National indicators for observing ecosystem service change

Daniel S. Karp[a,b,*], Heather Tallis[b], René Sachse[c], Ben Halpern[d,e,f], Kirsten Thonicke[g,h], Wolfgang Cramer[i], Harold Mooney[j], Stephen Polasky[k], Britta Tietjen[h,l], Katharina Waha[g,m], Ariane Walz[c,g], Stacie Wolny[n]

[a] *Department of Environmental Science, Policy and Management, University of California, Berkeley, CA 94720, USA*
[b] *The Nature Conservancy, 1107 Laurel Ave., Felton, CA 95018, USA*
[c] *Institute of Earth and Environmental Science, University of Potsdam, D-14476 Potsdam, Germany*
[d] *Bren School of Environmental Science and Management, University of California, Santa Barbara, CA 93106, USA*
[e] *NCEAS, 735 State St., Santa Barabara, CA 93101, USA*
[f] *Imperial College London, Silwood Park, Buckhurst Rd., Ascot, UK*
[g] *Potsdam Institute for Climate Impact Research e. V. (PIK), Telegrafenberg A31, D-14473 Potsdam, Germany*
[h] *Berlin-Brandenburg Institute of Advanced Biodiversity Research (BBIB), D-14195 Berlin, Germany*
[i] *Institut Méditerranéen de Biodiversité et d'Ecologie Marine et Continentale (IMBE), Aix Marseille Université, CNRS, IRD, Avignon Université, Technopôle Arbois-Méditerranée, Bât. Villemin, BP 80, F-13545 Aix-en-Provence Cedex 04, France*
[j] *Department of Biology, Stanford University, Stanford, CA 94305, USA*
[k] *Department of Applied Economics/Department of Ecology, Evolution and Behavior, University of Minnesota, St. Paul, MN 55108, USA*
[l] *Freie Universität Berlin, Institute of Biology, D-14195 Berlin, Germany*
[m] *CSIRO Agriculture, 306 Carmody Road, 4067 St.Lucia, QLD, Australia*
[n] *The Natural Capital Project, Stanford University, Stanford, CA 94305, USA*

Earth's life-support systems are in rapid decline, yet we have few metrics or indicators with which to track these changes. The world's governments are calling for biodiversity and ecosystem-service monitoring to guide and evaluate international conservation policy as well as to incorporate natural capital into their national accounts. The Group on Earth Observations Biodiversity Observation Network (GEO BON) has been tasked with setting up this monitoring system. Here we explore the immediate feasibility of creating a global ecosystem-service monitoring platform under the GEO BON framework through combining data from national statistics, global vegetation models, and production function models. We found that nine ecosystem services could be annually reported at a national scale in the short term: carbon sequestration, water supply for hydropower, and non-fisheries marine products, crop, livestock, game meat, fisheries, mariculture, and timber production. Reported changes in service delivery over time reflected ecological shocks (e.g., droughts and disease outbreaks), highlighting the immediate utility of this monitoring system. Our work also identified three opportunities for creating a more comprehensive monitoring system. First, investing in input data for ecological process models (e.g., global land-use maps) would allow many more regulating services to be monitored. Currently, only 1 of 9 services that can be reported is a regulating service. Second, household surveys and censuses could help evaluate how nature affects people and provides non-monetary benefits. Finally, to forecast the sustainability of service delivery, research efforts could focus on calculating the total remaining biophysical stocks of provisioning services. Regardless, we demonstrated that a preliminary ecosystem-service monitoring platform is immediately feasible. With sufficient international investment, the platform could evolve further into a much-needed system to track changes in our planet's life-support systems.

1. Introduction

Human activities and associated pressures have caused more rapid global change now than Earth has experienced over the past 12,000 years (Barnosky et al., 2012; Ehrlich et al., 2012). As climate

* Corresponding author at: Department of Environmental Science, Policy and Management, University of California, Berkeley, CA 94720, USA.
E-mail address: danielsolkarp@gmail.com (D.S. Karp).

change, biodiversity loss, and biogeochemical alterations continue, it is expected that sudden, rapid, and surprising global state shifts will degrade the benefits that nature provides and that support human wellbeing—ecosystem services (Rockström et al., 2009; Barnosky et al., 2012). For example, the Millennium Ecosystem Assessment (MA) (Millenium Ecosystem Assessment, 2005) brought global attention to the state of ecosystem services, and the relevance of their ongoing loss, by reporting on the change in 24 ecosystem services (Millenium Ecosystem Assessment, 2005). This one time assessment, however, did not indicate what has happened since, and we currently have no centralized monitoring system for detecting and reporting on global ecosystem service change. Without a tracking system, we are flying blind, unable to understand mounting risks or anticipate future ecosystem state changes and how they will affect the services upon which we rely (Tallis et al., 2012).

Moreover, the MA calculated changes over relatively long time horizons (e.g., between ~1960 and 2000), at best reporting decadal average changes. Estimates were done this way to show longer-term trends and to take best advantage of temporally sparse data. Such long-term analyses are powerful for bringing attention to large changes and for identifying major opportunities for bolstering ecosystem services. However, many regular government and private sector decisions are made on much shorter time scales, and adaptive management can be informed, most ideally, by paired long-term and short-term views of ongoing changes. For example, governments generally function on administrative terms ranging from ~2 to 5 years. Therefore, a monitoring system that reports the state of biodiversity, ecosystems, and ecosystem services regularly and on shorter time scales would be very relevant to short-term decisions. To address the current lack of such a system, the world's governments formed a Biodiversity Observation Network through the Group on Earth Observations (GEO BON) that functions as a centralized platform to coordinate, harmonize, and combine existing biodiversity and ecosystem-service monitoring streams (Scholes et al., 2008, 2012).

We focus here on the immediate need for an ecosystem-service monitoring platform. Major governmental and non-governmental conservation decisions informed by international assessments such as the Global Biodiversity Outlook (GBO) and Sub-Global Assessments (SGA) are made on limited data (Tallis et al., 2012). Countries struggle to report on progress towards environmental goals such as the Convention on Biological Diversity's (CBD) targets. These CBD targets now explicitly include ecosystem services, but tracking the ecosystem services targets for 2010 failed in part because necessary data were not globally available for calculating indicators and reporting progress (Walpole et al., 2009; CBD, 2014). Furthermore, efforts are underway by The World Bank and other international organizations to measure natural capital and more holistically account for the wealth of nations. Such accounting will require regular monitoring to assess changes in natural capital (stocks) and ecosystem services (flows) over time (The World Bank, 2011; UNSD EEA and The World Bank, 2011; UNU-IHDP and UNEP, 2014), but often the relevant data are lacking.

Effective monitoring of ecosystem services requires tracking multiple types of services at multiple stages of delivery (Tallis et al., 2012). Broadly, ecosystem services can be classified into three categories. Provisioning services are the material goods that flow from nature, such as food, fuel, and water. Regulating services are processes that control the dynamics of socio-ecological systems, including pollination, water filtration, and flood control. Cultural services are the benefits from nature that enrich human life and often seem intangible; for example, the spirituality, heritage, and identity derived from nature (Chan et al., 2012; CBD, 2014). An ideal monitoring system would track the supply, delivery, and value of services in each of these categories (Tallis et al., 2012).

Services in any of these categories flow from nature to people along a "supply chain," which can be measured and monitored at several distinct steps along the path. Supply refers to the total biophysical potential of an ecosystem to provide a service to people, irrespective of whether people actually benefit. For example, the supply of coastal protection may measure how coastal habitats buffer storm surge in areas with and without human habitation. The delivery of a service is the degree to which humans actually consume, access, receive, or enjoy an ecosystem service. At the final stage of ecosystem service delivery to people, value reflects people's preferences for the amount of benefits provided by ecosystem services, which can be expressed in several ways, including but not limited to monetary values. Regional ecosystem-service mapping programs often seek to develop and map indicators of all three stages of the ecosystem-service cascade. For example, efforts are underway to map the supply, delivery, and value of a suite of services across Europe (Maes et al., 2012a,b) and in other regions worldwide for diverse decision contexts (Ruckelshaus et al., 2013). Yet few elements of the ecosystem-service cascade are reported regularly over time in large-scale monitoring programs. Instead, indicators focus on the prevalence of habitats, species, or populations that could potentially provide services (CBD, 2011), and one is left to infer if or how changes in these indicators translate into changes in service supply, delivery, or value.

