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Indicators from the global and sub-global Millennium Ecosystem Assessments: An analysis and next steps

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ABSTRACT

There is growing interests among policy-makers in applying ecosystem services concepts to inform strategies that provide for peoples' needs while sustaining ecosystems and maintaining biodiversity. Since many policy dialogs and decisions rely on metrics and indicators to communicate concise and relevant information, an assessment of ecosystem service indicators can help identify gaps hindering policy-makers from more fully adopting ecosystem service approaches. In this study, we present an evaluation of ecosystem service indicators compiled from over 20 ecosystem assessments conducted at multiple scales and many countries. Based on criteria used to assess the compiled indicators, the strengths and weaknesses of indicators for different ecosystem services are explored, and possible reasons for these patterns examined. We then outline some priority steps for identifying and applying indicators to improve the ability of policy-makers to more fully mainstream ecosystem service approaches.

1. Introduction

Ecosystem services are the benefits that people derive from nature (MA, 2005a,b). Some benefits, such as crops, fish, and freshwater (provisioning services), are tangible. Others such as pollination, erosion regulation, climate regulation (regulating services) and aesthetic and spiritual fulfillment (cultural services) are less tangible. All, however, directly or indirectly underpin human economies and livelihoods. The findings of the global Millennium Ecosystem Assessment (MA) and many sub-global assessments (SGAs) emphasize the important contributions these services make to human well-being and the accomplishment of long-term development goals (MA, 2005a,b; SCBD, 2006; Shackleton et al., 2008).

Despite their critical importance, the capacity of ecosystems to provide these myriad services is being degraded at an alarming rate. In 2005 the MA, a four-year study of the state of the world's ecosystems involving more than 1300 experts from 95 countries, reported that over 60 percent of ecosystem services were already degraded (MA, 2005a,b). The negative trend, they concluded, was set to continue and accelerate over the next half century. This global degradation of ecosystem services presents a significant threat to achieving Millennium Development Goals (MDGs), worsening poverty and trigger social conflicts (MA, 2005a,b; SCBD, 2006; Huitric et al., 2009).

The MA built interest in using ecosystem service approaches to identify links between ecosystems and economic and human development. Since publication of the MA, researchers and decision-makers are increasingly developing applying these approaches (Naidoo et al., 2008; Ranganathan et al., 2008). However, the under-developed information base and methods needed to apply ecosystem service concepts in policy dialogs and decision processes is hindering wide-spread mainstreaming of these concepts (MA Follow-up Advisory Group, 2008). Metrics and indicators to track and communicate trends in the quantity and quality of ecosystem services are essential to knowing whether or not these services are being sustained or lost, and how policies should be designed to ensure the sustainable flow of services to support human welfare and maintain biodiversity (Meyerson et al., 2005; Feld et al., 2007; Walpole et al., 2009; Layke, 2009).

The MA emphasized the need for indicators (MA, 2005a,b), as have evaluations and research building on the MA (Wells et al., 2006; Balmford et al., 2005a,b; Dobson, 2005; Feld et al., 2007). Recent reviews have demonstrated that these indicators are still wanting (Layke, 2009; Walpole et al., 2009). This analysis is intended to help inform future research to supply these metrics and indicators, and the data gathering needed to apply them. By taking stock of the metrics and indicators used in most of the ecosystem assessments done thus far, at both global and sub-global scales, the conceptual and data gaps can be better understood. By addressing

Abbreviations: MA, Millennium Ecosystem Assessment; ESPA, Ecosystems Services for Poverty Alleviation; SGAs, Sub-global Assessments.

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these gaps, it will become increasingly possible to reduce artificial barriers between ecosystems and development in decision-making processes.

2. Methodology

The authors compiled the metrics and indicators used in the MA global assessment and 21 sub-global assessments and ranked them for "ability to convey information" and "data availability". The differences in the rankings for indicators of different services were then analyzed. This paper builds on *Measuring Nature's Benefits: A Preliminary Roadmap for Improving Ecosystem Service Indicators* (Layke, 2009) by including indicators compiled from sub-global assessments in addition to the global MA. By examining the metrics applied in local, national and multi-national regional assessments, a more comprehensive understanding of indicator availability and data availability can be developed.

2.1. Compiling ecosystem service indicators

Metrics and indicators were compiled by identifying them in the text of the assessments and recording them. This was necessary since authors of the assessments had not systematically organized the indicators they used into tables or databases.

