A Global System for Monitoring Ecosystem Service Change

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Earth's life-support systems are in flux, yet no centralized system to monitor and report these changes exists. Recognizing this, 77 nations agreed to establish the Group on Earth Observations (GEO). The GEO Biodiversity Observation Network (GEO BON) integrates existing data streams into one platform in order to provide a more complete picture of Earth's biological and social systems. We present a conceptual framework envisioned by the GEO BON Ecosystem Services Working Group, designed to integrate national statistics, numerical models, remote sensing, and in situ *measurements to regularly track changes in ecosystem services across the globe. This information will serve diverse applications, including stimulating new research and providing the basis for assessments. Although many ecosystem services are not currently measured, others are ripe for reporting. We propose a framework that will continue to grow and inspire more complete observation and assessments of our planet's life-support systems.*

Keywords: biodiversity, global change, GEO BON, trade-offs, sustainability

In the cabin of a large airplane, there is an impressive array of dials and screens monitoring all of the vital components of these complicated pieces of machinery. The monitoring arrays ensure that the failure of any one component is detected in time to avoid a catastrophic failure of the entire integrated machine and to avoid the demise of its passengers and cargo. Unfortunately, on the vastly complex planet on which we live, there is no comprehensive and integrated set of measurement devices to give us a full sense of how all of the pieces are operating and interacting to maintain continuous functional capacity. In a sense, we are all flying partially blind on the only planet with a known life-support system.

We do have some observation systems in place, but they are incomplete and not consistently integrated to provide systems-level information and understanding. For example, a vast network of weather stations across the globe has proven vital in detecting global climate change. Satellites are monitoring the changing extent of our forests with ever-increasing accuracy, and of course, nations and international organizations track the status and flows of many material goods and services in markets and through economic indicators. In addition, an array of programs is dedicated to compiling data on the status of species and populations, such as the Global Biodiversity Information Facility and the International Union for Conservation of Nature Red List of Threatened Species.

However, many vital processes are not monitored globally or subglobally, in spite of accumulating experiences that indicate life- and livelihood-threatening system failures. For example, the Millennium Ecosystem Assessment (MA) concluded that some 60% of the basic ecosystem services that support human well-being have been degraded, with particularly strong losses this past half century (MA 2005), and yet, no information is being generated systematically on how these ecosystem services change through time. We are seeing more and more examples of ecosystems crossing thresholds and shifting from one state to another, often with unfavorable consequences for people (CBD 2010). These events come as surprises because no wide-ranging warning system is in place. There are indications that we are approaching or have crossed the safe boundary limits of many fundamental Earth system processes (Rockström et al. 2009), and we still know little about the tipping points in our socioecological systems and how fast they might be approaching.

Technically, the capacity exists right now to begin to detect many of the subtle and adverse changes that are occurring on the planet. We also have sufficient knowledge to provide a warning to the world community that we need action to stem the tide of the loss of the fundamental pieces and processes that support our collective livelihoods. However, there are significant gaps in the information we do have, particularly surrounding the societal consequences of the losses of these building blocks. Furthermore, existing information is not organized and regularly reported in a science-based consensus view in a way that could lead to rapid recognition and understanding of our Earth-system problems.

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The role of GEO BON

Understanding the Earth system, anticipating changes in it, and responding to those changes are not outcomes we can achieve simply by making observations. However, observations underpin these processes by providing the raw material for research, providing input to assessments of the state and change in the Earth system, and by providing evidence of the effectiveness of implemented decisions (figure 1). The world's governments, through the Group on Earth Observations (GEO), have proposed a platform through which existing information streams from monitoring and observation programs can be compiled into a system that produces a more comprehensive view of the status of biodiversity and socioecological systems. GEO's Biodiversity Observation Network (GEO BON), under the umbrella of GEOSS (the Global Earth Observation System of Systems), is focused on improving the availability and interoperability of information relating to the global environment (Scholes et al. 2011) as a means to facilitate research, assessments, and decisionmaking (figure 1).

GEO BON is structured around eight working groups focused on genetics, terrestrial species monitoring, terrestrial ecosystem change, freshwater ecosystem change, marine ecosystem change, ecosystem services, *in situ* and remote-sensing integration, and data integration and interoperability. Each of the topical groups has developed a plan for organizing and synthesizing existing data streams and motivating the creation of new data streams (GEO BON 2010a), all of which will feed into a physical platform that will allow access to and documentation of these resources (GEO BON 2010b). The focus of this article is the vision and plan of the GEO BON Ecosystem Services (ES) group.

A vision for GEO BON ES

The GEO BON ES group will be focused on information that describes spatial and temporal patterns in the production, delivery, and value of many ecosystem services at local to global scales. The MA provided such information, but as a one-time historic analysis (MA 2005). GEO BON ES will work in three key ways to provide this information on a regular basis: (1) efficiently connecting and providing access to existing databases and resources that provide or compile information on ecosystem services, (2) helping to identify gaps in observation systems, and (3) developing and communicating standards and protocols for the collection of new ecosystem service observations or for existing observations that do not have established guidelines.