Here, we explore how diverse, existing data streams could be combined, in the short term, to create an initial ecosystem-service monitoring platform. We focus explicitly at the national scale so that monitoring could easily feed into major intergovernmental agreements such as CBD and the Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES) and major governmental activities such as national accounting. Rather than reporting changes in the abundance or protection of habitats or species that could potentially provide services, we combine biophysical models and national statistics to report, whenever possible, the supply, delivery, and value of services over time. As a starting point, we have extended the five services that were identified as possible to monitor globally (see Table 1 in Tallis et al., 2012) by four additional services, including three marine services. Despite these efforts, our exercise is coarse, incomplete, and subject to improvement, reflecting the current state of global monitoring systems. In conducting this initial assessment, however, we demonstrate what can be achieved with existing data as an example of what could be expanded upon if major gaps were filled to produce a more comprehensive ecosystem-service monitoring platform.

2. Methods

2.1. Overview of reported services

We compiled indicators of the supply, delivery, and monetary value of ecosystem services at national scales from 1996 to 2005, focusing only on services that are annually reported or can be modeled at that time step for a large number of countries worldwide. We have chosen this time frame to evaluate annual changes in ecosystem services over an exemplary decade, which can be regarded as a starting point for monitoring as well as a call for regularly updating datasets. We found adequate temporal and spatial coverage for eight provisioning services (water supply for hydropower, non-fisheries marine products, crop, livestock, game meat, fisheries, mariculture, and timber production), and one regulating service (carbon sequestration). Data were not sufficient to include any cultural services at this stage, although their relevance is well recognized. When possible, we calculated the supply, delivery, and monetary value for each service; however, data gaps precluded reporting of all three metrics for each service.

In several cases, we combined datasets to be able to report indicators for the different components of ecosystem service supply, delivery, and value. Indicators for these nine ecosystem services were extracted from three primary sources: (1) national statistics derived from census data, primarily reported through the Food and Agriculture Organization (FAO) of the United Nations, (2) a global dynamic vegetation model (LPJmL), and (3) an ecosystem-service production function model (InVEST).

2.2. National statistics

The FAO reports the trade, in-country production, and monetary value of several marketed provisioning services. The data are largely derived from national censuses, annually and voluntarily reported by countries to the United Nations. The data suffers from well-documented biases. First, nation-states do not always honestly report production data (Watson and Pauly, 2001). Second, activities outside markets are undocumented (e.g., self-consumption, local trade, or black markets). Third, monitoring infrastructure varies, meaning reporting can be irregular and inaccurate, especially for developing countries. Therefore, the FAO is often forced to fill reporting gaps with estimated and modeled data. While these compounded error sources introduce significant uncertainty, FAO data is irreplaceable—it represents the only current platform that annually reports provisioning services with global coverage.

We used FAO data to report, by nation-state, the annual total production and monetary value for crop, livestock, game meat, timber, mariculture, non-fisheries marine products, and fisheries production from 1996 to 2005. Countries and/or specific products in a country (e.g., maize production) were excluded if they did not regularly report both total production (tonnes) and monetary value (constant million 2004–2006 US$) each year. In all cases, production data were reported in tonnes. Some countries/specific products were excluded because production value was reported by the FAO only in constant million 2004–2006 international dollars.

To estimate food production, we differentiated between crop, livestock, and game meat production. For crop production, we chose to report the summed total output (tonnes) of 12 crop types that could be validated against a global vegetation model (see below): (1) groundnuts, (2) maize, (3) pulses, (4) rapeseed, (5) rice, (6) soybean, (7) sugarcane, (8) sunflower, (9) temperate cereals (barley; wheat; rye), (10) temperate roots (sugarbeet), (11) tropical cereals (millet; sorghum), and (12) tropical roots (cassava). Similarly, we calculated combined production and value of cow milk, chicken eggs, and cattle, chicken, pig, and sheep meat for total livestock production, as these products are regularly reported worldwide. Game meat production, the aggregate production of meat or offals from all wild animals, was reported directly from FAO.

Timber production was reported from FAO as “roundwood” or wood derived from inside or outside forests, felled intentionally or naturally, and intended for fuel, charcoal, or any other purpose. Roundwood is reported in cubic meters, excluding bark. Though it does not report the value of in-country roundwood production, the FAO does report both the total production and value for exported roundwood. We first estimated roundwood price as export production divided by export value. We then multiplied estimated price by in-country production to calculate the value of in-country roundwood production.

Production and value data for marine resources also came primarily from FAO statistics. As for the other services, FAO marine products data are invaluable but flawed. For example, fisheries data are know to suffer false reporting (Watson and Pauly, 2001). Reporting errors are compounded by known limitations and unknown errors in the algorithm needed to spatially allocate FAO reported data to countries. Despite these limitations, we reported three categories of marine ecosystem services.

First, we defined mariculture as the production of marine taxa from marine and brackish water environments as assigned by FAO, excluding seaweeds, which are treated as natural products (see below). Mariculture production data (but not monetary value) were available over our target decade. For the three exclusive economic zones (EEZs) that fall within the China region (China, Macau, and Hong Kong), we combined the values by summing across these EEZs.

Second, we reported six non-fisheries marine products (corals, fish oil, ornamental fish, seaweeds, sponges, and shells). Only export data were used, with commodity types and subcategories accessed as in (Halpern et al., 2012), although some subcategories are no longer reported.

Third, we reported production and value of wild-caught commercial fisheries. Data were derived from annual FAO fisheries statistics, which are reported in major fishing areas rather than EEZs or countries, and include total annual catch through 2005. The Sea Around Us Project at the University of British Colombia spatially allocated these FAO fishing areas into reporting regions associated with nation-states based on species range maps, fishing treaties and arrangements, and various other factors (Watson et al., 2004; Halpern et al., 2008, 2012). We obtained production data from (Halpern et al., 2012) and value data from The Sea Around Us Project.

2.3. Models

Many ecosystem services (especially regulating services) cannot be directly observed or direct observations are currently cost prohibitive for a worldwide monitoring program. Process-based models, however, can leverage a systems understanding to combine feasibly collected observations into estimates of ecosystem service supply, delivery, and/or value. We used two modeling platforms to supplement data from national statistics: the Lund-Potsdam-Jena managed land model (Gerten et al., 2004; Bondeau et al., 2007) and InVEST (Kareiva et al., 2011; Tallis et al., 2013).

2.3.1. LPJmL

The Lund-Potsdam-Jena managed land model (LPJmL) is based on the dynamic global vegetation and water budget model LPJ (Sitch et al., 2003). We used LPJmL to model carbon sequestration, timber supply, and water supply globally, as well as to estimate the production of 12 crop functional groups to compare against FAO reported data. LPJmL simulates the productivity of the most important annual crops worldwide as well as potential natural vegetation of terrestrial ecosystems with a spatial resolution of 0.5° longitude/latitude. LPJmL tracks 16 crop functional groups, including 12 arable crops, two types of managed grassland, and two bioenergy plants. Crop and grassland area is prescribed from a dataset combining global cropland extent in 2000 (Ramankutty et al., 2008), changes in historical cropland between 1700 and 2000 (Klein Goldewijk and van Drecht, 2006), and harvested areas for rainfed and irrigated crops in 2000 (Fader et al., 2010; Portmann et al., 2010). Each functional group is parameterized according to the plant’s phenology and growth.