To the extent possible, this indicators assessment sought to focus specifically on metrics and indicators that communicate the ecosystem services being provided rather than the capacity of ecosystem to provide the service—on the *flow* as opposed to the *stock* of ecosystem services. This distinction is relatively straightforward for most provisioning services. The volume of timber harvested, for example, is a flow metric while the area of forested land measures the stock. Reduction of faecal coli and ammonia due to wetland filtering, an indicator compiled from the Southern Africa sub-global assessment, provides an example of a flow indicator for a regulating service, in this case water purification and waste treatment services. However, due to conceptual constraints identifying relevant indicators and practical constraints getting data for the metrics there are significant barriers to using flow indicators for many regulating and cultural services (Layke, 2009). For this reason, the authors did include some stock indicators where they were deemed to provide a reasonable proxy. For example, in the case of natural hazard regulation, Mangrove area was included because it provides value as a leading indicator, while the indicators that communicate the flow, such as changes in seasonality of flood events, are lagging indicators.

The focus on flow indicators is intended to help answer the question of how well the value-added of the ecosystem services approach can be applied in decision-making. How effectively can the contribution of services to peoples' economic, physical, and spiritual well-being be communicated to policy-makers? Specifically: do they convey the range and quantity of benefits people and businesses derive from ecosystems? This is a different question from asking how well available metrics and indicators measure and communicate ecosystem condition—the capacity of ecosystems to continue to provide services. It should be noted, however, that both indicators of stocks and flows are needed for informing policy, and developing and deploying indicators of both is a priority.

2.2. Avoiding duplicate indicators

The various assessments used for this study often used similar indicators. In some cases they were formulated differently, but the underlying information they were seeking to communicate was similar. For this study, closely related indicators were treated only once. For example, many assessments used crop production in numerous ways, often listing the production of all major crops. In this case, only *crop production* was included, as opposed to including *maize production, rice production,* and *millet production*. Similarly, derivations of the same indicator were not used. *Crop yield*, for example, is a normalized variation on *crop production* and was not included in the compilation as a separate indicator.

Table 1
The MA classification of ecosystem services.

Service category	Ecosystem services
Provisioning	Food
	Crops
	Livestock
	Capture fisheries
	Aquaculture
	Wild Foods
	Biological raw materials
	Timber
	Fibers and resins, animal skins, sand, and ornamental resources
	Biomass fuel
	Freshwater
	Genetic resources
	Biochemicals, natural medicines, and pharmaceuticals
Regulating	Air quality regulation
	Climate regulation
	Global climate regulation
	Regional and local climate regulation
	Water regulation
	Erosion regulation
	Water purification and waste treatment
	Disease regulation
	Soil quality regulation
	Pest regulation
Cultural	Aesthetic/ethical values
	Recreation and ecotourism
	Spiritual and religious values (used for sub-global indicators only)
	Heritage (used for sub-global indicators only)
	Scientific/Education (used for sub-global indicators only)
Supporting	Primary production
	Nutrient cycling
	Soil formation
	Water cycling

Source: Adapted from the reports of the MA (2005a,b), Balmford et al. (2008), Hanson et al. (2008), and Ranganathan et al. (2008). For more information go to www.wri.org/ecosystems/esr.

2.3. Framework used to assess indicators

A slightly adapted version of the ecosystem services framework proposed by the MA (2005a,b) was used in this study (Table 1). This framework categorizes ecosystem services into four different classes: provisioning, regulating, cultural and supporting services. Within each category, there are multiple services. Some services, such as food, biological raw materials and climate regulation are further divided. Indicators were compiled by the most specific ecosystem service categories depicted in Table 1.

2.4. Sub-global assessments included in this study

21 of the 34 sub-global assessments (SGAs) undertaken as part of the MA were included in this study. The reports were located through the MA official website and websites of organisations that were involved in carrying out specific SGAs. The remaining 14 were excluded because they could not be located or had never been completed. The included SGAs, which can be found at the Millennium Ecosystem Assessment website (http://www.maweb.org/en/Multiscale.aspx), were:

- Alternatives to Slash-and-Burn – Tropical Forest Margins
- Altai-Sayan Ecoregion

- Brazil (São Paulo Greenbelt)
- Canada (Coastal British Columbia)
- Caribbean Sea Assessment (CARSEA)
- China (Western)
- Chile (Atacama)
- Colombia (Andean Coffee-growing Region)
- Downstream Mekong River Wetlands in Vietnam
- Egypt (Sinai)
- Indian (Urban Assessment)
- India (Local Villages)
- Indonesia (Jakarta Bay and Bunaken Ecosystems Sub-Global Assessment)
- Norway (Glomma River Basin)
- Papua New Guinea
- Peru (Vilcanota)
- Portugal
- Philippines (Laguna Lake Basin)
- Northern Range of Trinidad and Tobago
- Southern African Sub Global Assessment (SAfMA)
- Sweden (Kristianstad Wetlands).

In addition to these SGAs, indicators from 5 Ecosystems Services for Poverty Alleviation (ESPA) Programme assessment reports were also compiled. The included ESPA programme assessment reports, which can be accessed at http://www.nerc.ac.uk/research/programmes/espa/resources.asp, were:

- Sub-Saharan Africa
- Amazon Basin
- Marine and Coastal
- China
- India-Hindu Kush-Himalayas

Taken together, these SGAs and ESPA reports assessed nearly all ecosystem types. Between the SGAs and global assessment, scales from local to global were treated.