What follows is a description of how a global information platform for ecosystem services can be established to play these roles. The approach described here encompasses multiple spatial scales but has an emphasis on the national scale. There are practical advantages in focusing on nations, because national statistics on many critical biophysical and social trends are readily available. Many global policies, such as the Convention on Biodiversity, the Millennium Development Goals, the Commission on Climate Change and Development, and other sustainability-focused platforms, are governed by mutual agreement of the participating nations. However, the approach we describe here can work downward to local scales or upward to the globe. The use of a multiscale approach makes the information compatible with the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), which will also center on assessments at subregional, regional, and global levels (Larigauderie and Mooney 2010).

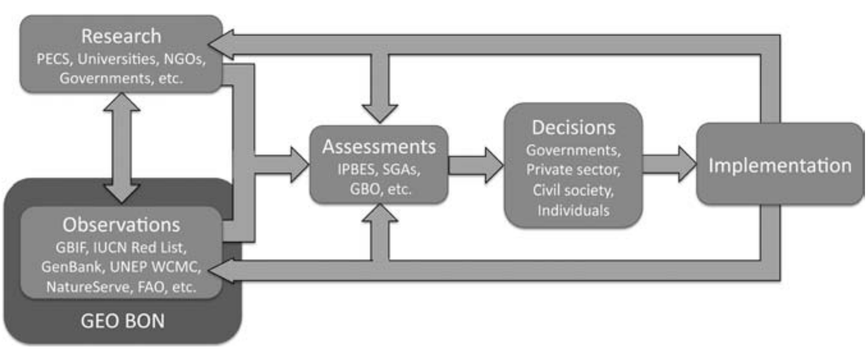

Figure 1. The Group on Earth Observations Biodiversity Observation Network (GEO BON) in context. GEO BON is intended to complement the efforts of existing monitoring and observing programs and compilation efforts such as the Global Biodiversity Information Facility (GBIF), the International Union for Conservation of Nature's (IUCN) Red List of Threatened Species, the United Nations Environment Program World Conservation and Monitoring Center (UNEP–WCMC), GenBank, the Food and Agriculture Organization of the United Nations (FAO), and others. GEO BON will be focused on improving the availability and interoperability of information relating to the global environment in order to provide the raw materials for research, synthesis, and assessment. Decisions made at any scale may influence the Earth system in observable ways that will feed in as new information, available for subsequent research and assessment. Abbreviations: GBO, Global Biodiversity Outlook; IPBES, Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services; NGO, nongovernmental organization; PECS, Program on Ecosystem Change and Society; SGA, the Sub-Global Assessment Network.

What will these data tell us?

A fully operational GEO BON ES platform will allow us to take more complete stock of our planet's life-support systems in ways that enhance research, assessment, and decision-making activities (figure 1). A multitude of entities explore key questions about the connections between nature and society (figure 1), but they are limited by the scope and scale of many existing observation systems. Several areas of research will be enhanced by access to data on multiple ecosystem services, tracked consistently and regularly. For example, changes in socioecological systems are often complicated, interacting, and nonlinear. The ability to track patterns in many services over time can complement modeling and forecasting to allow warning for approaching thresholds when they are known and can support additional research to identify thresholds that have not been previously identified.

Furthermore, by linking supply to service and benefits (described in detail below), a better picture of the consequences of ecosystem service and biodiversity loss for human well-being will emerge. Changes in socioecological systems are known to lead to trade-offs and synergies among services, but the relationships among many services remain unclear. For example, enhancing the supply of provisioning services (e.g., food production) can result in declines in regulating and cultural services (e.g., carbon sequestration, recreation; MA 2005), but these trade-offs are not inevitable (Nelson et al. 2009). The compilation of extensive, standard monitoring of multiple services will allow the scientific and assessment communities to explore and better understand the nature of trade-offs across scales and socioecological settings.

Finally, the global scope of the platform will allow more extensive research into the role of significant remote drivers and teleconnections such as trade in determining ecosystem service provision and benefit. For example, demand for biofuels in Europe may drive the conversion of tropical forests into oil palm plantations in Southeast Asia. Combining analyses of the supply of services with analyses of trade patterns may allow a more thorough understanding of how demand for certain services in one country (e.g., biofuels, food, timber) leads to changes in the provision of services in other countries (see, e.g., Mosnier et al. 2012).