The model also tracks biomass carbon, which is allocated daily or annually towards several vegetative carbon pools (leaf, sapwood, heartwood, root for trees; leaf, root for grasses, leaf, root, storage organ for crops) as well as to litter and soil. Additionally, the model has a global water routing and irrigation module (Rost et al., 2008), and considers large reservoirs for water retention (Biemans et al., 2009). The simulated water discharge from rivers has been validated against observed data of 213 globally distributed rivers (Biemans et al., 2009). Also the

suitability of the model for simulating soil moisture (Wagner et al., 2003), evapotranspiration (Gerten et al., 2004), irrigation water requirements (Rost et al., 2008), fire occurrence (Thonicke et al., 2011), and crop planting dates (Waha et al., 2012) has been extensively tested.

Fluxes of water, net primary productivity (NPP), net biome productivity (NBP), heterotrophic respiration, and evapotranspiration can be followed in the model, and the model can therefore be used to estimate supply of some ecosystem services. Similar to national statistics, however, ecosystem-service estimates are uncertain. Where the network of climate station data is scarce, length of data gathering is short, or soil degradation occurs rapidly, climate conditions and soil properties may not be adequately captured in the model input data sets, causing biases and increasing uncertainty in simulated crop yields, vegetation dynamics, and related fluxes. Additionally, the aggregation of plant diversity into plant functional types may leave out specific ecosystem responses, which are important in some regions beyond averages. Parameters for one plant within a given functional group regarded as "most representative" are taken, which could lead to over/underestimation of modeled ecosystem services.

To equilibrate carbon and water pools of the natural vegetation with soil and climate conditions, a 1000-yr spin-up period was simulated. This was followed by a 390-yr spin-up period for land use to equilibrate the model with repeated inputs from the years 1901–1930 and land-use patterns from 1901 (without irrigation and reservoirs). LPJmL was then run from 1901 to 2005 with monthly gridded values for temperature, precipitation, number of wet days, and cloud cover retrieved from the CRU TS 3.0 climate dataset at the global scale to simulate transient changes (Mitchell and Jones, 2005).

Carbon sequestration was calculated as the sum of carbon contained in vegetation, litter, and soil. Potential annual timber biomass (timber supply) was calculated from carbon bound in wood, summed for each country. Only wood from non-protected areas was included, as wood within protected areas is not available for legal harvest. Protected areas were estimated from the UN List of Protected Areas (IUCN and UNEP-WCMC, 2015) for which a finer raster of 0.125° was created from the vector data, thus subdividing each LPJmL grid cell into 4×4 cells (Chape et al., 2013). If more than half of the area of a sub-cell was protected, the sub-cell was counted as protected. The protected areas accounted for in the analysis include only strict nature reserves—wilderness areas (IUCN categories 1a/b) and National Parks (category II). Thus, only large natural or near natural areas were excluded from potential timber calculation rather than areas that explicitly allow yield of timber (e.g., IUCN category VI "Protected area with sustainable use of natural resources" = biosphere reserves). Because illegal logging can take place in protected areas, however, we also report potential timber biomass including protected areas (trends did not differ; Table S1). It was assumed that a fraction of 60% of the aboveground biomass of wood carbon is suitable for timber production, thus accounting for losses from branches and twigs. The conversion factor of 1/0.45 g biomass/g C was applied to convert carbon pool values, simulated in [gC/m^2] in LPJmL, to dry biomass values. A conversion factor of 4e-6m^3/g C was applied to convert biomass values to wood volume.

Total annual water supply was summed by country to obtain country-based water yields. Return flow from field irrigation was subtracted from water yields to avoid double accounting. The runoff per grid cell was routed to neighboring cells by the model based on an underlying digital elevation model. All water in excess of the soil's field capacity within a country's boundaries was considered potentially available and reported as supply.

Finally, we used LPJmL to model crop production, and thereby facilitate annual comparisons with FAO reported crop production for each country. Specifically, we modeled 12 crop functional types (see above list) on each grid cell, averaging across irrigated and non-irrigated land through area-weighting. A crop management intensity factor, derived from FAO data, was applied to integrate various types of agricultural management such as different crop varieties, application of fertilizers, mechanization, or other management practices that farmers apply in reality. The management factor was held constant over our target decade so that we could compare annual fluctuations in crop production for each country between LPJmL modeled data and FAO reported data. Therefore, simulated inter-annual variability of crop harvest for this study is a reflection of climate variability but not changes in farming practices. To account for possible multiple cropping events on the same areas within a year, the modeled country-based yields were multiplied by the average harvested area (per country across the target decade) for each group of crops as reported to the FAO. Again, harvested areas were held constant over the decade to facilitate FAO/LPJmL comparisons.

To compare FAO/LPJmL crop production, we first calculated the total production of the 12 crop functional types in each year and country using LPJmL and FAO data. To do so, we summed the total LPJmL predicted crop production for each crop functional type across all grid cells in each country. Then, for each country, we standardized crop production, subtracting the mean crop production across the 10 years and dividing by the standard deviation. Next, to compare FAO reported and LPJmL modeled crop production, we regressed FAO data against LPJmL data in each country, using years as replicates ($N = 10$).

2.3.2. InVEST

Integrated Valuation of Environmental Services and Tradeoffs (InVEST) is a suite of spatial models that takes a simplified yet scientifically robust approach to quantifying, mapping, and valuing a variety of terrestrial and marine ecosystem services, including water supply for hydropower production (Kareiva et al., 2011; Tallis et al., 2013). The InVEST models have components to estimate the supply, delivery, and value of included services. In this large-scale application, the more extensively validated LPJmL model was used to calculate water supply estimates, in the form of annual water discharge per grid cell. InVEST was then used to calculate the amount of energy that may be produced by reservoir hydropower plants from simulated water runoff at each facility.

Water discharge grids for each modeled year were overlaid with the point locations of global reservoirs provided by the World Water Development Report II (WWDRII) Reservoirs database (Vorosmarty et al., 1997, 2003). For each reservoir point, the corresponding water discharge grid cell value was assigned, giving the amount of water (m^3) available for hydropower production at that facility. The InVEST model calculates the amount of energy generated at each facility by a given annual discharge according to a formula slightly modified from (Edwards, 2003):

$$\text{energy} = 0.00272 \times \text{efficiency} \times \text{flow fraction} \times \text{height} \times \text{discharge} \quad (1)$$

where efficiency is the turbine efficiency percentage, flow fraction is the percent of water flow used to generate energy, height is the water height behind the dam at the turbine, and discharge is the supply estimates given by the LPJmL water discharge grids. This equation is the only component of the InVEST models that was used in this study.

We were able to collect the necessary hydropower facility information for 194 of the 668 dams represented in the WWDRII database, and so only calculated energy production at that subset of facilities. Dam height was given in the WWDRII database for each reservoir and efficiency data were derived from (Vorosmarty

et al., 2003). We were unable, however, to acquire specific data on flow fractions and therefore delineated a value of 1 for all facilities (100% of available water is used for energy generation). Assuming that all water above the turbine in reservoirs was available for hydropower production likely created over-estimates of the amount of energy production per dam. Many reservoirs are multi-use, and some fraction of water is not used for hydropower generation. Since we only capture large dams, not tens of thousands of small dams, the overall estimate is still likely conservative.

3. Results and discussion

3.1. What can be regularly reported?

We were able to capture changes in nine ecosystem services on a national scale, at an annual time step over the decade 1996–2005. The combination of ecosystem-service data reported here is unique, emphasizing the differences and similarities in service trajectories over time and across space. Some services declined over our target decade (e.g., hydropower production and fisheries production), while others increased (e.g., crop production, game meat production, livestock production) (Fig. 1, Table S1). While some of these decade-long patterns mirror those reported in the MA, annual patterns emphasize the importance of higher temporal resolution to inform decision-making. For example, timber value remained relatively unchanged if compared at the beginning and end of the decade, but underwent dramatic variability within the decade (Fig. 1). Because variation is lost in a decadal analysis, decision makers would have a false view of the supposed stability in the global value of timber without annual data.