2.5. Criteria applied to assign indicator scores

Numerous lists of characteristics and criteria for effective indicators have been published (see for example MA, 2005a,b; Jackson et al., 2000). This study applied criteria developed by Layke (2009). The criteria are grouped into two elements:

1. *Ability to convey information*: an indicator's capacity to summarize the characteristics of the flow of an ecosystem service at multiple spatial and temporal scales and communicate these characteristics to non-technical policy-makers
2. *Data availability*: whether sufficient data are available to support policy-makers' use of the ecosystem service indicator at multiple scales.

The criteria within each of these elements are:

2.5.1. Ability to convey information

1. *Intuitive*. Indicators communicate information about ecosystem services clearly without ambiguity. Good indicators avoid differing interpretations of the ecosystem service state or trend being presented. Indicators must be easily understood by policy-makers and other non-technical audiences.
2. *Sensitive*. Sensitive indicators are able to detect changes in time for policy adjustments before the changes are profound and the ability to take remedial or adaptive action is compromised.
3. *Accepted*. Accepted indicators adhere to agreed scientific methods and available data sets where possible.

2.5.2. Data availability

1. *Monitoring systems gather data at sufficient temporal and special scales*. Applying the ecosystem services framework requires information at multiple spatial and temporal scales; monitoring systems therefore need to gather data with sufficient regularity and at a relevant scale to track changes at a rate appropriate to the "characteristic scale" of ecosystem processes and flow of services (MA, 2005a,b).
2. *Processed and available*. For data to be available to populate indicators, they must be processed into formats that are widely used and made available for easy access. Effective data processing and sharing can take different forms, but often includes posting GIS data files, databases, or spreadsheet files on the internet or publishing them on CD.
3. *Normalized and disaggregated*. The ability to normalize and disaggregate data is necessary in order to conduct assessments and policy analysis at "spatial and temporal scales appropriate to the process of phenomenon being examined" (MA, 2005a,b). Data need to be able to support normalizing – e.g., total cereal harvest is normalized by fertilizer application to become cereal harvest per ton of nutrient applied, and disaggregating – e.g., separating cereal harvest into production of maize, wheat, and sorghum so as to inform analysis and possible policy actions.

2.5.3. Applying the ratings

To assess the compiled ecosystem service indicators, a rating of "high", "medium", or "low" (numerically 3, 2, or 1 respectively) was assigned for each criterion listed above for each indicator. An arithmetic mean of the scores for the three criteria under each element – ability to convey information, and data availability – was they produced to reach an overall score for that element.

2.6. Limitations of this analysis

The approach for this analysis was carefully designed. The approach as applied is intended to communicate a macro level understanding of the status of ecosystem service indicators. Because the results are based on generalizations, individual indicator scores should not to be used as a judgment on the possible relevance of that indicator in a specific context. The recognized limitations of the study approach are noted below.

1. *Limited scope*: This paper is based on an analysis of the indicators used in the global and sub-global assessments conducted as part of the MA and its follow-up activities. While this should have identified the majority of relevant indicators available to assess ecosystem services, it will not have captured all. Other limitations in scope include:
   - Regulating and cultural services such as pollination services, disease regulation, erosion regulation, and spiritual services were not assessed by enough MA assessments to draw or permit an analysis of indicators for those services.
   - Excluding indicators of ecosystem state (stock indicators) by limiting the study to indicators of service flows probably led to overlooking metrics that would serve as effective proxy indicators for flows.
   - The method of extracting metrics and indicators from the text may have overlooked some indicators.
   - Research since publication of the MA may address some of the gaps identified here by having applied new indicators or gathered new data.

2. *Subjectivity*: The ratings given to each indicator are subjective and based on the opinions of a limited number of people. The ratings for any given indicator are therefore less relevant than the means for each category they indicators are grouped under.
3. *Generalizations*: Ecosystem service metrics and indicators should be applied in different geographic locations, at different scales, and for varying policy purposes. The conclusions drawn here generalize. The situation in a given location may vary from the conclusions drawn here. Data constraints, for example, vary dramatically among countries and regions of the world. Depending on a reader's specific context, data availability may be better or worse than the generalizations presented here.

3. Findings for ecosystem service indicators

This analysis found that there are many gaps in ecosystem service metrics and indicators available at all scales from global to sub-national. The weaknesses identified in the indicators are broadly consistent across those scales. For the value of the ecosystem services conceptual framework to be fully realized, therefore, ecosystem service metrics need to be expanded and more fully developed. Data gathering and compilations must also be improved in order to support application of ecosystem service indicators to support policy dialogs and decisions.