Beyond providing new opportunities to the research community, GEO BON ES will enable novel assessments and syntheses and will improve existing assessments and decisionmaking. The data compiled will be relevant to and available for use in assessments being designed now under the newly established IPBES. Groups conducting assessments under IPBES will be challenged without a system such as GEO BON ES (UNEP 2011). These same data will provide valuable input to existing groups that report on intergovernmental policy targets for development and conservation (e.g., the Convention on Biological Diversity, IPBES, and Millennium Development Goals). For example, the Convention on Biological Diversity has set 20 ambitious targets for the world to achieve by 2020 (CBD 2011). One of these targets is that "by 2020, ecosystems that provide essential services, including services related to water, and contribute to health, livelihoods, and well-being, [be] restored and safeguarded, taking into account the needs of women, indigenous and local communities, and the poor and vulnerable." This is an aspirational target, but all treaty nations have committed to working toward achieving it. GEO BON ES will provide the information to track our progress in doing so. Because GEO BON ES will function at multiple scales, compiled information streams can be fed into national and regional assessments and synthesis that may clarify the consequences of past and future policies and management decisions, facilitating adaptive management and allowing better design of future policies.

Standardizing ecosystem service metrics

One of the first needs in compiling ecosystem service data is to establish a standard language and approach to measurement and observation. Although the MA rather generally defined *ecosystem services* as the benefits that ecosystems provide to humans, more recent work by groups such as the Natural Capital Project and The Economics of Ecosystems and Biodiversity project has further developed this definition in an attempt to disentangle the links from ecosystems and biodiversity to human well-being. Although a definition has still not been universally agreed on, these new frameworks usefully separate the biophysical supply, the service itself, and the social benefits and value (TEEB 2010, Tallis and Polasky 2011). To provide greater clarity on measuring important points along the ecosystem service supply chain, we distinguish among the structure and function of ecological systems relevant to a service (the *supply*), the service actually used or enjoyed by people (the *service*), and the change in people's well-being that results (the *benefit*).

Here, the *supply* is seen as the full potential of ecological functions or biophysical elements in an ecosystem to provide

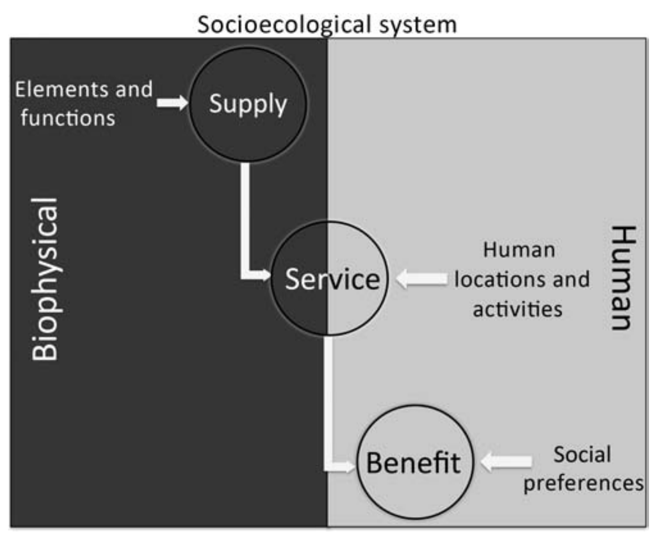

Figure 2. Components of the ecosystem service supply chain. The metrics of supply indicate the biophysical potential of a system to produce a given benefit. Service metrics add information on the location and activities of human beneficiaries and indicate the amount of service actually delivered to people. Benefit metrics add information on society's preference for a given level of benefit and indicate how important a given amount of service is in economic or noneconomic terms. Source: Adapted from Tallis and colleagues (2012).

Table 1. Examples of ecosystem services and the associated metrics that are currently monitored globally.

Ecosystem service	Type	Metric	Source	Available globally	Updated regularly
Crop production	Supply	n/a	n/a	n/a	n/a
	Service	Production of all commercial crops	FAOSTAT	X	X
		Caloric content of all commercial crops	FAOSTAT	X	
	Benefit	Market value of all commercial crops	FAOSTAT	X	X
		Number or percentage of malnourished people	World Bank	X	
Livestock production	Supply	n/a		n/a	n/a
	Service	Production of all commercial livestock	FAOSTAT	X	X
		Caloric content of all commercial livestock	FAOSTAT	X	
	Benefit	Market value of all commercial livestock	FAOSTAT	X	X
Wood production	Supply	Standing biomass in unprotected areas	LPJmL	X	X
	Service	Wood production	FAOSTAT	X	X
	Benefit	Market value of wood products			
Regulation of carbon dioxide	Supply	Carbon sequestration rate or avoided emissions	WDCGG, LPJmL	X	X
	Service	Carbon sequestration rate or avoided emissions	WDCGG, LPJmL	X	X
	Benefit	Market value of carbon credits	InVEST	X	X
		Social value of carbon sequestration	InVEST	X	n/a
Water supply for hydropower	Supply	Volume of surface water or groundwater yield	LPJmL, InVEST	X	X
	Service	Volume of water used for hydropower	InVEST	X	
	Benefit	Market value of hydropower	InVEST	X	

