Priorities to advance monitoring of ecosystem services using Earth observation

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Abstract:

Managing ecosystem services in the context of global sustainability policies requires reliable monitoring mechanisms. While satellite Earth observation offers great promise to support this need, significant challenges remain in quantifying connections between ecosystem functions, ecosystem services and human well-being benefits. Here, we provide a framework showing how Earth observation together with socio-economic information and model-based analysis can support assessments of ecosystem service supply, demand and benefit, and illustrate this for three services. We argue that the full potential of Earth observation is not yet realized in ecosystem service studies. To provide guidance for priority setting and to spur research in this area, we propose five priorities to advance the capabilities of Earth observation-based monitoring of ecosystem services in the future.

Main Text

The importance of monitoring ecosystem services

Human population growth, changing lifestyles and growing demands for natural resources (e.g., food, clean water, fertile soils and timber) put the world's ecosystems under increasing pressure [1], often with unfavorable impacts on their capacity to provide ecosystem services – the benefits people obtain from nature (see Glossary). By emphasizing this critical role of nature in securing human well-being [2], the ecosystem service framework integrates the various components of socio-ecological systems and can be used to develop sustainable strategies [3]. However, operationalizing and predicting the relationships between biodiversity, ecosystem functions, ecosystem services and human well-being (e.g., [4, 5]) to aid in decision-making is difficult and requires detailed understanding of specific ecosystems as well as generalizations born of comparisons among similar systems [6].

Monitoring the global status and trends of ecosystem services is crucial for policy and management. Such reporting is mandated by a suite of recent multilateral political agreements and (inter)national assessments that have adopted the ecosystem service framework, e.g., the Intergovernmental Platform on Biodiversity & Ecosystem Services – IPBES [2], the Aichi Biodiversity Targets [7], the EU Biodiversity Strategy [8], and the recent US memorandum directing federal agencies to factor ecosystem services into planning and decision-making [9]. Monitoring trends will also be critical to evaluate the extent to which ecosystem services can help countries meet the new standards set by the recently adopted United Nations Sustainable Development Goals (SDGs; [10]) – which more fully integrate the three pillars of sustainable development (social, economic, and environmental). However, we currently lack indicators and monitoring approaches for ecosystem services and their change that can be compared worldwide [11]. Approaches for mapping and assessing ecosystem services are currently being discussed and developed e.g. at the European scale [12], but global analyses remain at coarse spatial and temporal scales, making them impractical for supporting political decisions and adaptive management [13].

Earth observation by satellite enables spatially continuous, regular and repeatable observations over large areas and has become an indispensable tool for global monitoring of natural and anthropogenic patterns, processes and trends [14]. Satellite Earth observation provides essential information on the functioning of ecosystems and on the drivers of environmental change. It has been highlighted as a main source of information for global monitoring of ecosystem services, along with national statistics, field-based observations, and numerical simulation models [13]. For example, the question 'How can remote sensing-derived products be used to value and monitor changes in ecosystem services?' was included in a list of the 10 major ways that satellite Earth observation can contribute to conservation [15].

While ecosystem services and their benefits are the main variables we would like to track, the very nature of "services" is that they are often intangible and difficult to measure directly. Often, the ecosystem functions that underpin the supply of ecosystem services are more easily detected by Earth observation than demand or benefit; additional data and modeling is often needed to connect an ecosystem function (e.g., soil stabilization through plant biomass production) to a service (provision of clean water at a point of interest, such as drinking water intake) to a human well-being benefit (reduction in treatment cost, or improved health). This paper hence synthesizes in which respects satellite Earth observation can provide either critical "underpinning observations" on ecosystem functions, that can be translated to services through modeling and linking with measures of demand, or direct observations or measurements of the ecosystem service benefits themselves. To help demonstrate the potential of satellite Earth observation in monitoring ecosystem services and to spur research in this area, we (1) describe the differences and links between ecosystem functions and services, (2) highlight some of the opportunities and challenges for assessing ecosystem service supply and demand from space, (3) provide three in-depth examples of how Earth observation products together with socio-cultural and economic information as well as model-based analysis can be used to assess ecosystem service supply, demand and benefit, and (4) propose five priorities to advance the capabilities of Earth observation-based global monitoring of ecosystem services in the future.

Glossary

Biodiversity: the variability among living organisms from all sources including, *inter alia*, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems (as defined in Article 2 of the Convention on Biological Diversity – CBD, https://www.cbd.int/convention/text/default.shtml)

Earth observation (EO): the gathering of information about the Earth's biological, physical, chemical, and socioeconomic systems via remote sensing technologies to assess and monitor the status of, and changes in, the natural and built environment. Here, we focus on spaceborne observations acquired by satellites.

Essential Biodiversity Variables (EBVs): derived measurements required to study, report and manage biodiversity status and trends, comprising six classes (Genetic composition, Species populations, Species traits, Community composition, Ecosystem function, and Ecosystem structure). By providing the required level of abstraction, the variables are intended to bridge the gap between scientists, monitoring initiatives and decision makers. EBVs were first proposed and are currently further developed by the Group on Earth Observations Biodiversity Observation Network (GEO BON, [16]).