The gaps identified in ecosystem service metrics and indicators are summarized below:

1. The ability of indicators assessed to convey information is low overall. This ability varies widely among services, but is consistent across scales.
2. The metrics and indicators available for most ecosystem services are insufficient to completely communicate the quality and quantity of benefits provided by many ecosystem services.
3. Data limitations make it difficult to apply ecosystem services indicators.
4. Indicators for regulating and cultural services lag behind provisioning services in each of the limitations identified above.

Overall, this analysis found that there are clear patterns in the ecosystem service metrics and indicators compiled for each ecosystem service category. These can be summarized as follows:

- Ecosystem service metrics and indicators are dominated by the provisioning services in terms of quality and, especially at the sub-global level, in terms of quantity.
- Within provisioning services, metrics associated with food related services predominate.
- In addition to their being fewer overall indicators for cultural or supporting services than for provisioning services at all scales, there was less diversity in these indicators in sub-global assessments.
- Indicators of global climate regulating services are overrepresented within regulation services, although this weighting is less marked than for crop indicators within provisioning services.
- Recreation and ecotourism indicators predominate in the cultural services category, especially at in sub-global scales.
- Indicators of primary production make up the majority of indictors for supporting services.

Average scores for the indicators compiled for each ecosystem service are presented in Table 2. A sampling of the indicator compiled is presented in Table 3, and an online database of all indicators compiled for this analysis is available on the ecosystem service indicators database (http://www.esindicators.org/). Please note that the ecosystem service indicators database is still in development and is designed for users to contribute their knowledge.

To the right of the scores, the institutions that compile data for the indicators within each service are noted. In the case of the compiling agency for global indicators, an agency was named only if they have the responsibility to compile and report data for multiple countries. For compiling agencies for sub-global indicators, agencies were noted if they were identified as a source for a given service in two or more assessments.

The scores for ability to convey information and data availability illustrate the strengths, weaknesses, and gaps in ecosystem service indicators and allow for a comparison between the categories of ecosystem services. As illustrated in Table 2, ecosystem service indicators as a whole are characterized by many gaps in their ability to convey information and data availability. Fewer than one third of services have indicators that received an average score of *high* for "ability to convey information." For "data availability," none of the ecosystem services assessed had an aggregate score of *high*. These patterns hold true for indicators compiled from both global and sub-global assessments. In fact, the rankings assigned each ecosystem service were identical for both the global and sub-global assessments. The overall patterns within and among ecosystem service indicators described below, therefore, apply to both the global and sub-global indicators.

Indicators of provisioning services earned the best average scores. Of the 11 provisioning services, nearly half (5) received a score of *high*, while 4 rank *medium* for ability to convey information. Two services (*genetic resources* and *biochemicals and natural medicines*) rank *low* on this measure. Provisioning services also scored highest for data availability. 8 of 11 services received scores of *medium,* the remainder received ratings of *low*.

The scores for regulating service indicators were lower overall than those for provisioning. Fewer than one third (two) of these services assessed received an average score of *high* for ability to convey information. Four received a score of *medium* for this element, while one ranked *low*. For data availability, all but two services received rankings of *low*.

Cultural services scored worse than both provisioning and regulating services. None of the services assessed scored *high* for conveying information. Of the two services with indicators compiled from the global assessment, only *recreation and tourism* scored *medium* while the other scored *low*. Of the five assessed for sub-global assessments, three scored medium while two scored low. All services in both cases scored *low* for data availability.

Supporting service, which was only assessed at the sub-global scale, received similar scores as cultural services. Both services received scores of *medium* for ability to convey information, and low for data availability.

3.1. Indicators for provisioning services

Provisioning service indicators were strongest at all scales. People rely directly on food, water, and shelter provided by provisioning services, the strength of these indicators and data availability can probably be attributed to that immediate dependency. This possibility is supported by the patterns among provisioning services, especially at the sub-national level, which had many more individual indicators compiled overall. At the sub-global level, over half (98 of 194) of the provisioning services were related to food production. Other basic necessities made up the majority of the remainder. Freshwater had 37 indicators, and timber had 20.

The indicators applied in sub-global assessments are more focused on food services, and provisioning services overall, than the global assessment. In the global assessment, about 15% of the 115 indicators compiled are indicators of food ser-

Table 2
Ratings of compiled ecosystem service indicators' ability to inform policy-making.