Ecosystem services also exhibited substantial geographic variation. For several services, there was dramatic variation within a continent, indicating that generalization of trends for large regions such as Africa or South America is not advisable. No single service showed an entirely consistent trend in delivery over the decade across the globe, emphasizing the need for global coverage. Despite this need, multiple ecosystem services could not be tracked in most countries (Fig. 2; Supplementary material). Even for some of the most actively monitored services (e.g., crop and livestock production), we do not have full global coverage of both ecosystem-service delivery and value.

3.2. Data source accuracy

Any global monitoring system will rely on a combination of remotely sensed, directly observed, survey-based, and modeled data. Even when data sources meet the requirements for annual

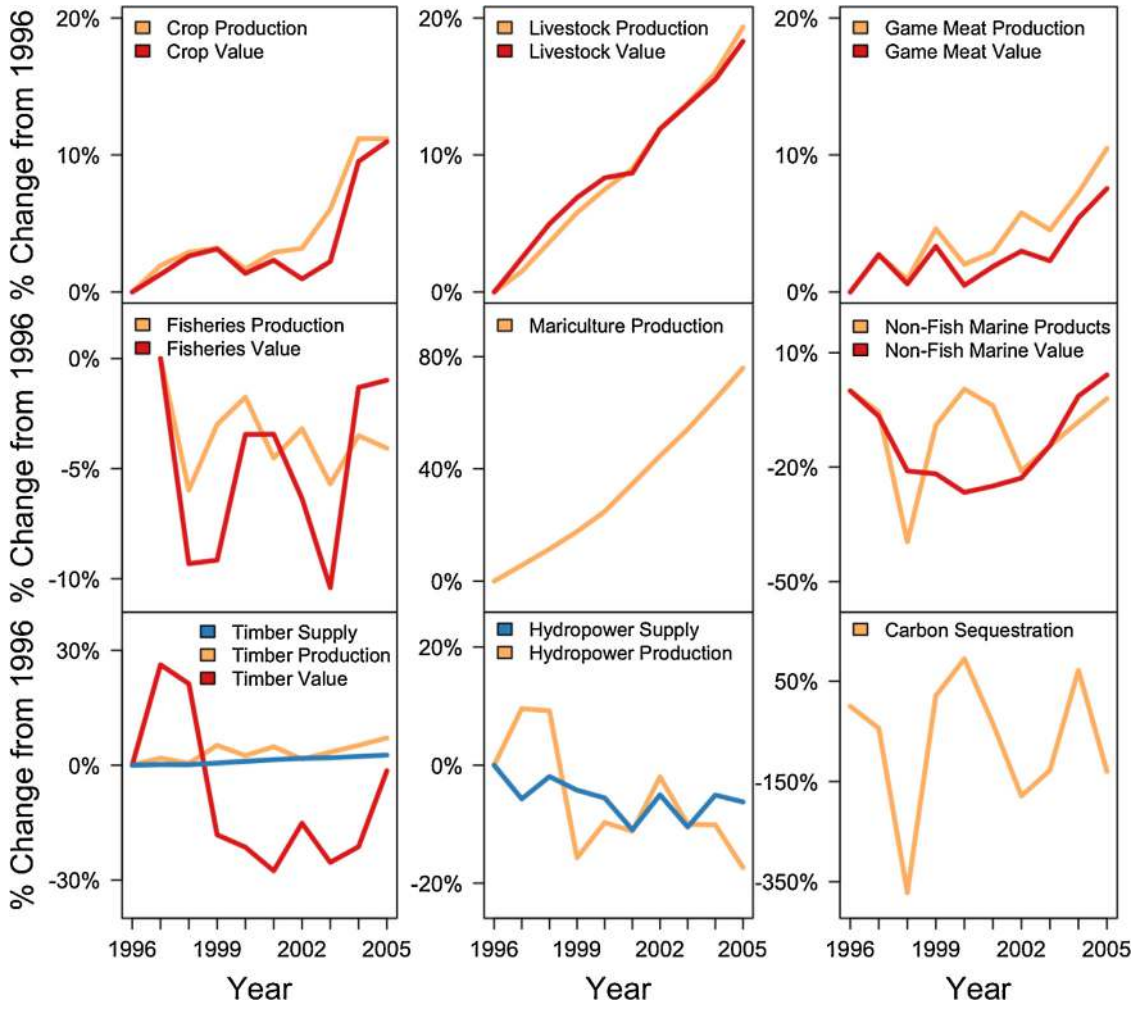

Fig. 1. Annual trends in the global provision of nine ecosystem services over 10 years (1996–2005). Lines depict the percent increase or decrease from 1996 levels in the supply (blue), delivery (yellow), and value (red) of each ecosystem service. Data were derived from national statistics (e.g., timber production) and models (e.g., timber supply). Countries were only included if they regularly reported each stage of ecosystem service provision (supply, delivery, or value) that we were able to track (Supplementary material). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

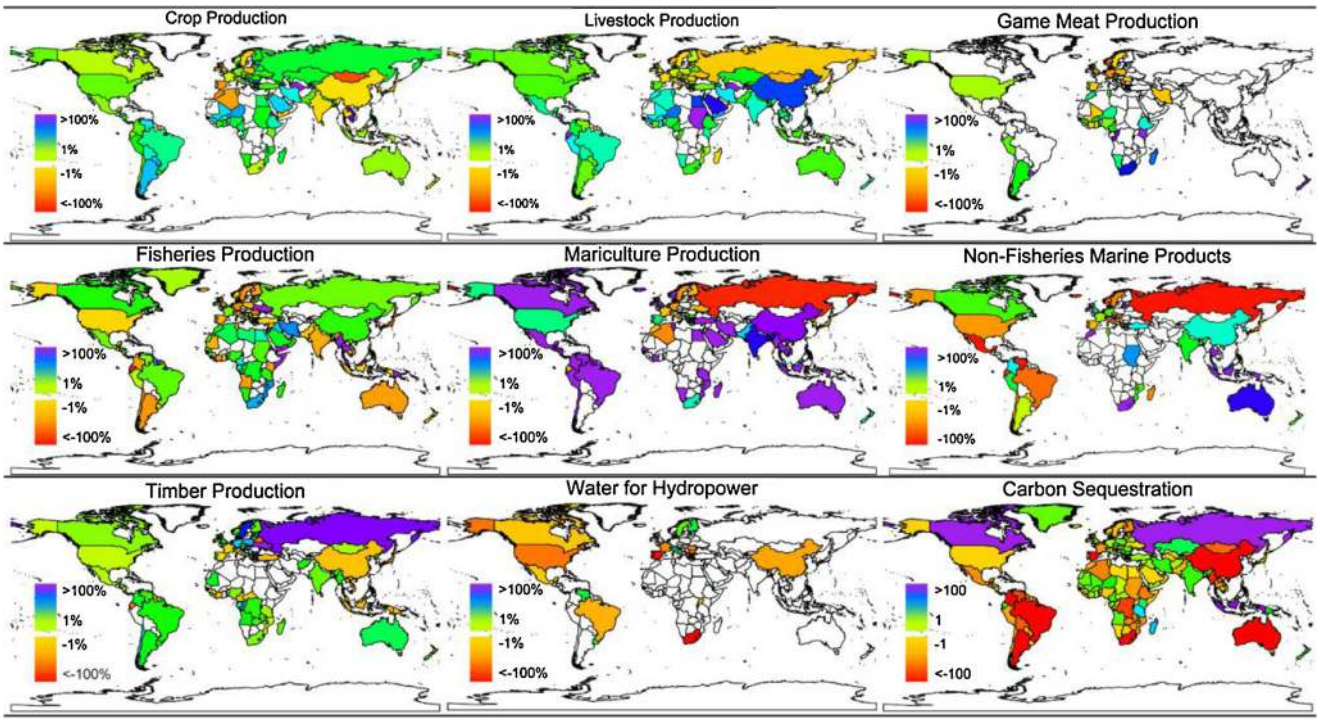

Fig. 2. Global distribution of the percent change in ecosystem-service delivery from 1996 to 2005. Ecosystem service delivery increased in countries filled with light green to purple colors and declined in countries filled with yellow to red colors. As in Fig. 1, only countries that regularly reported each stage of ecosystem-service provision are included (Supplementary material). For example, FAO does not report both the total production (delivery) and economic gain in US$ (value) from livestock production in several African countries. Those countries are thus not included. Other countries are white because they never produced a service (e.g., mariculture production in landlocked countries). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

reporting and global coverage at a national scale, it is important to consider data accuracy. We provide three examples of how accuracy can be assessed. We do not attempt to be exhaustive in establishing the validity and accuracy of data sources used, but rather to provide demonstrative examples of how data sources could be assessed for accuracy as they become available and are added to a global monitoring program.