Ecosystem functions: the physical, biogeochemical, and ecological components, processes, and outputs of ecosystems that are driven by multiple controls such as abiotic and climatic factors, ecosystem structure, biodiversity, human disturbance and land management [17] and largely depend on ecosystem condition and quality. Ecosystem functions often serve to define a particular ecosystem and are the foundation for an ecosystem's capacity to provide ecosystem services [18].

Ecosystem services: broadly defined as the delivery of a suite of material and nonmaterial benefits that people, directly and indirectly, obtain from nature and that sustain and fulfill human life [19], also denoted as "nature's benefit to people" in the IPBES conceptual framework [2].

Ecosystem service benefit: the ways in which ecosystems contribute to human well-being by providing ecosystem services ("good quality of life"; [2]). Constituents of well-being include materials essential for life and contributions to health, security, social relations, and freedom of choice and actions [19]. Benefits will differ among individuals and stakeholder groups; disentangling them requires understanding the diversity of and linkages among stakeholders as well as people's preferences for valuing ecosystem services [5].

Ecosystem service demand: the level of service provision desired or required by people, driven by human needs and preferences, cultural and behavioral norms, institutions, market prices etc. Demand is also influenced by factors external to service production but still integral to the socio-ecological system (e.g., technological substitutes; [20]).

Ecosystem service supply: the full potential of ecosystems given by their functions and elements to provide a given ecosystem service, no matter whether humans recognize, use, or value that service [13,21].

Monitoring: here defined in the context of environmental monitoring, i.e., the regular, systematic and purposeful observation of the (semi-)natural and built environment. This requires standardized and repeatable measurements allowing regular updates with sufficient spatio-temporal resolution to capture trends. In our understanding, monitoring also involves the long-term archiving of the acquired data (i.e., the generation of useful time series products) as well as the disclosure of information relevant to policy and decision-making.

Teleconnection: while being originally a concept from atmospheric sciences, the idea of teleconnections is recently being used to represent the virtual shrinking of distances between geographical places, thereby also emphasizing the growing spatial separation between places of ecosystem service supply (production) and demand (consumption) [22]. Teleconnections arise, for example, from international trade and often serve as drivers of environmental change, including deforestation and other types of land conversions.

Differences between ecosystem functions and services

Ecosystem functions are controlled by abiotic and climatic factors, ecosystem structure and biodiversity (in particular functional diversity; [23]), and human impacts such as land management [17]. In contrast, ecosystem services describe the benefits that people receive from those ecosystem functions and to which humans attach value [18]; ecosystem services therefore cannot exist in isolation from people's needs and are in most cases co-produced by a mixture of natural capital and various forms of social, human, financial and technological capital [24]. While ecosystem services can generally be thought of as a suite of ecosystem functions modified by human demand [18] as well as anthropogenic assets (e.g., built infrastructure; [2]), ecosystem functions do not correspond directly to services [17]. For example, the supply of the ecosystem service of carbon sequestration and storage relies upon multiple ecosystem functions such as plant biomass production, litter decomposition, respiration, and soil turnover. Also, many ecosystem services are the sum of contributions from multiple ecosystem compartments (e.g., total carbon storage of an ecosystem). Finally, certain changes affecting ecosystem functioning might increase one service while diminishing another (e.g., increasing tree cover on pastureland might increase carbon sequestration and provide additional habitat for culturally important species while decreasing the rate of groundwater recharge supplying downstream demand for drinking water; [25]).

To monitor ecosystem services, it is therefore critical to assess not only their supply (being more closely linked to ecosystem functions), but also their demand by different social actors [26] and their actual benefit experienced by people [21]. For example, old-growth forests in a catchment help stabilize soils and prevent erosion. However, whether these ecosystem functions lead to a service depends upon whether soil erosion (leading to reduced soil productivity, damaged roads, siltation of reservoirs, reduced water quality etc.) is affecting people in a downstream location and whether the restriction of soil erosion is beneficial to those people. People and society will value ecosystem services differently in different places at different times [27]. Therefore, understanding spatial context (geographical location) as well as societal choices and values (both monetary and non-monetary) is as important as monitoring ecosystem structure and functions [27]. Practically, however, it is often necessary to articulate and measure the supply and demand of ecosystem services separately. We therefore discuss here what the measurement of ecosystem functions, when carefully defined, linked to measures of demand, and interpreted within appropriate ecosystem service models, can tell us about ecosystem service status and trends.

State-of-the-art and challenges for assessing ecosystem services from space

Our current expertise in assessing ecosystem services by means of Earth observation (see Box 1) largely builds on experience gained and methods developed in the context of using satellite data for estimating biodiversity (e.g., [28]) and ecosystem functioning (e.g., [29]). In particular, satellite Earth observation has been used to (1) detect species and assemblages (more recently also functional diversity, [30]), (2) classify the type, extent and variety of habitats [31], and (3) to directly measure ecosystem conditions and functions (e.g., vegetation carbon pools and losses, [32,33].