Ecosystem service	Global indicators				Sub-global indicators			
	Number of indicators identified	Ability to convey information	Data availability	Compiling agency	Number of indicators identified	Ability to convey information	Data availability	Compiling agencies
Provisioning								
Food								
Crops	4			FAO	65			FAO, USDA-FAS and national statistics
Livestock	3			FAO	8			FAO and national statistics
Capture fisheries	7			FAO	19			FAO and national statistics
Aquaculture	2			FAO	2			FAO and national statistics
Wild foods	1			None	4			FAO and national statistics
Biological raw materials								
Timber	6			FAO	20			FAO and national statistics
Fiber and resins, animal skins, sand and ornamental resources	4			FAO	17			FAO and national statistics
Biomass fuel	4			FAO	14			FAO, IEA, ITTO, CIFOR, INBAR, WHO & national statistics
Freshwater	5			FAO	37			UN Millennium Indicators, UNICEF ORT, UNDP
Genetic resources	3			None	No indicators identified			
Biochemicals, natural medicines and pharmaceuticals	2			None	8			National statistics
Regulating								
Air quality regulation	2				4			National statistics
Climate regulation								
Global climate regulation	7			IPCC	14			IPCC
Regional climate regulation	4			None	1			None
Water regulation	2			None	1			None
Erosion regulation	No indicators compiled				9			None
Water purification and waste treatment	3			None	13			None
Disease regulation	3		None		No Indicators identified			
Soil quality regulation	No indicators identified							
Pest regulation	No indicators identified							
Pollination	No indicators identified							
Natural hazard regulation	7			None	8			None
Cultural								
Aesthetic/ethical values	4			None	1			None
Spiritual and religious values	No indicators compiled				3			None
Recreation and ecotourism	5			None	5			AfDB, WTO, KPMG
Heritage	No indicators compiled				1			
Scientific/education	No indicators compiled				1			
Supporting								
Nutrient cycling	No Indicators compiled				3			None
Primary production	No Indicators compiled				12			None

High: indicators and data availability are sufficient to inform policy-making.
Medium: indicators and data availability are sufficient to partially inform policy-making.
Low: indicators and data availability are inadequate for supporting policy-making.
AfDB, African Development Bank; FAO, Food and Agriculture Organization of the United Nations; IEA, International Energy Agency; INBAR, International Network for Bamboo and Rattan; IPCC, Intergovernmental Panel on Climate Change; ITTO, International Tropical Timber Organization; KPMG, Klynveld Peat Marwick Goerdeler; UNDP, United Nations Development Programme; UNICEF, United Nations Children's Fund Database; USDA-FAS, United States Department of Agriculture – Foreign Agricultural Service; WHO, World Health Organization; WTO, World Tourism Organisation.

vices, and about 35% are provisioning service indicators. The indicators from sub-global assessments are much more heavily weighted toward these services, with 31% of indicators focused on food and 61% of indicators overall pertaining to provisioning services.

In addition to peoples' direct dependency on provisioning services, the large number of indicators for these services is also probably due in part to the fact that services such as crops, livestock, timber production and freshwater are comparatively easily quantified, and national statistical systems make data more

Table 3
Examples of compiled ecosystem service indicators organized by ecosystem service. Indicators of similar nature are combined. All sources using the indicator or a similar one are noted.

Indicator	Data units	Compiled from
Provisioning		
Food		
Multiple food sub-categories		
Dietary energy supply/daily calorie supply estimated from cereal and meat production	Kilocalories/person or % of RDA	Global MA, Brazil, Tropical Forest Margins, Portugal
Crops		
Crop production	Tonnes	Global MA, Brazil, Tropical Forest Margins
Employment in crop production and processing	Number of people	Global MA
Livestock		
Livestock production	Tonnes	Global MA, Brazil SGA
Value of livestock products production	Currency	Global MA
Capture fisheries		
Employment in the marine products sector	Number of people	Global MA, Philippines, Portugal, India
Fish products as a percent of total animal protein in peoples	Percent	Global MA
Marine production/value of marine production (includes fish catch)	Tonnes/currency	Global MA, Brazil, Papua New Guinea, Trinidad
GDP growth rate-fishery sector	Percent	Portugal
Aquaculture		
Production from aquaculture (fish and non-fish)	Tonnes	Global MA, China ESPA,
Fish products as a percent of total animal protein in peoples' diets	Percent	Global MA
Wild too		
Number of wild species used for human food	Number species	Global MA, Papua New Guinea
Hunt yields	Number animate/tonnes	Norway
Fiber		
Multiple sub-categories		
Contribution of forest to GNP	Percent	Portugal
Employment in the forest sector	Thousands of people	Global MA, Portugal
Timber		
Forest biomass production	Cubic meters, tonnes	Global MA, Portugal
Round wood/timber production	Cube meters, tonnes	Global MA, Portugal
Value of forest products	Currency	Global MA
Volume of forest products used for local crafts	Tonnes	Global MA
Cotton, hemp, silk, etc.		
Employment in fibers production	Number of people	Global MA
Fibers production/value of fibers production	Tonnes/currency	Global MA
Production of wildlife-derived skins, wool and feathers	Tonnes	Global MA
Biomass fuel		
Charcoal/fuelwood production/value of production	Cubic meters/currency	Global MA
Industrial energy production from forest systems	Terawatts	Global MA
Monetary value of fuel production	Currency	Global MA
Fresh water		
Renewable water supply/population saved by renewable water resource	Cubic kilometers/yr	Global MA/Chie/Egypt
Water storage capacity	Days of river discharge	Global MA
Hydroelectricity production	Tarawatts	Brazil
Production of desalinated water	Cubic meters	India SGA
Genetic resources		
Investment into natural products prospecting	Currency	Global MA
Number of species that have been the subject of major investment or have become a commercial product	Number species	Global MA
Value of genet resources	Currency	Global MA
Biochemicals, natural medicines and pharmaceuticals		
Number of organisms from which drugs have been derived	Number	Global MA
Value of pharmaceutical products developed in natural systems	Currency	Global MA
Exports of medicinals	Tonnes, currency	Tropical Forest Margins
Number of bioactive substances (such as color products) produced by plants	Number	Downstream Mekong
Regulating		
Air quality regulation		
Flux in atmospheric gases	TgC/yr, TgC/yr, TgN/yr	Global MA
Atmospheric cleansing capacity (tropospheric oxidizing capacity)	No units noted	Global MA
Levels of pollutants in the air such as nitrogen and sulphur dioxide, ozone, file particulates		Southern Africa, India
Climate regulation		
Global climate regulation		
Atmospheric gases flux (CO_2, CH_4, etc.)	TgC/yr, TgC/yr, TgN/yr	Global MA, China SGA
Carbon uptake/accumulation/carbon stock	Teragrams, Tonnes	Global MA, China ESPA, China SGA, Amazon basin ESPA, Portugal, Philippines
Evapotranspiration	Percent	Global MA
Carbon sequestration capacity	Megagrams/ha, tonnes	Global MA, Caribbean Sea, Portugal
Surface albedo	Albedo	Global MA
Regional and local climate regulation		
Canopy stomatal conductance	No units noted	Global MA
Evapotranspiration	Cubic meters	Global MA, China