For many ecosystem services, the most likely method for reaching global, consistent coverage in the near term is modeling. No global models can accurately reflect services everywhere, so clear communication about where models agree with observed data is essential.

We applied the global vegetation and water model LPJmL to estimate river discharge and InVEST to estimate energy production from hydropower. Validating results for 213 globally distributed catchments, Biemans et al. (2009) showed that in 95 out of 213 river basins the discharge estimations as simulated by LPJmL agree well with the observations, and in another 23 basins the simulated discharge differs by less than 10%. For some tropical basins (e.g., the Nile), LPJmL tends to overestimate the observed discharge, mainly because neither evaporation from the stream nor water extraction for irrigation was taken into account in these simulations.

In some cases, multiple data sources can be compared for a single ecosystem service metric to validate observed trends. For example, we used linear regression to compare annual variation in reported FAO statistics and LPJmL modeled outputs for the production of 12 crop functional types in each country: (1) groundnuts, (2) maize, (3) pulses, (4) rapeseed, (5) rice, (6) soybean, (7) sugarcane, (8) sunflower, (9) temperate cereals (barley; wheat; rye), (10) temperate roots (sugarbeet), (11) tropical

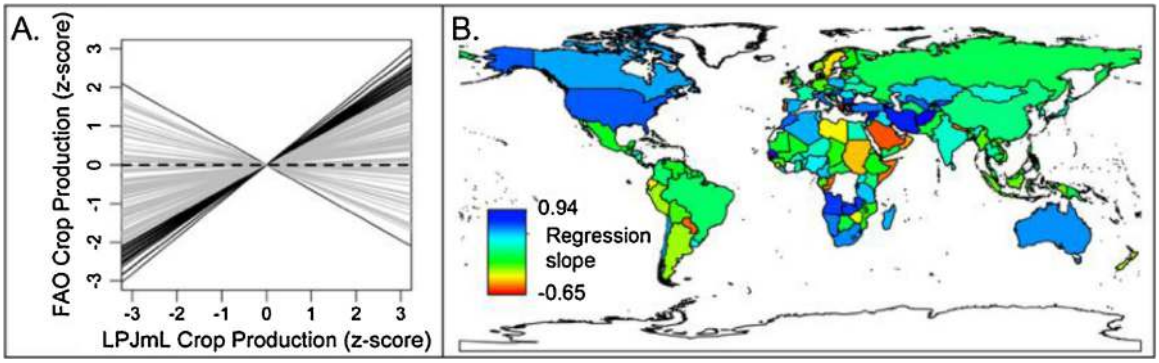

Fig. 3. Correlation between FAO reported and LPJmL modeled crop production in 1996–2005. In 77% of countries, total annual production of 12 crop functional types (see methods) was positively correlated between FAO reported and LPJmL modeled data. For each country ($N = 149$), we regressed standardized modeled LPJmL crop production against standardized reported FAO crop production. In panel A, each line corresponds to the correlation between FAO and LMPmL data within one country, based on 10 data points (total crop production in each of 10 years). Black lines depict significant correlations ($P < 0.05$); gray lines are not significant. Panel B depicts regression slopes spatially.

cereals (millet; sorghum), and (12) tropical roots (cassava) (Fig. 3). Despite the fact LPJmL did not account for temporal changes in farm management practices, FAO and LPJmL crop production positively correlated over time in 77% of the 149 countries analyzed. Positive correlations were well distributed across the world, thereby increasing our confidence in both data sources. However, positive correlations were statistically significant in only 13% of countries, which could either be a result of incomplete or false reporting to FAO or problems with the LPJmL model such as (1) poor climate data not representing inter-annual variability correctly, (2) missing processes in the crop model, or (3) changes in agricultural management practices over time from agricultural policies, investments, or innovations.

Another method for assessing accuracy is confirming whether data trends reflect major fluctuations in service supply, delivery, or value that would be relevant to decision makers. For example, while global livestock delivery and value increased steadily over the analysis decade (Fig. 1), FAO livestock production data for the United Kingdom reflected two major livestock disease outbreaks that caused different patterns in that country (Fig. 4). First, after an outbreak of bovine spongiform encephalopathy (mad cow disease), the European Union banned beef exports from the United Kingdom in 1996, reflected as a drop in livestock production in following years. Second, a food-and-mouth disease outbreak in 2001 led to the culling of millions of cattle, and a low in total British beef production over our target decade. Similarly, even as FAO crop production data was increasing globally, FAO and LPJmL data show that crop production in Kenya and India declined following major droughts in 2000 (Huho et al., 2010) and 2002 (Bhat, 2006), respectively (Fig. 4).

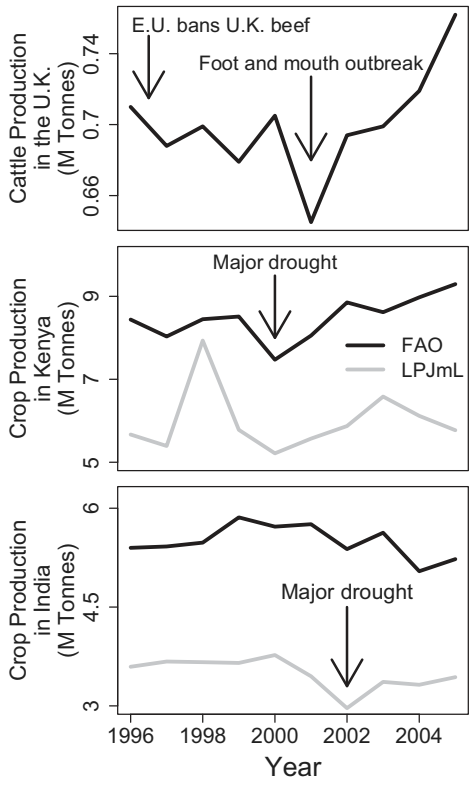

Fig. 4. FAO and LPJmL data can reflect major shocks to livestock and crop production at a national scale. An outbreak of bovine spongiform encephalopathy in the U.K. in 1996 precedes a decline in cattle production, as does an outbreak of foot and mouth disease in 2001. Similarly, major droughts in Kenya and India (in 2000 and 2002, respectively) were associated with declines in total crop production.

3.3. Expanding coverage of regulating and cultural services

Unfortunately, we were unable to provide annual, global maps for any cultural or regulating service apart from carbon sequestration. All other reported services were provisioning services. Because tradeoffs likely exist between managing for provisioning versus regulating services (Raudseep-Hearne et al., 2010), incorporating regulating services into ecosystem-services monitoring programs is critical. If provisioning services alone are monitored, then decision-makers could be led to falsely believe that their policies or practices are improving natural capital when critical ecological benefits are in fact rapidly declining.