A significant proportion of the literature using Earth observation in ecosystem service assessments disregards human demand, well-being or benefits and therefore addresses only ecosystem service supply (Box 1). We believe that this bias towards the supply side arises from the significant challenges that the multi-dimensional nature of ecosystem services creates for assessing them from space. Satellite Earth observation is a physical-based approach for recording characteristics of objects and features and is therefore generally more suitable for estimating ecosystem conditions relevant for service supply. While detecting potential beneficiaries of ecosystem services is generally possible using Earth observation methods, often models are needed to translate this information to human demand (see Figure 1). Also, Earth observation techniques require the collection of ground measurements for calibration and validation of results. Socio-economic data, which is required to calibrate estimates of demand, is often much more time- and context-dependent than biophysical estimates of ecosystem attributes and typically not available at the granularity needed to link to Earth observation data (e.g., UN-FAO national statistics). Due to the labor-intensive and slow processes by which such information can be gathered at high spatial detail based on interviews or surveys, we often face a lack of relevant information to feed into Earth observation-based studies.

The complex spatio-temporal dynamics of ecosystem services [34] further contribute to the fact that the full potential of satellite Earth observation is not yet realized in ecosystem service studies. These complex dynamics require a thorough *a priori* understanding of the respective socio-ecological system and the consideration of appropriate system boundaries (that might not match the available Earth observation data). Given that satellite Earth observation is a globally available technique, this is not a major problem as such, but means that different methods have to be developed for different scales and settings – significantly limiting the transferability to other study sites or Earth observation sensors.

Box 1. Overview of Earth observation data and techniques used to assess ecosystem services.

Satellite Earth observation for assessing ecosystem services has been a fast-growing research field in the past 15 years, mostly for terrestrial ecosystems (summarized in [35-38]). However, many of these recent efforts do not explicitly consider human demand and are therefore limited to monitoring ecosystem service supply or addressing ecosystem functions rather than services (even though they might state differently in their objectives). Optical and radar data has been analyzed in four distinct ways in ecosystem service studies: First, Earth observation-based biophysical parameters have been used to estimate statistical relationships with ecosystem properties and functions (e.g., carbon stock in live biomass, [32]), which are then sometimes conflated with their associated services (e.g., woody biomass with timber provisioning). Second, satellite data has been used to parameterize (as input, initial conditions or variables) or to validate spatially-explicit, process-based models of ecosystem service supply (e.g., using MODIS-Leaf Area Index to simulate plant growth in the Soil and Water Assessment Tool, [39]). Third, though much more rarely done, a few studies have used Earth observation data to estimate the location, size and economic well-being of communities as potential beneficiaries (e.g., using satellite night lights, high-resolution optical or radar data; [40,41]) or to map the demand for specific ecosystem services (e.g., pollination-dependent crops, [42]). Finally, by monitoring land use change activities Earth observation has been applied to evaluate the effectiveness of ecosystem service intervention or incentives programs (e.g., Payments for Ecosystem Services – PES, [43]).

Three trends in the use of Earth observation in ecosystem service assessments suggest ways that the field can evolve. First, this research focuses primarily on provisioning (e.g., food provision) and regulating (e.g., climate regulation) services (Figure I). Applications for cultural services are generally scant [37]. Second, many studies fail to take advantage of the large temporal extent of Earth observation products, which is one of their great strengths for ecosystem service assessment (56 % of studies cover 10 years or less, 28 % use monotemporal imagery; [37]). Third, while the Earth observation products utilized differ among ecosystem services (Figure I), land use and/or land cover (LULC) data remain the most commonly used type of information and a key input to most ecosystem service models (e.g., InVEST [44] or ARIES [45]). In this approach, biophysical or economic ecosystem service values are linked to LULC categories and changes in ecosystem services are estimated from changes in LULC (e.g., due to deforestation) using various models. These models generally use a categorical representations of LULC combined with a paint-by-numbers approach to assign the same biophysical value to all pixels in the same class, thereby overlooking the sometimes dramatic impacts of differences in ecosystem quality or condition that affect the provision of ecosystem services [46]. While novel LULC products are constantly being improved (e.g., regarding spatial resolution, thematic detail) and hold promise for advancing ecosystem service modeling beyond these first-generation approaches, they still suffer from inconsistent classification methods, include spatial generalization errors, do not incorporate functional trait variation within vegetation types [30], and are produced infrequently [13].