Table 3 (*Continued*)

Indicator	Data units	Compiled from
Water regulation		
Soil water infiltration	No units noted	Global MA
Soil water storage	No units noted	Global MA
Erosion regulation		
Area in shaded coffee under forest canopy	Hectares	Columbia SGA/Portugal
Siltation transfer/sediment load into the Caribbean Sea	Tonnes	Caribbean Sea/Brazil
Landslide frequency	Landslides per year	Brazil
Water purification and waste treatment		
Capacity of ecosystem to process waste/amount of waste processed by ecosystems	Volume/mass of waste	Global MA, Southern Africa
Value of ecosystem waste treatment and water purification	Currency	Global MA
Level of pollutant in surface waters	Varies	Southern Africa SGA, India SGA
Disease regulation		
Disease vector predator populations	Number	Global MA
Change in disease burden due to changing ecosystems	Number of disease cases	Global MA
Population increase in disease vectors mosquitoes (blowing ecosystem conversion.	Mosquito population	Global MA
Natural hazard regulation		
Changes in number and seasonally of Hood events, other natural disasters	Percentage change in # of events by season	Global MA, China
Mortality and economic losses from natural disasters	Currency	Global MA, Marine and Coastal, Caribbean Sea
Floodplain water storage capacity	Days of river discharge floodplain can store	Global MA
Reef, mangrove area as % coastline	Percent	Marine & Coastal, Caribbean Sea
Cultural		
Aesthetic values		
Comparative value of real estate near nature or deaner water bodies	Currency	Global MA
Number of nature/rural visitors	Number of people	Global MA
The number of people who place high value on the place where they were born	Number	India SGA
Amount of cut flowers sold in the city	Currency	India SGA
Recreation and ecotourism		
Numbers of tourists visiting for nature and/or rural tourism employment/spending	Number of people	Global MA, Chile, Southern Africa, Chie, Portugal, Marine and Coastal
Number and value of recreational anglers and hunters	Number of people	Global MA, Caribbean Sea SGA
Total recreational value	Currency	Global MA, Sweden SGA, Portugal SGA
Visitors to natural areas	Currency	Global MA

readily available. In fact, for the sub-global indicators, data compilation agencies are noted for nearly all provisioning services – a marked contrast to regulating, cultural and supporting services.

Indicators of food production included crop production: grain production in kilogrammes per hectare per year, agricultural production, employment in vegetable and fruit marketing; livestock production: quantity of meat produced: capture fisheries: employment in fisheries, total fish catch/production, fish landings; and wild foods: number of wild plants utilised for food.

There were also a sizeable number of indicators of freshwater indicators. These included: *water quality and lake depth* and *water supply-demand analysis*. Indicators of biological raw materials included indicators of timber and other wood products such as *production of timber* and *percentage of plants used for construction and crafts*; indicators of fibers and resins included: *volume of fiber produced, leather production,* and *standing stock of fiber*. Indicators of biochemicals, natural medicines and pharmaceuticals services that were identified included: *percentage of plants used for medicines, the condition of populations of medicinal plants and economic values of medicinal plants*).

