer, J. A. Godbold, R. E. Parker, A. Romero-Ramirez, et al. 2013. A bioturbation classification of European marine infaunal invertebrates. *Ecol. Evol.* 3, 3958–3985.

Queirós, A. M., J. Bruggeman, N. Stephens, Y. Artioli, M. Butenschön, J. C. Blackford, et al. 2015. Placing biodiversity in ecosystem models without getting lost in translation. *J. Sea Res.* 98, 83–90.

Racault, M.-F., T. Platt, S. Sathyendranath, E. Aigirbaš, V. Martinez Vicente, and R. Brewin. 2014. Plankton indicators and ocean observing systems: support to the marine ecosystem state assessment. *J. Plankton Res.* 36, 621–629.

Ribeiro, I. O., R. A. F. de Souza, R. V. Andreoli, M. T. Kayano, and P. dos Santos Costa. 2016. Spatiotemporal variability of methane over the Amazon from satellite observations. *Adv. Atmos. Sci.* 33, 852–864.

Roe, D., J. Elliott, C. Sandbrook, and M. Walpole. 2013. Linking biodiversity conservation and poverty alleviation: what, why and where? *Pp. 3–18 in* D. Roe, J. Elliott, C. Sandbrook and M. Walpole, eds. *Biodiversity conservation and poverty alleviation: exploring the evidence for a link*. John Wiley & Sons, Chichester.

Schlerf, M., C. Atzberger, J. Hill, H. Buddenbaum, W. Werner, and G. Schüler. 2010. Retrieval of chlorophyll and nitrogen in Norway spruce (*Picea abies* L. Karst.) using imaging spectroscopy. *Int. J. Appl. Earth Obs. Geoinf.* 12, 17–26.

Schmidt, M., R. Lucas, P. Bunting, J. Verbesselt, and J. Armston. 2015. Multi-resolution time series imagery for forest disturbance and regrowth monitoring in Queensland, Australia. *Remote Sens. Environ.* 158, 156–168.

Schröter, M., C. Albert, A. Marques, W. Tobon, S. Lavalop, J. Maes, et al. 2016. National ecosystem assessments in Europe: a review. *Bioscience* 66, 813–828.

Schulp, C. J., and R. Alkemade. 2011. Consequences of uncertainty in global-scale land cover maps for mapping ecosystem functions: an analysis of pollination efficiency. *Remote Sens.* 3, 2057–2075.

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 Convention on Biological Diversity, Montréal, Canada. Technical Series No. 72.

Semmens, K. A., M. C. Anderson, W. P. Kustas, et al. 2016. Monitoring daily evapotranspiration over two California vineyards using Landsat 8 in a multi-sensor data fusion approach. *Remote Sens. Environ.* 185, 155.

Senay, G. B., N. M. Velpuri, H. Alemu, S. M. Pervez, K. O. Asante, G. Kariuki, et al. 2013. Establishing an operational waterhole monitoring system using satellite data and hydrologic modelling: application in the pastoral regions of East Africa. *Pastoralism* 3:20.

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.

Solan, M., B. J. Cardinale, A. L. Downing, K. A. M. Engelhardt, J. L. Ruesink, and D. S. Srivastava. 2004. Extinction and ecosystem function in the marine benthos. *Science* 306, 1177–1180.

Spera, S. A., G. L. Galford, M. T. Coe, M. N. Macedo, and J. F. Mustard. 2016. Land use change affects water recycling in Brazil’s last agricultural frontier. *Glob. Change Biol.* 22, 3405–3413.

Spichtinger, N., M. Wenig, P. James, T. Wagner, U. Platt, and A. Stohl. 2001. Satellite detection of a continental scale plume of nitrogen oxides from boreal forest fires. *Geophys. Res. Lett.* 28, 4579–4582.
Spruce, J. P., S. Sader, R. E. Ryan, J. Smoot, P. Kuper, K. Ross, et al. 2011. Assessment of MODIS NDVI time series data products for detecting forest defoliation by gypsy moth outbreaks. Remote Sens. Environ. 115, 427–437.