Methods for tracking and reporting regulating and cultural services have improved in recent decades (Van Jaarsveld et al., 2005; Egoh et al., 2008; Kareiva et al., 2011; Chan et al., 2012; Daniel et al., 2012; Halpern et al., 2012), which has allowed some countries and regions to begin incorporating all service categories into ecosystem-service mapping programs. For example, a European Union commissioned, ecosystem-service mapping effort recently developed 327 ecosystem-service indicators to be mapped across Europe (Maes et al., 2014). Yet, even in such data rich countries, the final report concluded that only 15%, 27%, 13%, and 42% of the indicators developed for forests, agro-ecosystems, freshwater, and marine systems respectively could be mapped in the short term. Extending such analyses to data-poor countries would represent a major challenge. Further, although this European effort, the Millennium Ecosystem Assessment (MA) (Millenium Ecosystem Assessment, 2005), and other one-time studies are able to capture snapshots in the provision of a wide array of services, regulating and cultural services remain largely absent from regular monitoring systems.

A promising path forward would be to utilize any one of a growing number of existing ecosystem-service models hosted in platforms such as InVEST (Tallis et al., 2013), ARIES-Artificial Intelligence for Ecosystem Services (Bagstad et al., 2013), or MIMES—Multiscale Integrated Models of Ecosystem Services (Altman et al., 2014) to model regulating and/or cultural services globally. While critical data gaps currently preclude the global application of these models at regular time points, investing in the development of key data streams could make a wider suite of services available (Table 1). For example, land-use/land-cover maps are required to drive most ecosystem-service models, and although global land-use/land-cover maps exist (Gong et al., 2013), such maps are not regularly updated. Even regional ecosystem-service monitoring programs are constrained by land-use data; for example, the European Union commissioned effort relied heavily on a land-use dataset (Corine Land Cover) which is updated at a minimum of 5-yr time intervals (Maes et al., 2014).

Advances in remote sensing technology or post-processing that allowed for regular updating, and hence accurate determination of global land-use change, could open the door to regular use of multiple ecosystem-service models at global scales (Table 1). Alternatively, models could be developed to estimate ecosystem-service supply and delivery directly from remotely sensed products, thus bypassing the need for land-use/land-cover classifications to be improved.

Yet another alternative for some services would be to avoid models entirely through creative use of existing data. For example, recreation value could be incorporated into a global monitoring system through utilizing geo-tagged social media to estimate tourist visitation rates (Wood et al., 2013). Another more direct and common means of service tracking is through reporting of direct observations by national governments. For example, FAO and World Bank data are accumulated in this way, and could be expanded to achieve global coverage and regular reporting for several data sets that are initiated but incomplete, or for new data

Table 1
Examples of data gaps for reporting ecosystem services. This list is not comprehensive, but rather identifies key data gaps for several services of interest. Some services are regionally variable in terms of specific products or goods so representative examples are provided (e.g., charcoal as one of many non-timber forest products). In some cases, such as for many regulating services, the service is not directly observable, so model limitations are exposed. In other cases, such as water supply for drinking, data could be generated through a number of pathways, including direct observation or models.

Type	Ecosystem service	Source	Data gap	Reason for gap	
				Not updated annually	Global coverage incomplete
Provisioning services	Nutrition from crops	Direct observation	Malnourishment rate		x
	Crop pollination	Direct observation	Crop yield from wild pollination	x	x
		Model	Land use/land cover	x	x
	Water supply for drinking	Direct observation	Surface water withdrawal rate	x	x
		Direct observation	Groundwater withdrawal rate	x	x
		Direct observation	Percent of people with access to clean water	x	x
		Model	Land use/land cover	x	
	Water supply for irrigation	Direct observation	Volume of withdrawals for irrigation	x	x
		Direct observation	Marginal market value of crops from irrigation	x	x
	Water supply for hydropower	Direct observation, model	Hydropower market value		x
	Non-timber forest products	Direct observation	e.g., Charcoal harvest rates	x	x
		Direct observation, model	e.g., Charcoal market value	x	x
		Model	Land use/land cover	x	x
Regulating services	Water pollution regulation	Model	Land use/land cover	x	
		Direct observation	Water treatment costs	x	x
	Erosion control for reservoir benefits	Direct observation	Dredge costs	x	x
	Coastal inundation protection	Model	Marine habitat extents	x	x
		Model	Coastal asset value	x	
	Air quality regulation	Model	Urban tree density (high resolution)	x	x
	Air temperature regulation	Model	Tree density (high resolution)	x	x
	Flood regulation	Model	Land use/land cover	x	
		Model	Stream channel profile		x
	Crop pollination	Direct observation	Crop yield from wild pollination	x	x
		Model	Land use/land cover	x	x
Cultural services	Recreational hunting	Direct observation	Hunter days	x	x
	Recreational fishing	Direct observation	Recreational landings	x	x
		Direct observation	Recreational fishing expenditures	x	x
	Nature-based tourism	Direct observation, model	Tourist visitation rate	x	x
		Direct observation	Tourism expenditures		x
	Property value	Model	High resolution property values		x
		Model	Land use/land cover	x	
	Cultural site access	Direct observation	Cultural site locations	x	x
		Direct observation	Cultural site access rates	x	x

sets that could be established by expansion of existing data collection efforts (Table 1).

3.4. Gaps in reporting the supply of ecosystem services

We attempted to track and map changes in indicators representing each of the three steps in ecosystem-service provision (supply, delivery and value), yet timber provision was the only service for which we could regularly report indicators for each of the three stages (Fig. 1). Analyzing all three indicators together emphasizes how each provides a different view of the underlying socio-ecological system. While timber supply and delivery remained relatively constant globally across the decade of analysis, timber value dipped substantially, indicating that demand, markets, consumer preference, or government regulation were likely more important determinants of timber value than decreasing supply or harvest intensity.

Surprisingly, supply data, indicating trends in the underlying capacity of the environment to provide a service, were only available for timber and hydropower production. Supply data are not applicable to some services such as crop, livestock, and mariculture production because there is no supply without human intervention. We also chose not to report the supply of carbon sequestration because supply and delivery are equivalent (due to the well-mixed nature of the atmosphere). Yet supply data are very relevant to other services. For example, although many environmental monitoring programs exist, none sufficiently capture total stocks of fish, non-fish marine resources, and game meat in consistent terms at a national scale and on an annual basis. Without supply data regularly monitored for these services, we have little ability to understand when and how environmental conditions could be placing these services in jeopardy, precluding evaluation of the sustainability of ecosystem-service provision.

Indicators have been developed and implemented to evaluate global population trends and extinction risks for species that humans are known to utilize in some way (e.g., for food, medicine, pets, or clothing) (Butchart et al., 2010). Disaggregating underlying data to national scales and to highlight specific ecosystem services (e.g., game meat, fisheries, and non-fisheries marine production) in a monitoring system would provide a mechanism for decision-makers to identify critical trends and adapt their management plans to allow for more sustainable resource use. Because some species are more effective service providers than others (e.g., bee species differ greatly in pollination efficacy), an even more

informative system would account for differences among species in the quality and quantity of ecosystem services provided (Kremen, 2005; Winfree et al., 2015).

3.5. Valuing ecosystem services

Unlike supply data, value data were widely available for provisioning services, and we were able to report monetary value metrics for all but three of the nine services. We did not report hydropower or mariculture value, as hydropower prices and mariculture values were not consistently reported, and existing, disparate sources did not provide enough geographic coverage to warrant inclusion for a global reporting system. We also lacked value data for carbon sequestration because there was no globally functioning carbon market during the period of study. We could have applied the social cost of carbon to estimate value, but we would have been forced to use a single value applied globally, with no ability to reflect regional or annual changes in social impact. Either setting up a global carbon market or integrating regional carbon markets as are in place in Europe (European Union Emissions Trading System, EU ETS, established 2005) would benefit UNFCCC negotiations to combat climate change and allow regular reporting of the value of this service.