Indicators of genetic resources were absent from the sub-global reports assessed. However, three indicators for this serve were compiled from the global MA: *investment into natural products prospecting, number of species that have been the subject of major investment or have become a commercial product and value of genetic resources.* All three of these indicators are focused on a narrow aspect of genetic resources – efforts to develop commercially valuable products. Identifying indicators of how genetic resources contribute in other ways such as traditional crop breeding, is an important area for further research.

3.2. Indicators for regulating service

Indicators for most regulating and cultural services are weak at both global and sub-global scales. The smaller number of regulating services indicators compared with provisioning services is not surprising. Most regulating services are not as immediately tangible for meeting peoples' needs as provisioning services, and have been a lower priority to measure and track. Some regulating services have long been recognized as important for provisioning services – erosion regulation for example – appears to have more developed indicators. 9 erosion control metrics were identified in sub-global assessments, for example. Similarly, 13 indicators of waste treatment and water purification, which is important for human health, were compiled.

Few patterns of difference between regulating indicators compiled from the global assessment and sub-global assessment emerged. There were proportionally greater numbers of indicators for some services like water purification in the sub-global indicators, and fewer for others, like regional and local climate regulation. However, there did not seem to be any consistency in these differences.

Some examples of regulating services indicators compiled for this study included: for air quality regulation: *ambient air quality, levels of pollutant in the air*; for climate regulation: e.g., *carbon sequestration capacity of sea grass, CO_2 storage, carbon stock exchanges*; for erosion regulation *area under shade coffee, areas with exposed soil, landslide frequency*; for water purification and waste treatment: *level of reduction of faecal coli and ammonia due wetland filtering, regulatory effect of tidal variation on total coliforom contamination*; for natural hazard regulation: *area of mangrove extent, economic value of environmental protection role of forests, estimated flood mitigation capacity of wetlands;* and for erosion regulation services: *area under shade coffee, areas with exposed soil, landslide frequency*.

No indicators of pollination, disease or pest regulation were identified in the sub-global assessments used in this study. However, three indicators of disease regulation were compiled from the global MA. These were: *disease vector predator populations*, *estimated change in diseases burden as a result of changing ecosystems*, *population increase in disease vector and mosquitoes following ecosystem conversion*. These indicators all received a rating of *low* for both ability to convey information and data availability. These are essential regulating services that are crucial not only to human health but to food and livestock production.

3.3. Indicators for cultural services

There were very few indicators of cultural services compiled from the global or sub-global assessments. The majority of indicators in both the global and sub-global assessments were on recreation and ecotourism. As this is the most tangible and least subjective cultural services, this was not a surprising result. The assessment of cultural services in the majority of SGAs and ESPA assessments almost always relied on descriptive information rather quantitative data, and most of this data was generated through participatory processes.

While there were proportionally more cultural indicators compiled from the global assessment (9 of 115 in from the global assessment versus 12 of 316 from the sub-global assessments) the difference was too small to attribute much relevance or to assess whether possible reasons for it. In addition, the differences in how the cultural services were compiled for the global and sub-global assessments makes it difficult to compare them.

Examples of cultural indicators include: for recreation and ecotourism: number of visitors to ecotourism farms, number of visitors to national parks and reserves, income from nature based tourism, total employment in the tourism industry, value of recreation fisheries; for spiritual services the number of people who place high value on the place they were born, number of sites and species that are fundamental to the performance of rituals and maintaining relations with ancestors).

Other possible reasons for the shortage of cultural services indicators include:

- Cultural ecosystem services are context specific and need to be tailored for different locations and purposes.
- Perceptions of cultural services vary among individuals and are often qualitative in nature.

3.4. Indicators for supporting services

Few supporting services indicators were used in the SGAs and ESPA assessments (supporting service indicators were not compiled for the global MA). In fact, supporting services had the fewest indicators of the 4 ecosystem service categories. The most common indicators of supporting services were nutrient cycling services such as: *value of nutrient cycling for terrestrial ecosystems, value of organic matter production.* There were also some indicators for primary production, including: *net primary productivity* and *net ecosystem production*. There were no indicators that accounted for the water cycling indicator service theme.

As with many regulating services, the shortage of indicators for supporting services highlights the need for investments into research on ways to measure and communicate the contribution of supporting services to human well-being. How do these services underpin the supply of tangible ecosystems services such as food and livestock production, timber production, and capture fisheries, and how are these traits changing over time?

Some recent research raises questions about the usefulness of supporting service indicators as an important input for policy (e.g., Layke, 2009). Future research should therefore investigate (1) how important supporting services are for different policy purposes compared with other ecosystem services, and (2) to seek approaches to measure and communicate those services that are deemed important for policy-makers to track and act on.