Notes: X indicates that global data are available or that the source is regularly updated. Abbreviations: FAOSTAT, the Statistics Division of the Food and Agriculture Organization of the United Nations; InVEST, the Natural Capital Project's Integrated Valuation of Environmental Services and Tradeoffs software program; LPJmL, the Lund–Potsdam–Jena Managed Land Dynamic Global Vegetation and Water Balance Model; n/a, not applicable; WDCGG, World Data Centre for Greenhouse Gases.

a given ecosystem service, without consideration of whether humans actually recognize, use (sustainably or unsustainably), or value that function or element (figure 2, table 1). Much of the prior work on ecosystem services has been focused solely on this biophysical evaluation of maximum potential supply.

Measuring supply is necessary but not sufficient to determine the level of ecosystem service provision or the resultant benefits to society. Measuring the actual delivery of services to people also requires information concerning the demand for and use of ecosystem services (figure 2, table 1). The spatial distribution of people, infrastructure, and ecosystems and the control of institutions over access and human behavior determine how humans interact with the ecosystem in ways that turn the supply into a service that is used or enjoyed. Distinguishing between supply and service metrics provides more accurate information about the ecosystem services affected by management decisions and enables us to better predict the consequences of those decisions for a broad range of social benefits.

The final step in the supply chain represents how much the flow of a given service contributes to human well-being (figure 2, table 1). GEO BON ES will ideally be used to observe changes in all critical components of human well-being affected by biodiversity and ecosystem services. Complete representation of these connections in a global monitoring system is probably impossible. In a perfectly functioning market economy, people choose how much to consume of each good or service on the basis of how much it contributes to their well-being relative to its price. In such a system, we could use observed market prices and quantities purchased to measure the benefits that people receive from ecosystem services, but in the current global economic system, not all benefits are captured in existing markets (tables 2 and 3). Many ecosystem services have characteristics of public goods (e.g., climate regulation, improved water or air quality) that make it difficult to provide these services through markets. Other ecosystem services benefit primarily the poor, and these benefits do not get much weight precisely because the people enjoying them do not have the capital necessary to influence the market. Still others, such as cultural values, provide intangible experiences that are not captured well in current valuation approaches.

In the context of measurement, each benefit can have a separate set of service and benefit metrics. Our framework differs slightly from others that identify the benefits that people receive and those benefits' monetary value as independent steps in the supply chain from nature to people

Table 2. Examples of emerging services for monitoring.

Ecosystem service	Type	Metric	Source	Available globally	Updated regularly
Fisheries production	Supply	Biomass or abundance of all (commercially) important fishes			
	Service	Landings of (commercially) import species	FAOSTAT	X	X
		Caloric content of those landings			
	Benefit	Market value of the landings			
		Number or percentage of malnourished people			
Biofuel production	Supply	n/a		n/a	n/a
	Service	Production of commercial oil seed crops	FAOSTAT	X	X
	Benefit	Market value of commercial oil seed crops	FAOSTAT	X	X
Water supply for domestic use	Supply	Volume of surface water or groundwater yield	LPJmL, InVEST	X	
	Service	Volume of freshwater withdrawals for domestic use	FAOSTAT		
	Benefit	Percentage of a population with access to clean water	World Bank		
Water supply for irrigation	Supply	Volume of surface water or groundwater yield	LPJmL, InVEST	X	
	Service	Volume of freshwater withdrawals for agriculture	FAOSTAT		
	Benefit	Marginal market value of crops attributable to irrigation			
Nutrient retention for clean drinking water	Supply	Mass of nitrogen or phosphorus retained	InVEST	X	
	Service	Mass of nitrogen or phosphorus retained upstream of the extraction points	InVEST	X	
	Benefit	Avoided water treatment costs	InVEST	X	
Erosion control for reservoir maintenance	Supply	Mass of retained soil	InVEST, SWAT	X	
	Service	Mass of soil retained upstream of reservoirs	InVEST	X	
	Benefit	Avoided dredge costs	InVEST	X	
Flood regulation	Supply	Flood volume regulated by vegetation and soils			
	Service	Area of avoided flood damage due to regulation by vegetation or soil			
	Benefit	Avoided costs due to loss of property or infrastructure			
Nature-based tourism	Supply	Area with attractive natural features or high habitat quality			
	Service	Area with accessible attractive natural features or high quality habitat			
	Benefit	Income from nature-based tourism	IUCN–WCPA		

Notes: These services are important to include in a global monitoring program, but they are not currently globally available, they are not regularly updated, or there is not sufficient confidence in their reported values. This is not meant to be an exhaustive list of all services that could be monitored but, rather, a subset that could become part of a global monitoring system in the near future, given existing and emerging monitoring systems. X indicates that global data are available or that the source is regularly updated. Abbreviations: FAOSTAT, the Statistics Division of the Food and Agriculture Organization of the United Nations; InVEST, the Natural Capital Project's Integrated Valuation of Environmental Services and Tradeoffs software program; IUCN–WCPA, the International Union for Conservation of Nature and the World Commission on Protected Areas; LPJmL, the Lund–Potsdam–Jena Managed Land Dynamic Global Vegetation and Water Balance Model; n/a, not applicable.