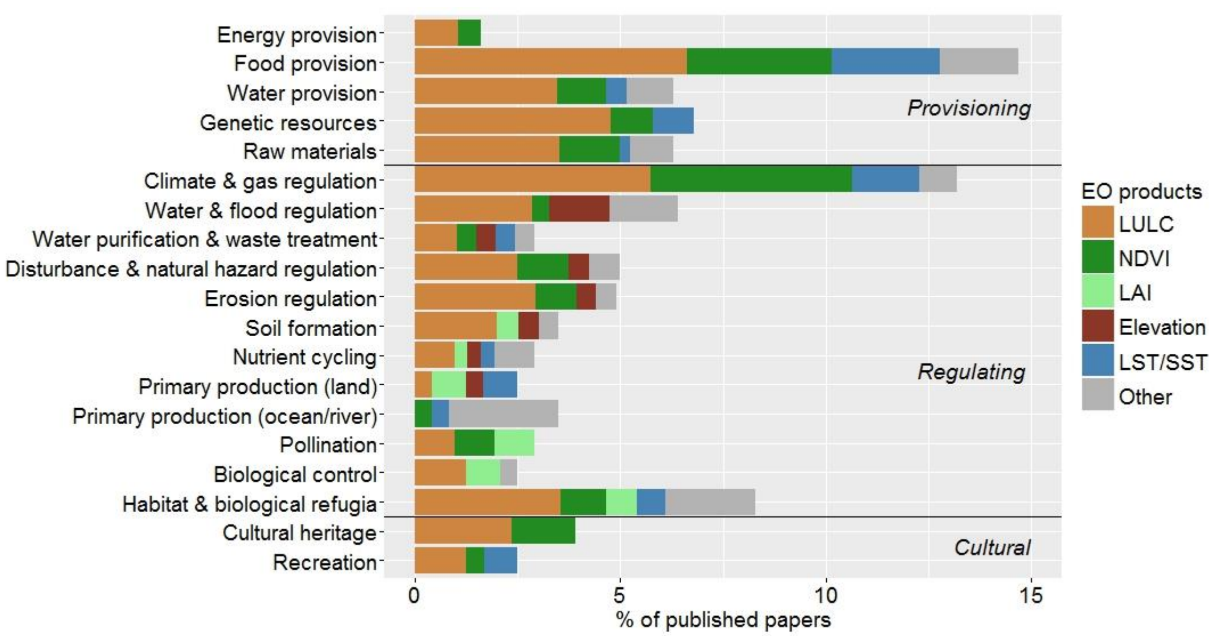

Figure I. Relative distribution of studies making use of satellite Earth observation data among ecosystem service categories (provisioning, regulating and cultural), including the most frequently used products (based on the review work by [37]). Abbreviations: LULC: Land use and/or land cover, NDVI: Normalized Difference Vegetation Index, LAI: Leaf Area Index, LST:

Land Surface Temperature, SST: Sea Surface Temperature. The category "Other" includes for example Earth observation data on chlorophyll concentrations, colored dissolved organic matter and bathymetry.

Future directions in quantifying ecosystem service supply, demand and benefit using Earth observation

Assessing the different components of ecosystem services – supply, demand and benefit – from space necessitates the combination of multiple Earth observation products with socio-cultural and economic information and various models. To spur research in this area, we provide a framework for the integration of these different sources of information, using three examples (Figure 1, Box 2) that illustrate provisioning (non-timber forest products, NTFPs), regulating (water purification), and cultural (outdoor recreation) ecosystem services. These examples show that (1) Earth observation products can support assessment of many types of ecosystem services, though to differing extents, (2) different aspects of ecosystem service demand, not just supply, can be characterized using Earth observations, (3) the creative combination of multiple satellite products and various types of other information (including household surveys, geolocated social media data etc.) is the key to move the field forward, and (4) much information that can be obtained from Earth observation (e.g., population density to estimate demand) is relevant across multiple ecosystem services.