While we could report metrics of monetary value for most services, a global monitoring system would be narrowly constrained at present to only consider marketed ecosystem-service values. Yet marketed values neglect critical externalities that affect true service values (Guerry et al., 2015). For example, human health impacts associated with common agricultural practices (e.g., Marks et al., 2010) are not incorporated into agricultural commodity prices, nor are changes in carbon storage (e.g., Bateman et al., 2013; Lawler et al., 2014), or impacts on water quality (Keeler et al., 2012). A better monitoring system would seek to adjust monetary value estimates for marketed provisioning services to account for such social opportunity costs. Such estimates could also be used to inform on-going work to estimate inclusive wealth (Arrow et al., 2012; UNU-IHDP and UNEP, 2014).

Non-monetary estimates of ecosystem-service values should also be developed (e.g., equity in service delivery) (Tallis et al., 2012). The world's governments have called for more targeted assessments that quantify the contributions of ecosystem services to human health and livelihoods, especially for underserved groups. For example, the Convention on Biodiversity's Aichi Target 14 explicitly identifies "women, indigenous and local communities, and the poor and vulnerable" (http://www.cbd.int/sp/targets/) as critical beneficiaries. Household surveys could be paired with ecosystem-service models to evaluate how changes in ecosystem services affect local livelihoods. Therefore, one path forward would be adding queries about ecosystem-service values directly into existing household surveys and national censuses.

3.6. Conclusions

Our work demonstrates that setting up a natal global ecosystem-service monitoring platform is possible. Nine ecosystem services can now be reported at national scales and annual time steps. This set of services further expands previously published lists of ecosystem services that could be currently monitored at a global scale (Tallis et al., 2012). Ecosystem-service supply could be quantified for only 2 out of 5 services where that stage is relevant. Service delivery could be quantified for all 9 reported services. Service value could be assessed for 6 out of 9 services.

Overall, however, our work highlights ecosystem-service data scarcity and deficiencies. Many services cannot currently be reported, and regulating as well as cultural services were almost entirely absent. Moreover, observable differences between global trends in timber production (increasing) and value (decreasing) were evident, underscoring the necessity of tracking all three stages of the ecosystem-service supply chain (supply, delivery, and value). Yet timber production was the only service for which we were able to report information on supply, delivery, and value.

Demand for socio-environmental ecosystem-service data is outpacing what the scientific and governmental communities can deliver. Outside governments, even the financial sector is moving towards including natural capital in financial products and services (NCD, 2012) but remains sidelined in part due to sparse data. Further, companies such as Puma aim to report their environmental profits and losses, but are constrained by limited data across their supply chains (PUMA, 2011). Looking forward, improving collection and quality of related biophysical and socio-economic data and further developing relevant ecosystem and ecosystem-service models would provide the means to monitor our planet's life-support systems and redirect global conservation efforts, from informing national accounting to forecasting future shocks to critical goods and services.

Acknowledgements

This work has been supported by funding from GEO BON, DIVERSITAS, the European Environment Agency, NASA, the Gordon and Betty Moore Foundation, the European Commission Seventh Framework Programme under Grant Agreement No. FP7 ENV-2012-308393-2 (OPERAs), and a NatureNet Science Postdoctoral Fellowship from the Nature Conservancy to DSK.

References

Altman, I., Boumans, R., Roman, J., Gopal, S., Kaufman, L., 2014. An ecosystem accounting framework for marine ecosystem-based management. In: Fogarty, M., McCarthy, J. (Eds.), The Sea, Ideas and Observations on Progress in the Study of the Seas. Harvard University Press, Cambridge, MA.

Arrow, K., Dasgupta, P., Goulder, L.H., Mumford, K.J., Oleson, K., 2012. Sustainability and the measurement of wealth. Environ. Dev. Econ. 17, 317–353.

Bagstad, K.J., Johnson, G.W., Voigt, B., Villa, F., 2013. Spatial dynamics of ecosystem service flows: a comprehensive approach to quantifying actual services. Ecosyst. Serv. 4, 117–125.

Barnosky, A.D., Hadly, E.A., Bascompte, J., Berlow, E.L., Brown, J.H., Fortelius, M., et al., 2012. Approaching a state shift in Earth's biosphere. Nature 486, 52–58.

Bateman, I.J., Harwood, A.R., Mace, G.M., Watson, R.T., Abson, D.J., et al., 2013. Bringing ecosystem services into economic decision-making: land use in the United Kingdom. Science 341, 45–50.

Bhat, G.S., 2006. The Indian drought of 2002—a sub-seasonal phenomenon? Quart. J. R. Meteorol. Soc. 132, 2583–2602.

Biemans, H., Hutjes, R.W.A., Kabat, P., Strengers, B.J., Gerten, D., Rost, S., 2009. Effects of precipitation uncertainty on discharge calculations for main river basins. J. Hydrometeorol. 10, 1011–1025.

Bondeau, A., Smith, P.C., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W., et al., 2007. Modelling the role of agriculture for the 20th century global terrestrial carbon balance. Glob. Change Biol. 13, 679–706.

Butchart, S.H.M., Walpole, M., Collen, B., van Strien, A., Scharlemann, J.P.W., Almond, R.E.A., et al., 2010. Global biodiversity: indicators of recent declines. Science 328, 1164–1168.

CBD, 2011. Developing Ecosystem Service Indicators: Experiences and Lessons from Sub-global Assessments and Other Initiatives. CBD, Montreal.

CBD, 2014. Global Biodiversity Outlook 4. CBD, Montreal.

Chan, K.M.A., Guerry, A.D., Balvanera, P., Klain, S., Satterfield, T., Basurto, X., et al., 2012. Where are cultural and social in ecosystem services? A framework for constructive engagement. Bioscience 62, 744–756.

Chape, S., Blyth, S., Fish, L., Fox, P., Spalding, M., 2013. United Nations List of Protected Areas.

Daniel, T.C., Muhar, A., Arnberger, A., Aznar, O., Boyd, J.W., Chan, K.M.A., et al., 2012. Contributions of cultural services to the ecosystem services agenda. Proc. Natl. Acad. Sci. U. S. A. 109, 8812–8819.