(e.g., TEEB 2010). As we discussed above, market values usually represent a subset of the benefits that flow from supply. We use monetary value as one benefit metric when it is available, but it often needs to be augmented with other benefit metrics to represent the full contribution to human well-being. For example, agricultural crop production provides nutritional benefits to the rich and the poor alike, but in many cases, market values only adequately capture the contribution of crop products to the well-being of the more wealthy members of society, who are able to purchase food in markets. To more accurately capture the benefits to all members of society, we need to track both the market value of crops and the contribution of those crops to the nutritional health of the poor (who are likely not paying for food through a market).

GEO BON ES needs to ensure that reporting many forms of benefit metrics does not lead to misinterpretations such as double counting—and that each metric closely approximates the marginal contribution of nature to human well-being. For example, using nonmonetary metrics, such as child malnutrition rates, to indicate the importance or value of crop production for the poor can be problematic in two ways: First, including both market value and malnutrition metrics will lead to double counting (Boyd and Banzhaf 2007) in areas where the poor do purchase food in a market, because their well-being from that product is already captured in

Table 3. Examples of distributional equity benefits to target for future monitoring.

Ecosystem service	Type	Metric
Equitable crop production	Service	Proportion of crop production for groups of special interest
		Proportion of crop calories consumed by groups of special interest
	Benefit	Proportion of the market value for groups of special interest
		Proportion of malnourished people in groups of special interest
Equitable livestock production	Service	Proportion of production of all commercial livestock for groups of special interest
		Proportion of caloric content of all commercial livestock for groups of special interest
	Benefit	Proportion of market value of all commercial livestock for groups of special interest
Equitable wood production	Service	Proportion of wood production for groups of special interest
	Benefit	Proportion of wood product market value to groups of special interest
Equitable water supply for hydropower	Service	Proportion of water yield or power for groups of special interest
	Benefit	Proportion of market value of hydropower for groups of special interest
Equitable fisheries production	Service	Proportion of fish landed by groups of special interest
		Proportion of nutrition consumed by groups of special interest
	Benefit	Proportion of market value for groups of special interest
		Proportion of malnourished people in groups of special interest
Equitable biofuel production	Service	Proportion of oil seed produced by groups of special interest
	Benefit	Proportion of market value to groups of special interest
Equitable water supply for domestic use	Service	Proportion of domestic water supply to groups of special interest
	Benefit	Proportion of the population from groups of special interest with access to clean water
Equitable water supply for irrigation	Service	Proportion of irrigation water used by groups of special interest
	Benefit	Proportion of marginal market value of irrigated crops to groups of special interest
Equitable nutrient retention for clean drinking water	Service	Mass of nitrogen or phosphorus retained upstream of extraction points accessible to groups of special interest
	Benefit	Proportion of avoided water treatment costs for groups of special interest
Equitable erosion control for reservoir maintenance	Service	Mass of soil retained upstream of reservoirs accessed by groups of special interest
	Benefit	Proportion of avoided dredge costs for groups of special interest
Equitable flood regulation	Service	Proportion of avoided flood damage to groups of special interest due to regulation by vegetation or soil
	Benefit	Avoided costs for groups of special interest due to the loss of property or damaged infrastructure
Equitable nature-based tourism	Service	Area of lands or waters with attractive natural features or high-quality habitat accessible by groups of special interest
	Benefit	Proportion of income from nature-based tourism for groups of special interest

Note: None of these sample service or benefit metrics are currently measured with global coverage or with regular updates.

the market value. Second, child malnutrition rates are not necessarily driven only by agricultural crop production (or a lack thereof), and so, the metric does not perfectly capture the marginal contribution of the ecosystem service to the health component of human well-being. Although we strive for metrics that accurately and fully represent each benefit, the absence of regularly tracked metrics that meet these standards may necessitate the use of some imperfect metrics in the interim, and the limitations of those metrics must be recognized.

In some cases, we do not even have imperfect metrics that can be used as proxies for nature's contribution to well-being. For example, distributional equity—especially regarding the needs of women, indigenous groups, local communities, and the poor and vulnerable—is a benefit that should have its own service and benefit metrics (e.g., to track progress toward the CBD 2020 target mentioned above). However, these metrics are not well represented in current market values or other regularly reported metrics (table 3). These gaps in benefit metrics provide major opportunities for new research in both the social and the ecological scientific communities.