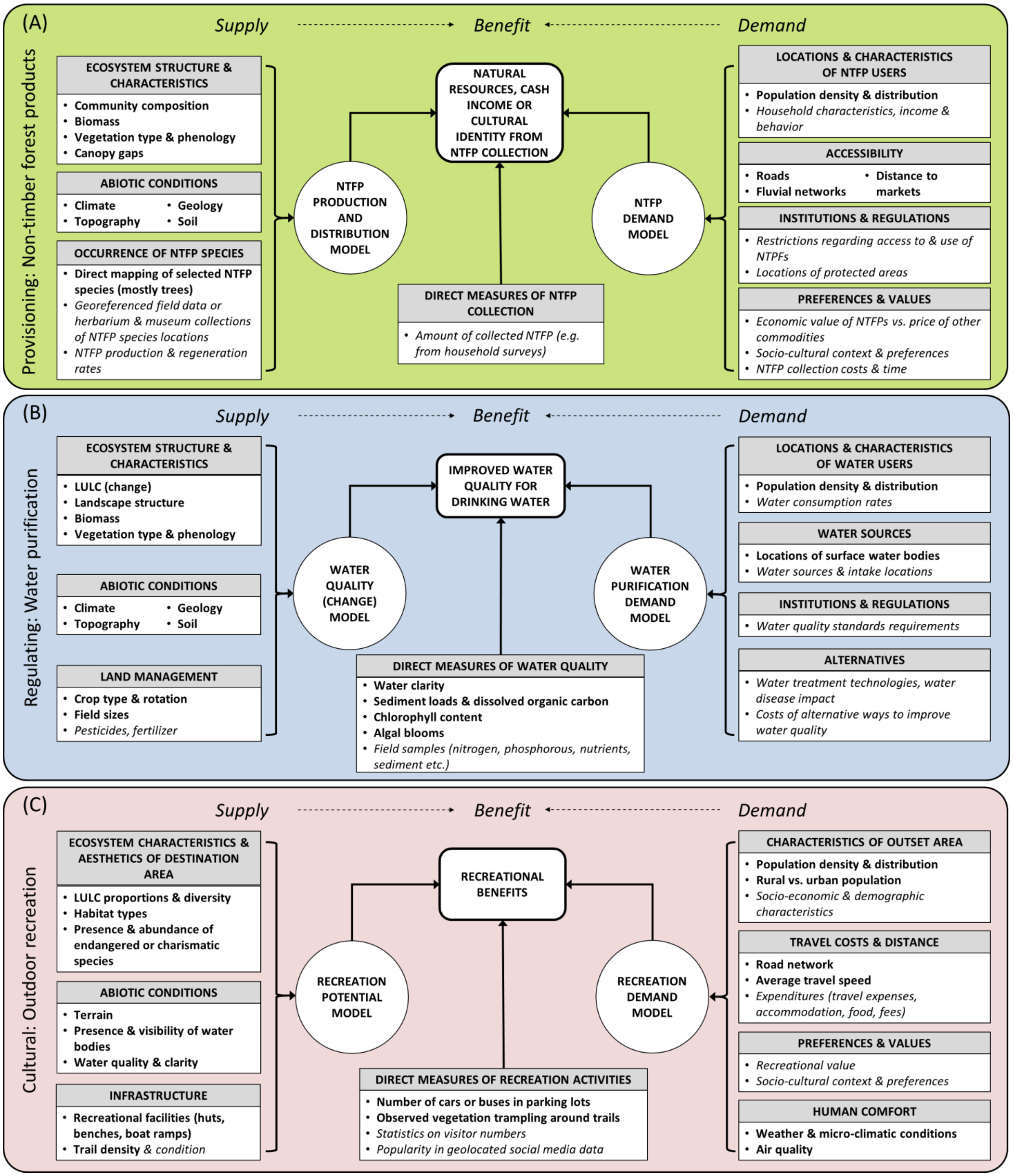

Figure 1. Analysis framework for the assessment of ecosystem service supply, demand and benefit using Earth observation products together with socio-cultural and economic

information and model-based analysis. *Information that can (at least partly) be obtained from satellite imagery is written in bold, information that requires other sources than Earth-observation (e.g., household surveys) is written in italics. We provide three show case examples for the services (A) non-timber forest products (NTFPs), (B) water purification, and (C) outdoor recreation. Specific information mentioned (e.g., community composition, population density) is intended as examples only not an exhaustive list. References to studies using the mentioned Earth observation products are given in Box 2.*

Box 2. Examples for assessing ecosystem services from Earth observation and other data.

Non-timber forest products (NTFPs, Figure 1A) comprising food, fiber, fuel, and medicinal resources (e.g., mushrooms, berries, nuts, medicinal plants, honey and game animals) make substantial contributions to the livelihoods, economic viability and the cultural heritage and sense of place of many cultures [47]. However, NTFPs are extremely heterogeneous, no generalized models for NTFPs are readily available, and the data demands for mapping NTFP supply and demand across landscapes are high [48]. Earth observation offers much promise for filling these gaps, enabling better use of spatially-explicit information on NTFPs in management and decision-making. The supply of NTFPs can be modeled by combining Earth observation-based estimates of ecosystem structure and abiotic conditions with information on presence and abundance of NTFP-providing species from georeferenced field samples or herbarium and museum collections. For example, multispectral imagery was analyzed to derive forest type and density maps for mapping NTFP provided by trees [49] and for predicting mushroom distributions [50]. The latter study applies a species distribution modeling framework (e.g., [51]) and we expect that this area of research will greatly benefit from new sensors and novel remotely sensed predictor variables (summarized in [28,52]). Direct mapping of NTFP species from satellite data is possible in some cases (e.g., using hyperspectral EO-1 Hyperion data to map specific species of tropical trees, [53]) but needs to be combined with NTFP production and regeneration rates to obtain estimates of NTFP potential. While being governed by multiple, interacting factors, demand for both subsistence and commercial NTFPs is generally a function of population density and distribution, household characteristics, accessibility to NTFP harvest areas and markets, institutions and regulations, and NTFP preferences and values [47,54]. Population density and economic well-being [40,41] as well as roads and fluvial networks [55] can be extracted from satellite imagery in some cases, but information on the other factors fully relies on household surveys as well as other economic and socio-cultural data.

Water purification (Figure 1B) leading to improved freshwater quality for drinking water as well as for recreation, fishing etc. is among the most demanded ecosystem services [25,56]. On the supply side of water quality regulation, Earth observation can be used to assess abiotic conditions (e.g., climate, topography) as well as to monitor changes in ecosystem structure and characteristics (e.g., biomass, landscape structure, vegetation type) that can be linked to changes in water quality using biophysical models [57]. In addition, some relevant management practices such as crop types can be mapped using satellite imagery [58]. In lieu of modeling water quality (changes), Earth observation can also be used to directly monitor water quality. A range of such empirical and analytic approaches to interpreting water quality from

Earth observation of inland waters have been developed, but most require substantial calibration, have poor validation against ground-measured data, are generally only applicable in lakes, lagoons, and estuaries but not rivers and streams, and have limited to no generalizability to other water bodies [59,60]. In addition, while excess nutrients are a water quality parameter of particular interest to ecosystem service studies, Earth observation cannot detect chemicals that do not change the energy spectra of water [61]. Proxies might be used to overcome this hurdle, such as tracking algal blooms in lakes and coastal areas [62]. On the demand side, Earth observation again provides promise and suffers from limitations. Satellite-based monitoring of human settlements and population density [40] can provide critical information about where people are likely to demand improved water quality. Availability of surface-water sources within a defined radius can be assessed from Earth observation data (e.g., [63]) and might indicate use of surface vs. groundwater resources. However, rigorous assessment requires information such as water sources, intake locations, water quality standards and regulations as well as treatment technology, which cannot be obtained from satellites.