Edwards, B., 2003. The Economics of Hydroelectric Power. Edward Elgar Publishing, Cheltenham, UK.
Egoh, B., Reyers, B., Rouget, M., Richardson, D.M., Le, D.C., Jaarsveld, A.S.V., 2008. Mapping ecosystem services for planning and management. Agric. Ecosyst. Environ. 127, 135–140.
Ehrlich, P.R., Kareiva, P.M., Daily, G.C., 2012. Securing natural capital and expanding equity to rescale civilization. Nature 486, 68–73.
Fader, M., Rost, S., Müller, C., Bondeau, A., Gerten, D., 2010. Virtual water content of temperate cereals and maize: present and potential future patterns. J. Hydrol. 384, 218–231.
Gerten, D., Schaphoff, S., Haberlandt, U., Lucht, W., Sitch, S., 2004. Terrestrial vegetation and water balance—hydrological evaluation of a dynamic global vegetation model. J. Hydrol. 286, 249–270.
Gong, P., Wang, J., Yu, L., Zhao, Y., Zhao, Y., Liang, L., 2013. Finer resolution observation and monitoring of global land cover: first mapping results with Landsat TM and ETM+ data. Int. J. Remote Sens. 34, 37–41.
Guerry, A., Polasky, S., Lubchenco, J., Chaplin-Kramer, R., Daily, G.C., et al., 2015. Natural capital informing decisions: from promise to practice. PNAS 112, 7348–7355.
Halpern, B.S., Walbridge, S., Selkoe, K.A., Kappel, C.V., Micheli, F., D'Agrosa, C., et al., 2008. A global map of human impact on marine ecosystems. Science 319, 948–952.
Halpern, B.S., Longo, C., Hardy, D., McLeod, K.L., Samhouri, J.F., Katona, S.K., et al., 2012. An index to assess the health and benefits of the global ocean. Nature 488, 615–620.
Huho, J.M., Ngaira, J.K.W., Ogindo, H.O., 2010. Drought severity and their effects on rural livelihoods in Laikipia district, Kenya. J. Geogr. Reg. Plan. 3, 35–43.
IUCN, UNEP-WCMC, 2015. The World Database on Protected Areas (WDPA). IUCN and UNEP-WCMC.
Kareiva, P.M., Tallis, H., Ricketts, T.H., Daily, G.C., Polasky, S., 2011. Natural Capital: Theory and Practice of Mapping Ecosystem Services. Oxford University Press, Oxford.
Keeler, B., Polasky, S., Brauman, K.A., Johnson, J., Finlay, J., et al., 2012. Linking water quality and well-being for improved assessment and valuation of ecosystem services. PNAS 109, 18619–18624.
Klein Goldewijk, K., van Drecht, G., 2006. Current and historical population and land cover. In: Bouwman, A.F., Kram, T., Klein Goldewijk, K. (Eds.), Integrated Modelling of Global Environmental Change. An Overview of IMAGE 2.4. Netherlands Environmental Assessment Agency (MNP), Bilthoven, The Netherlands.
Kremen, C., 2005. Managing ecosystem services: what do we need to know about their ecology? Ecol. Lett. 8, 468–479.
Lawler, J.J., Lewis, D.J., Nelson, E., Plantinga, A.J., Polasky, S., et al., 2014. Projected land-use change impacts on ecosystem services in the U. S. PNAS 111, 7492–7497.
Maes, J., Egoh, B., Willemen, L., Liquete, C., Vihervaara, P., Schagner, J.P., et al., 2012a. Mapping ecosystem services for policy support and decision making in the European Union. Ecosyst. Serv. 1, 31–39.
Maes, J., Hauck, J., Paracchini, M.L., Ratamäki, O., Termansen, M., Perez-soba, M., et al., 2012. A Spatial Assessment of Ecosystem Services in Europe: Methods, Case Studies and Policy Analysis—Synthesis Report.
Maes, J., Teller, A., Erhard, M., 2014. Mapping and Assessment of Ecosystems and Their Services—Indicators for Ecosystem Assessments Under Action 5 of the EU Biodiversity Strategy to 2020.
Marks, A.R., Harley, K., Bradman, A., Kogut, K., Barr, D.B., Johnson, C., et al., 2010. Organophosphate pesticide exposure and attention in young Mexican–American children: the CHAMACOS study. Environ. Health Perspect. 118, 1768–1774.
Millenium Ecosystem Assessment, 2005. Ecosystems and Human Well-being: Synthesis. Island Press.
Mitchell, T.D., Jones, P.D., 2005. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. Int. J. Climatol. 25, 693–712.
NCD, 2012. Natural Capital Declaration. NCD, New York.
PUMA, 2011. Environmental Profit and Loss Account for the Year Ended 31 December 2010. PUMA, Herzogenaurach.
Portmann, F.T., Siebert, S., Döll, P., 2010. MIRCA 2000—Global Monthly Irrigated and Rainfed Crop Areas Around the Year 2000: A New High-resolution Data Set for Agricultural and Hydrological Modeling. Glob. Biogeochem. Cycl. 24, 1–24.
Ramankutty, N., Evan, A.T., Monfreda, C., Foley, J.A., 2008. Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. Glob. Biogeochem. Cycl. 22, 1–19.
Raudsepp-Hearne, C., Peterson, G.D., Bennett, E.M., 2010. Ecosystem service bundles for analyzing tradeoffs in diverse landscapes. Proc. Natl. Acad. Sci. U. S. A. 107, 5242–5247.
Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., Lambin, E.F., et al., 2009. A safe operating space for humanity. Nature 461, 472–475.
Rost, S., Gerten, D., Bondeau, A., Lucht, W., Rohwer, J., Schaphoff, S., 2008. Agricultural green and blue water consumption and its influence on the global water system. Water Resour. Res. 44, 1–17.
Ruckelshaus, M., Mckenzie, E., Tallis, H., Guerry, A., Daily, G., Kareiva, P., et al., 2013. Notes from the field: lessons learned from using ecosystem service approaches to inform real-world decisions. Ecol. Econ. 115, 11–21.
Scholes, R.J., Mace, G.M., Turner, W., Geller, G.N., Jürgens, N., Larigauderie, A., et al., 2008. Toward a global biodiversity observing system. Science 321, 5892.
Scholes, R.J., Walters, M., Turak, E., Saarenmaa, H., Heip, C.H., Tuama, É.Ó., et al., 2012. Building a global observing system for biodiversity. Curr. Opin. Environ. Sustain. 4, 139–146.
Sitch, S., Smith, B., Prentice, I.C., Arneth, A., Bondeau, A., Cramer, W., et al., 2003. Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. Glob. Change Biol. 9, 161–185.
Tallis, H., Mooney, H., Andelman, S., Balvanera, P., Cramer, W., Karp, D.S., et al., 2012. A global system for monitoring ecosystem service change. Bioscience 62, 977–986.
Tallis, H.T., Ricketts, T., Guerry, A.D., Wood, S.A., Sharp, R., Nelson, E., et al., 2013. InVEST 2.5.3 User's Guide. Stanford.
The World Bank, 2011. The Changing Wealth of Nations Measuring Sustainable Development in the New Millennium. The World Bank, Washington, D.C.
Thonicke, K., Spessa, A., Prentice, I.C., Harrison, S.P., Dong, L., 2011. The influence of vegetation, fire spread and fire behaviour on biomass burning and trace gas emissions: results from a process-based model. Biogeosciences 7, 1991–2011.
UNSD EEA, The World Bank, 2011. SEEA Experimental Ecosystem Accounts: A Proposed Outline, Road Map and List of Issues, New York.
UNU-IHDP, UNEP, 2014. Inclusive Weath Report: Measuring Progress Toward Sustainability. Cambridge University Press, Cambridge.
Van Jaarsveld, A.S., Biggs, R., Scholes, R.J., Bohensky, E., Reyers, B., Lynam, T., et al., 2005. Measuring conditions and trends in ecosystem services at multiple scales: the Southern African Millennium Ecosystem Assessment (SAfMA) experience. Measuring conditions and trends in ecosystem services at multiple scales: the Southern African Millenni. Philos. Trans. R. Soc. B 360, 425–441.
Vorosmarty, C.J., Sharma, K., Fekete, B.M., Copeland, A.H., Holden, J., Marble, J., 1997. The storage and aging of continental runoff in large reservoir systems of the world. AMBIO 26, 210–219.
Vorosmarty, C.J., Meybeck, M., Sharma, K., Vo, C.J., Meybeck, M., Green, P., et al., 2003. Anthropogenic sediment retention: major global impact from registered river impoundments. Glob. Planet. Change 39, 169–170.
Wagner, W., Scipal, K., Pathe, C., Gerten, D., Lucht, W., Rudolf, B., 2003. Evaluation of the agreement between the first global remotely sensed soil moisture data with model and precipitation data. J. Geophys. Res. 108 1–10.
Waha, K., Bussel, L.G.J.V., Bondeau, A., 2012. Climate-driven simulation of global crop. Glob. Ecol. Biogeogr. 21, 247–259.
Walpole, M., Almond, R.E., a, B., esancon, C., Butchart, S.H.M., Campbell-Lendrum, D., Carr, G.M., et al., 2009. Tracking progress toward the 2010 biodiversity target and beyond. Science 325, 1503–1504.
Watson, R., Pauly, D., 2001. Systematic distortions in world fisheries catch trends. Nature 414, 534–536.
Watson, R., Kitchingman, A., Gelchu, A., Pauly, D., 2004. Mapping global fisheries: sharpening our focus. Fish Fish. 5, 168–177.
Winfree, R., Fox, J.W., Williams, N.M., James, R., Cariveau, D.P., 2015. Abundance of common species, not species richness, drives delivery of a real-world ecosystem service. Ecol. Lett. 18, 626–635.
Wood, S.A., Guerry, A.D., Silver, J.M., Lacayo, M., 2013. Using social media to quantify nature-based tourism and recreation. Sci. Rep. 3 1–7.