In the GEO BON ES approach, we do not advocate for metrics focused on one step in the ecosystem service supply chain (i.e., supply, service, benefit) as more correct or useful. Rather, metrics should be tracked for all three stages of ecosystem service delivery whenever that is possible. Supply metrics will be useful in understanding the sustainability of natural resource use and will serve as a guide for whether and how much services are likely to flow from ecosystems in the future. Supply metrics have been the most commonly tracked metrics in the past, and therefore, the global monitoring platform will probably better represent ecosystem service supply in the near future. Service metrics will be useful in understanding what society is actually gaining from ecosystems by representing how supply interacts with demand, infrastructure, institutions, and behavior, which all vary spatially and temporally. These service metrics are currently available for many provisioning services, such as timber production and agricultural yields (table 1). New tracking systems need to be developed to broaden this set to include service metrics for regulating and cultural services, such as flood mitigation, erosion control, and tourism (table 2).

Benefit metrics will reveal how important changes in ecosystem service provision are to human well-being. In some cases, the benefit metrics will be the most critical, because they most closely match those used in national accounting and common natural resource decisionmaking processes. Such metrics are readily available only for marketed goods (table 1), and the monitoring systems for nonmarketed goods, nonmonetary values, and the distribution of services and benefits need to be developed (tables 2 and 3). Overall, marine ecosystem services are severely underrepresented in current monitoring systems at all stages of the supply chain (Wood et al. 2008).

Approaches to tracking ecosystem service change

The information needed to track the supply, service, and benefit of ecosystem services will come from a diverse set of approaches. We envision GEO BON ES compiling information from national statistics, numerical models, *in situ* observations and remote sensing at a range of spatial scales and resolutions (figure 3). To date, the list of services and the corresponding approaches are largely limited by data availability and our understanding of how some ecosystem services work (e.g., regulating and cultural services); as knowledge and monitoring efforts expand, new services and methods will be included. The sections below lay out what is possible today, starting with the methods that currently provide the most information.

National statistics. Census data provide an excellent opportunity to aggregate household-level data up to the national scale. GEO BON ES will be focused on two efforts with respect to census data: linking to existing national summaries for some services and developing a standard core set of additional questions to be included in census surveys to expand the suite of ecosystem services that we can track through this mechanism (figure 3). Changes in provisioning services (e.g., crops, livestock, timber production) are well represented in national census data, whereas regulating, cultural, and supporting services are not. The Food and Agriculture Organization of the United Nations (FAO) publishes a global database of the quantity, value, and trade in crop, timber, and livestock production (FAOSTAT). Although data accuracy is high for developed countries, it can be low for developing countries, and these data gaps are filled with FAO estimates. Water withdrawal by sector (e.g., industrial, municipal, agricultural) is also available for a small subset of nation states; however, the coverage is limited and updated infrequently (around every 5 years). In all cases, uncertainty analyses are essential, because the data are derived from government-administered censuses. Given these caveats, FAOSTAT is very useful and is heavily employed not only for providing the state of the global production systems base but also as a tool for validating numerical process models that can provide scenarios for the future (Bondeau et al. 2007, Deryng et al. 2011).

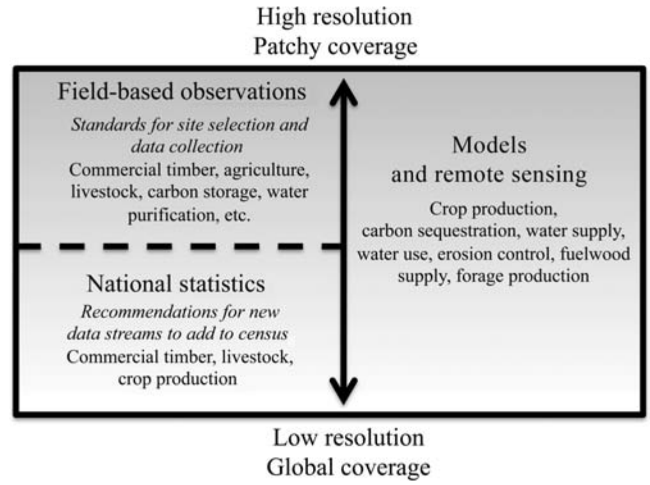

Figure 3. ***Components compiled in the GEO BON ES (the Group on Earth Observations Biodiversity Observation Network's Ecosystem Services group) global platform and their associated resolutions and extent of global coverage. The terms in italics identify products that the GEO BON ES will generate. The services listed under each area are examples of what could be included in the GEO BON ES platform.***

Analogous information is needed on a broader range of ecosystem services. Part of GEO BON ES's contribution will be to establish a working subgroup with broad scientific and geographic representation that will develop a standard set of additional questions to be included in national censuses. These questions will expand the set of ecosystem services regularly monitored and reported through household surveys. Although the list of questions that could be added is long, our recommendations will be focused on services provided locally and those enjoyed outside of markets. With these questions, we will attempt to isolate the marginal contribution of natural capital and its associated ecosystem service flows to many components of household well-being, including nutrition, health, and livelihood options.