Outdoor recreation (Figure 1 C) is a widely recognized benefit that people gain from nature and contributes significantly to modern economies [64]. Yet, the difficulty in remote sensing of such cultural ecosystem services is that we have much less experience in assessing landscape aesthetic – a cognitive socio-psychological appreciation we as human beings impose on the landscape – than the ecological functions that underpin the previous two examples. However, there are existing and prospective approaches to estimate them using Earth observations. It was shown that location characteristics such as LULC diversity and proportions (e.g., % forest cover), special and rare habitat types, terrain, presence and condition of water bodies, as well as abundance of endangered or charismatic species are key for determining recreation potential and supply [65-67]. Many of these explanatory variables are routinely mapped from satellite data (e.g., [28,31,63]). In addition, some important recreational infrastructure and facilities (e.g., tourist huts, benches, boat ramps, trail density) can be identified using very-high resolution imagery [68]. Looking at the demand for recreational services, studies have shown that estimates can be made by combining information on rural population and social welfare of nearby urban areas [65] as well as on accessibility [67]. Travel time from people's residence can be estimated from geospatial data of road networks with assumptions on travel speed (which can be monitored remotely because of the time lag between acquisitions of different bands in WorldView-2; [69]). Finally, weather and micro-climatic conditions such as temperature, humidity, wind, radiation and cloudiness are important in determining people's physiological comfort – as measured by indices such as Physiological Equivalent Temperature [70]. With very-high resolution imagery, it is also possible to resolve individual hiking trails – and even monitor the degradation caused by trampling from visitors, which can be a direct proxy for recreational use [71].

Five priorities

In light of recent achievements illustrated in the examples above (Figure 1, Box 2) and beyond, we propose five priority areas to advance monitoring of ecosystem services using satellite Earth observation and describe their expected outcomes (Table 1).

Priority 1: Defining standardized and monitorable Essential Ecosystem Service Variables. The ecosystem service field has historically seen much ambiguity in definition and still lacks standards that define terminology, methods, and reporting requirements [72]. However, such a standard set of variables capturing the different components of ecosystem services (supply, demand, and benefit) is exactly what is needed to foster the best possible use of Earth observation data (see [11,13] and our examples above). Essential Biodiversity Variables (EBVs; [16]) have already been developed, fourteen of which (e.g., phenology, habitat structure) have a fully or partly remotely-sensed component [73], and this framework can be used as a blueprint for the creation of an analogous set of Essential Ecosystem Service Variables. Standardization in ecosystem service research is on the scientific and political agenda (e.g., [12]), and being undertaken by several different initiatives and projects (e.g., GEO BON, IPBES, INCA - Integrated system for Natural Capital and ecosystem services Accounting, Natural Capital Coalition (previously TEEB for Business)). For global implementation, these variables need to be scalable, and their measurement technically feasible, economically viable and relevant for assessing the state and trends of ecosystem services. We recommend that consideration of available (and soon-to-be available) Earth observation products be taken into account when defining indicators of those Essential Ecosystem Service Variables, so that their global monitoring is supported.

Priority 2: Advancing methods for integrating Earth observation and socio-economic data. The firmer the "handshake" between biophysical and social analysis, the better our ability to understand both the cause of changes in ecosystem services and the solutions to these environmental challenges [74]. As illustrated in our examples, we need more research into the development and improvement of techniques for integrating biophysical estimates derived from Earth observation and different sources of socio-cultural and economic information into ecosystem service models. For instance, links between satellite information and data from semistructured interviews [43] and household surveys [75] have already successfully been established to evaluate the monetary and non-monetary benefits of ecosystem services at local scale. Efforts are underway to provide similar sets of information with continental to global coverage based on household microdata and agricultural landscape data [76]. The rise in information technologies and increasing opportunities for crowdsourced citizen science and location-tagged social media (e.g., Twitter, Facebook, Flickr, Panoramio, Instagram) augur well for a rapid growth in the number of relevant geospatial social data. Despite the evident challenges of these 'Big Data' (see [77]), their suitability for complementing Earth observation product validation activities [78] and for estimating recreational ecosystem services and values [56] has been demonstrated in pilot analyses. Better integration of Earth observation with ecosystem service variables will help expand the range of studies beyond the focus on provisioning and regulating services we identified (Box 1).