Srivastava, D. S., and M. Vellend. 2005. Biodiversity-ecosystem function research: is it relevant to conservation? Annu. Rev. Ecol. Evol. Syst. 36, 267–294.

Steenweg, R., M. Hebblewhite, R. Kays, J. Ahumada, J. T. Fisher, C. Burton, et al. 2017. Scaling-up camera traps: monitoring the planet’s biodiversity with networks of remote sensors. Front. Ecol. Environ. 15, 26–34.

Stephens, P., N. Pettorelli, J. Barlow, M. Whittingham, and M. Cadotte. 2015. Management by proxy? The use of indices in applied ecology. J. Appl. Ecol. 52, 1–6.

TEEB. 2010. The economics of ecosystems and biodiversity: ecological and economic foundations. Earthscan, London and Washington.

Thompson, D. R., I. Leifer, H. Bovensmann, M. Eastwood, M. Fladeland, C. Frankenberg, et al. 2015. Real-time remote detection and measurement for airborne imaging spectroscopy: a case study with methane. Atmos. Meas. Tech. 8, 4383–4397.

Tilstone, G., S. Mallor-Hoya, F. Gohin, A. Belo Couto, C. Sá, P. Goela, et al. 2017. Which ocean colour algorithm for MERIS in North West European waters? Remote Sens. Environ. 188, 132–151.

Tong, C., J. Wu, S. Yong, J. Yang, and W. Yong. 2004. A landscape-scale assessment of steppe degradation in the Xilin River Basin, Inner Mongolia, China. J. Arid Environ. 59, 133–149.

Tulloch, A. I. T., P. Sutcliffe, I. Naujokaitis-Lewis, R. Tingley, L. Brotons, K. M. P. M. B. Ferraz, et al. 2016. Conservation planners tend to ignore improved accuracy of modelled species distributions to focus on multiple threats and ecological processes. Biol. Cons. 199, 157–171.

Valente, A. S., and J. C. da Silva. 2009. On the observability of the fortnightly cycle of the Tagus estuary turbid plume using MODIS ocean colour images. J. Mar. Syst. 75, 131–137.

Valiela, I., J. L. Bowen, and J. K. York. 2001. Mangrove Forests: one of the World’s Threatened Major Tropical Environments. Bioscience 51, 807–815.

Veraverbeke, S., F. Sedano, S. J. Hook, J. T. Randerson, Y. Jin, and B. M. Rogers. 2014. Mapping the daily progression of large wildland fires using MODIS active fire data. Int. J. Wildl. Fire 23, 655–667.

Vierling, K. T., L. A. Vierling, W. A. Gould, S. Martinuzzi, and R. M. Clawges. 2008. Lidar: shedding new light on habitat characterization and modeling. Front. Ecol. Environ. 6, 90–98.

Villar, R. E., J. M. Martinez, M. Le Texier, J. L. Guyot, P. Fraizy, P. R. Meneses, et al. 2013. A study of sediment transport in the Madeira River, Brazil, using MODIS remote-sensing images. J. S. Am. Earth Sci. 44, 45–54.

Walker, J. J., K. M. De Beurs, R. H. Wynne, and F. Gao. 2012. Evaluation of Landsat and MODIS data fusion products for analysis of dryland forest phenology. Remote Sens. Environ. 117, 381–393.

Wallace, K. J. 2007. Classification of ecosystem services: problems and solutions. Biol. Cons. 139, 235–246.

Webb, T. J., and B. L. Mindel. 2015. Global patterns of extinction risk in marine and non-marine systems. Curr. Biol. 25, 506–511.

Werling, B. P., T. L. Dickson, R. Isaacs, H. Gaines, C. Gratton, K. L. Gross, et al. 2014. Perennial grasslands enhance biodiversity and multiple ecosystem services in bioenergy landscapes. Proc. Natl Acad. Sci. 111, 1652–1657.

WWF Living Planet Report. 2016. Risk and resilience in a new era. WWF International, Gland, Switzerland.