Field-based observations. It is important to complement national statistics with methods that capture information about ecosystem services at local or landscape scales in order to validate measures derived from numerical modeling and remote sensing and to directly monitor ecosystem services that do not function or cannot be observed at national and global scales (e.g., pollination, some cultural values, some water quality components; figure 3).

At this scale, measuring the entire supply chain becomes more feasible for a wider range of services (e.g., Nelson et al. 2009), but global coverage is far from complete. Knowledge and data on the social components of ecosystem services, including institutions, human demography, perceptions, and use, are better defined at this scale and should enable us to execute measurements that capture the use and distribution of the benefits from these services.

In parallel to its global analysis, the MA began the process of coordinating smaller-scale approaches to ecosystem service measurement and assessment and brought together 33 subglobal projects from across the world. This coordination was mostly focused on a shared conceptual framework rather than on standardized sampling protocols. Although the subglobal assessments had impacts at a subglobal scale, the lack of standards was one factor that limited their value at the global scale in validating and complementing top-down approaches (Wells et al. 2006). Furthermore, there is a need for a priori site selection to ensure that local and regional observations are representative of global social and ecological diversity.

In following the GEO model of collaboration and cooperation, GEO BON ES aims to work with several ongoing subnational initiatives to establish site selection processes and standardized sampling protocols. GEO BON ES will identify and provide access to existing standards (Andelman 2011) and will develop new standards for ecosystem services that have not yet been addressed by other groups.

Once these processes and protocols exist, the global research, observation, and assessment communities will need to foster their broadscale adoption. GEO BON will promote this adoption and use by engaging directly with initiatives such as the Sub-Global Assessment Network; with programs such as the International Long Term Ecological Research Network, the Tropical Ecology Assessment and Monitoring network, the International Council for Science's Program on Ecosystem Change and Society (Carpenter et al. 2012), and IPBES, but GEO BON will rely on the broader scientific community to promote established approaches more extensively in all relevant *in situ* observation endeavors. Once standards are in wide use, the aggregation of local and regional data to national and global scales will be possible.

Remote sensing. Remote sensing has the potential to capture biodiversity status and ecosystem service changes through time, from local to global scales. Many evaluations of the changing status of ecosystem services have been based on—and limited by—spatially explicit land-use change information (Hibbard et al. 2010). Although this kind of analysis is routinely done for small geographic areas, the data available at the global level are too infrequent to be of use in a regularly updated ecosystem service monitoring platform. Existing approaches also use inconsistent classification methods, which makes changes unquantifiable. There is a critical need to achieve this capability, and it should be a high research priority for the remote-sensing community (Herold et al. 2008).

We do have global annual information on gross primary productivity and net primary productivity through the use of NASA's Moderate Resolution Imaging Spectroradiometer (MODIS; Running et al. 2004). In addition, a MODIS-based global disturbance index is available that accounts for major landscape disturbances (e.g., wildfires, insect outbreaks, deforestation; Mildrexler et al. 2009), but it has not yet been validated outside of temperate North America. These inputs, with corrections for climate-driven interannual changes in net primary productivity, could provide a metric for annual global land-use change. Remote sensing can also provide information for assessing the delivery of ecosystem services directly, such as climate regulation through carbon sequestration. Saatchi and colleagues (2011) mapped tropical stocks of carbon using a combination of remotely sensed canopy height from the Geoscience Laser Altimeter System, samples of ground-level biomass measurements made in various regions, and models to derive spatially explicit estimates of carbon stocks. The need for carbon accounting to meet the requirements of international agreements has stimulated this research area, aided by advances in remote-sensing technology. However, *in situ* data from a network of geographically representative plots are needed to calibrate these remotely sensed measurements.

New advances coupling LIDAR (light detection and ranging) measurements with hyperspectral remote sensing are extending this monitoring capability for a wide range of applications, extending from carbon stores and deforestation to phylogenetic signatures of forest composition (Asner et al. 2009). At present, this technology is most highly developed for aircraft platforms and needs to be scaled up for global analyses. Remote sensing is also showing potential in efforts to monitor inland and marine water quality (Matthews et al. 2010).

In summary, the capacity to use remote sensing as a tool to track critical ecosystem structure and function over wide areas with regular frequency must be developed further to support this proposed global biodiversity observation system. GEO BON ES will compile existing observations, but we call on the research community to further establish clear links between remotely observable changes in ecosystem function and ecosystem service delivery.