Priority 3: Ensuring open access, maintenance and interoperability of Earth observation products for ecosystem service assessments. The promise of ecosystem services is in making the connections between people and nature visible for decision-making. For greatest uptake, the tools and data for assessment hence need to be easily accessible and freely available. Most ecosystem service tools are already open source (InVEST, ARIES etc.), and ecologists often make their models available in other pre-existing open source software such as R packages [79]. It is critical that linkages between ecosystem service models and Earth observation data are maintained in the same way. This requires not only open access to satellite data [80] but also maintenance of products through time [11] and developing a culture of sharing code in the Earth observation community, such as Open Science Initiatives (e.g., https://osf.io/g65cb/). This will help address the issue noted in Box 1 that relatively few Earth observation products are used in ecosystem service analysis. As changes in ecosystem services might exhibit long lag-times in response to drivers and complex dynamics at multiple temporal scales, long-term monitoring for reporting on ecosystem services (e.g., EU Biodiversity Strategy 2020, Water Framework Directive, Marine Strategy Framework Directive, SDGs) is ultimately reliant on products and methodologies that have durability. However, differences between versions of Earth observation products resulting from algorithm updates can substantially affect conclusions on ecosystem trends (e.g., the AVHRR-based $GIMMS_{3g}$ NDVI data showed significant increases in vegetation productivity in northern latitudes not seen in its predecessor $GIMMS_{g}$, [81]). Updated information on the algorithms used, assumptions made, auxiliary inputs and pixel-level uncertainty of Earth observation products that are accessible to non-experts is therefore crucial. Maintaining accessible long-term Earth observation data will better enable ecosystem service assessments to take advantage of the long time-series of much satellite-based data, which we note in Box 1 they currently do not do.

Priority 4: Utilizing Earth observation to assess spatial disconnects between service supply and demand, trade-offs across regions and global teleconnections. Global policies and trade have significant impact on regional ecosystem service flows and lead to spatial disconnects between service supply and demand [3] as well as 'embedded' ecosystem services (e.g., virtual water content of traded agricultural commodities; [82]). For example, about 13% of global cropland and pasture is used for international food trade, and embedded crop and pasture land is disproportionately allocated among countries [83], meaning that human activities, decisions and consumption in one area have a large impact on socio-ecological systems, ecosystem integrity and biodiversity elsewhere [5,84]. Earth observation provides a unique opportunity to (1) help better understand those ecosystem service flows between countries by providing more detailed and spatially-explicit estimates of supply and demand at different locations, (2) capture local and regional differences in ecosystem services (c.f., global and regional assessments of IPBES), and (3) thereby help inform policy decisions at different spatial scales. We therefore propose combining the unique information derived from Earth observation at the global scale (e.g., on tree density [85], surface water [63], and cropland extent and field sizes [86]) with global trade data and national statistics, economic simulation models, statistical studies, place-based empirical studies, value chain analyses, and biophysical accounting (cf. [87]).

Priority 5: Providing long-term opportunities for collaboration and synthesis across disciplines. As illustrated here, an ambitious interdisciplinary effort that takes account of the holistic or 'joined up' thinking of the ecosystem service framework [27] is needed to move beyond the current state-of-the-art. Research into the development of monitoring capabilities for ecosystem services indeed requires mixed-method approaches and stakeholder engagement to integrate across social sciences, natural sciences and the humanities [3]. Until now, the expertise of Earth observation and ecosystem service researchers have been largely separated (e.g., different university faculties, departments and research institutes), thus preventing cross-fertilization of ideas and interests. Expertise required to address Priorities 1-4 is therefore disparate and fragmented. It is likely that the lack of knowledge and technical capabilities on the part of the ecosystem service researchers and model developers, explains in part why only a limited number of ready-made Earth observation products are used in ecosystem service studies [38]. However, as illustrated in our examples above, there is great potential for lesser-known Earth observation products (i.e., beyond LULC data and other standard products) to improve assessments of specific components of ecosystem service. More dialogue between the ecosystem service and Earth observation communities is also needed to minimize semantic confusion, to help manage expectations of the possibilities, limitations, and uncertainties of Earth observation products, and to ensure that the collected satellite data are used in the most appropriate and useful way. Similar calls have been made regarding collaboration between biodiversity researchers and Earth observation experts (e.g., [14,73]); however, this involves mostly natural sciences. We therefore should build on successful examples of institutional socio-ecological synthesis research (e.g., those gathered in the International Synthesis Consortium, http://synthesis-consortium.org/) as well as recent research programmes (e.g., ECOPOTENTIAL: improving future ecosystem benefits through earth observations, http://www.ecopotential-project.eu/) to bridge social, ecological and Earth observation perspectives and to create new opportunities for educating young scientists.

Table 1. Five priority areas to advance Earth observation-based ecosystem service assessments and monitoring.

Priority area	Rationale & key challenges	Recent achievements	Expected outcomes
1. Defining standardized and monitorable Essential Ecosystem Service Variables	- Standards defining terminology, methods and reporting requirements for ecosystem services missing - Common set of variables capturing the different components of ecosystem services (supply, demand, benefit) needed	- Standardization in ecosystem services is on the scientific and political agenda - EBVs (partly Earth observation-based) developed that can be used as a blueprint	- Coherent framework of Essential Ecosystem Service Variables that allows monitoring and cross-scale comparisons - Better support of the global monitoring of these variables using Earth observation techniques

2. Advancing methods for integrating Earth observation and socio-economic data	- Understanding causes of changes in ecosystem services and finding solutions requires bridging biophysical and social analyses	- Recent studies successfully integrate satellite and socio-economic data at local scale - Increasing opportunities for crowdsourced citizen science and location-tagged social media data	- Improved capacities for assessing supply, demand, and benefit of ecosystem services in combination with Earth observation data - Enhanced capabilities for validating ecosystem service assessments
3. Ensuring open access, maintenance and interoperability of Earth observation products	- Versioning of Earth observation products can affect conclusions of ecosystem trends - Long-term monitoring and reporting on ecosystem services requires durable Earth observation products and methods	- Increasing efforts to improve continuity and free access to Earth observation data (e.g., from Landsat, Sentinel) - Continuously improving computing power - Most ecosystem service tools are open source	- International reporting supported by frequent updates and uncertainty or error estimates of Earth observation products - Improved ecosystem service estimates at sub-national scale (i.e., beyond national statistics)
4. Utilizing Earth observation to assess spatial disconnects, trade-offs across regions and global teleconnections	- Global policies and trade lead to spatial disconnects between ecosystem service supply and demand - Changes of ecosystem services are not necessarily caused by processes occurring at the same location	- Conceptual, theoretical and empirical examples of relationships between ecosystem services published - Improved capabilities of Earth observation allow producing global environmental datasets with unprecedented detail	- Identification of mismatches of ecosystem service supply and demand - Improved capacities to capture local and regional differences and to monitor teleconnections among ecosystem services - Development of methods to identify and analyze distant

			drivers of ecosystem service change
5. Providing long-term opportunities for collaboration and synthesis across disciplines	- Ambitious, interdisciplinary effort needed to move beyond the state-of-the-art - High efforts to pre-process satellite imagery remain an important barrier to its use by non-experts	- Successfully established synthesis centers - Interdisciplinary thinking plays increasingly important role in education of students and young scientists	- Improved dialogue to help manage expectations of the possibilities of Earth observation products - Best practice guidelines on how to assess ecosystem services bridging social, ecological and Earth observation perspectives - Accelerated scientific synthesis on the transferability of Earth observation-based case study findings

Conclusion: The road ahead

Satellite Earth observation is not a panacea but one of the most promising approaches to regionalize and globalize our understanding of socio-ecological systems. We can now build on over 35 years of experience using satellite data for ecosystem assessments and monitoring. Drawing on this knowledge as well as advanced products from recently launched (e.g., Landsat 8, Sentinel-2) or planned (e.g., EnMAP, GEDI, Tandem-L, FLEX) missions, free access to satellite data and novel analytical techniques (e.g., cloud computing, Google Earth Engine), will open up new opportunities in socio-environmental research in the near future. We are at a critical juncture in international decision-making about natural capital and about how to resolve conflicting objectives that arise from the SDGs [88] and that are perceived to lead to potential trade-offs between short-term economic and societal benefits (cf. SDGs 8 and 9) versus the long-term insurance of functioning of aquatic, marine and terrestrial ecosystems (cf. SDGs 6, 14 and 15). Integrating Earth observation in ecosystem service research will provide more timely and accurate information to help inform in these key decisions globally.

Here, we have outlined the most important challenges to Earth observation-based ecosystem service assessments and have proposed five priorities to address them. Joint work among social scientists, ecologists, and remote sensing specialists is needed to operationalize and implement these recommendations and to address important gaps in current knowledge (Box 3). Earth observation researchers should be guided by the concepts of co-design and co-production (i.e., research programs should be jointly developed by researchers and stakeholders; cf. FutureEarth agenda), which are often overlooked given the plethora of tools, data and mapping techniques available. It is time to seize the opportunity for developing a unified strategy for ecosystem service monitoring, in which Earth observation must play a crucial role. Only if we succeed in developing such capabilities to monitor the state of the planet and its ecosystem services, will we develop a common understanding regarding our limited resources.

Box 3. Outstanding questions

- How will the next generation of satellites - which will provide information at unprecedented levels of temporal, spatial and spectral detail - support ecosystem service assessments, in particular for under-researched services?

- How can Big Data from citizen science and social media together with Earth observation be used to assess and monitor ecosystem services? Which conceptual and technical barriers must be overcome?
- How robust and reliable are Earth observation-based estimates of ecosystem service supply and demand, i.e. can they be transferred in space and/or time and can they be compared among different satellites and sensors? How does transferability of findings differ among ecosystem service categories (provisioning, regulating and cultural)?
- How can Earth observation help assessing spatial disconnects between service supply and demand as well as 'embedded' ecosystem services (e.g., virtual water content of traded agricultural commodities) resulting from global trade?
- How can space-borne Earth observation be integrated with regional airborne methods based on drones (unmanned aerial vehicles) or airplanes?
- How can information derived from Earth observation be effectively integrated into global policy and decision-making related to ecosystem services? To which extent can it provide information on progress towards e.g. the SDGs?

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