Numerical simulation models Simulation models have demonstrated the ability to capture many essential processes of ecosystem functioning and dynamics and can therefore fill critical gaps in ecosystem service monitoring left by observation approaches. Biophysical processes, such as carbon and water cycling, vegetation dynamics, and species population dynamics, that act as key inputs to critical ecosystem services can be modeled at varying degrees of complexity. When combined with data or models of human demography, behavior, and infrastructure, these models can provide quantitative information on the status, distribution, and change in many ecosystem services, including some that are regularly monitored (e.g., crop, timber, and fisheries production) and some that are not (e.g., the provision of water for irrigation or hydropower production, flood or climate regulation).

Specifically, dynamic vegetation models have been shown to consistently simulate carbon- and water-related processes, as well as the associated vegetation dynamics in one platform (Sitch et al. 2003, Bondeau et al. 2007). Such systems models are generally focused on supply, and in some cases, on service metrics, but they can be complemented by economic or other valuation models to estimate benefits. Simpler production-function models estimate the biophysical levels and economic values of a suite of ecosystem services on the basis of environmental condition and human demand. Such models can help expand the list of services that can be considered and provide one way of assigning economic values to services. As with all modeling, we can describe the uncertainty in predictions and can improve model structures as the monitoring system expands and provides additional field observations for validation.

The list of models providing outputs that could be compiled in the GEO BON ES platform is long and continually growing. We will initiate our contribution to the GEO BON platform with the outputs of two models: the dynamic global vegetation model LPJmL (Lund–Potsdam–Jena Managed Land Dynamic Global Vegetation and Water Balance Model) (Sitch et al. 2003, Bondeau et al. 2007) and the simple InVEST (Natural Capital Project's Integrated Valuation of Environmental Services and Tradeoffs software program) models that use environmental production functions (Nelson et al. 2009, Kareiva et al. 2011). These models were chosen as initial examples of the spectrum of model types that can provide useful input to the platform, and this choice provides the opportunity to look across scales (LPJml is a global model that can be applied to regional cases; InVEST is a local or regional model for which some global applications have been made; Nelson et al. 2010). These two models also provide the chance to test the ability to link existing biogeophysical systems models to simple economic valuation models. LPJmL is a useful integration tool in this context, because it uses FAO data but extends and connects those data to other ecosystem services (e.g., carbon cycling, nutrient cycling) through dynamic processes (Müller et al. 2006). In a European study, Metzger and colleagues (2008) demonstrated the usefulness of LPJmL for ecosystem service assessment. We encourage the scientific community to independently, or in collaboration with GEO BON, demonstrate how additional models could be used in an ecosystem services monitoring context. Successful demonstrations would lead to the incorporation of outputs from a broader model set.

Data limitations currently present challenges for using these models in a monitoring context, and we anticipate that improved data compilation and standardization through the other GEO BON ES approaches (i.e., remote sensing, field-based observations, national statistics) will improve the utility and accuracy of these and other models. For example, LPJmL requires high-quality gridded global climate inputs that are available with a time lag of approximately 5 years. However, there is no technical reason that appropriate data could not be provided faster, dramatically enhancing the usability of this model in decision contexts. Land-use and landcover maps are key inputs to both LPJmL and InVEST. Although remote-sensing products can now easily detect a loss of forest cover, no regularly updated global land-use or landcover map currently exists, which limits the usefulness of these models in a monitoring context.

We view the needs for frequently updated, high-quality climate and land-use or landcover data as critical challenges to the land-classification and climate-monitoring communities for innovation in the rapid assessment of change. We also see the opportunity for developing individual service models to fill data gaps for services that function at local and regional scales. Many of these services are currently addressed with biophysical models that need to be tied to socioeconomic models that represent the full supply chain.

Conclusions

Although the GEO BON ES platform has great potential for yielding fundamental insight into our life-support systems, it is not without limitations. The information is only as good as the available data sets, and, as we mentioned above, many national statistics are fraught with errors and estimates. Furthermore, much of the input data required for regular reporting is not updated frequently enough. Perhaps more pressing is the need for a regularly updated global land-use or landcover map based on remote sensing. Finally, the set of ecosystem services that may be currently reported is severely limited, and there is a complete absence of marine services. Many regulating and cultural services are difficult to measure or model at any scale and are not regularly reported in public data streams. That being said, interest in global ecosystem service modeling and national accounting is increasing rapidly, and the GEO BON ES platform may be able to incorporate many more services in the coming years.

Being able to take the pulse of our planetary life-support system and respond accordingly is undeniably one of the most important requirements if we are to achieve global sustainability. Although this sounds overly ambitious to many, the GEO BON ES platform outlined here is an achievable approach that would fill the pulse-taking role well. Its feasibility is clear in that we can already measure and monitor key services at multiple scales. The gaps that we have identified are specific and mostly involve key data sets (e.g., landcover, land use), key scientific knowledge (e.g., the production functions of regulating services, how humans use ecosystem services), and achievable advancements in models and remote-sensing technology. These advances will require funding, scientific collaboration, and intergovernmental commitment, and in return, we will gain a clearer understanding of the status of and change in our planet's life-support systems.

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