3.5. Data availability

The availability of relevant data is a major constraint in applying ecosystem service indicators, especially for regulating, cultural and supporting services. Few agencies compile data on ecosystem services at global, regional sub-global levels, making it difficult to identify consistent and high-quality data. Most of the data used in the global and SGAs and ESPA assessments were obtained from the following agencies:

- African Development Bank (AfDB),
- Botswana Tourism Development Programme,
- Center for International Forestry Research (CIFOR),
- Food and Agriculture Organization of the United Nations (FAO),
- Intergovernmental Panel on Climate Change (IPCC),
- International Energy Agency (IEA),
- International Network for Bamboo and Rattan (INBAR),
- International Tropical Timber Organization (ITTO),
- Klynveld Peat Marwick Goerdeler (KPMG),
- United Nations Development Programme (UNDP),
- United Nations Children's Fund (UNICEF) Database,
- United Nations Millennium Indicators Database,
- United States Department of Agriculture – Foreign Agricultural Service (USAD – FAS),
- World Resources Institute (WRI) EarthTrends Database,
- World Health Organisation (WHO),
- World Tourism Organisation (WTO).

In the analysis of indicators used for the global assessment, the FAO and IPCC were the only two organizations identified as having significant role in gathering and disseminating data that inform ecosystem service indicators.

At the national level, statistics from government agencies such as ministries of agriculture forestry, energy, tourism, economic planning, and national statistics offices, and data gathered and compiled by research institutes and universities were the predominant sources of national and sub-national levels data used by assessments. In Table 2, these are captured under the generic term "national statistics." Mainstreaming ecosystem services into policy-making will require strengthening the capacity of these agencies to gather relevant data and make it readily available for policy analysis. Even in some of the most data-rich rich countries like the USA, data limitations limit the ability to track the health of ecosystems and ecosystem services (Heinz Center, 2008). The international community therefore has an important role to play in supporting national institutions and facilitating strengthened partnerships between government agencies, academic and NGO groups. Uganda, for example, launched an Environmental Information Network intended to compile data from multiple agencies and non-governmental organizations as a strategy toward mainstreaming environment, but is facing numerous constraints in realizing the promise of the network (Gowa, 2009). Supporting efforts such as these will be vital to ensuring the supply of data needed to develop indicators that will help policy-makers identify strategies that provide for peoples' needs without continuing the degradation of ecosystems and biodiversity.

4. Opportunities and challenges in developing ecosystem service indicators

The gaps in existing ecosystem services metrics and indicators are significant, as are conceptual challenges to filling those gaps for some ecosystem services. As research to fill these gaps proceeds, however, some practical opportunities will provide some support to these efforts. Some of the conceptual challenges facing developing ecosystem service indicators are outlined below.

4.1. Measuring ecological processes

Many provisioning services are tangible goods such fish, timber, fuelwood, or water. These can readily be measured and quantified for metrics. In many cases, the units are similar enough that they can be aggregated for more complex indicators. Many regulating services, however, are ecological functions or processes (Balmford et al., 2008; Braat and ten Brink, 2008; Turner et al., 2008). By their nature, most such processes cannot readily be quantified directly. Recognizing this difference between many of the provisioning, regulating, cultural and supporting services should help clarify the conceptual challenges efforts to improve these indicators must overcome. In the global MA, indicators of ecosystem condition were frequently used as proxies for these ecosystem services (Layke, 2009).

While it may prove necessary to continue using proxies like ecosystem condition as indicators for some ecosystem services, research to positively link the proxy indicator to the service should be undertaken. Concepts such as functional traits hold promise for being able to establish these links. Traits, are "characteristics... required for service provision" (Vandewalle et al., 2008). The concept can be applied at scales from the microbial to the landscape, depending on the service the trait provides (Kremen, 2005). In agricultural landscapes, at the plant and field scale rooting depth, height, and branching structure of a plant are traits that provide erosion, water, and nutrient regulation services. At the landscape level, nectar-producing plants and structurally diverse vegetation are traits that provide bee habitat that support pollination services (Vaughan et al., 2004).

Applying the traits concept to develop high-quality indicators of regulating services will require establishing clear links between various ecological traits and the quantity and quality of services enabled. Moreover, for the trait-based indicators to have broad applicability, it will be necessary to identify traits that can be measured at landscape scales via remote sensing technologies, as well as those that can be measured using more resource-intensive methods. Approaches to conduct a "functional inventory" – an inventory of the functional traits that enable an ecosystem service in a given area – has been proposed and applied (see Kremen, 2005; Vandewalle et al., 2008).

4.2. Measuring "avoided change"

Another challenge to overcome in identifying metrics and indicators for some ecosystem services is that the positive contribution of the service is more difficult to detect that the negative consequence of having lost that service. For example, intact erosion regulation services will hold soil in place. When this service is degraded, soil is blown by wind or carried away by water. These negative consequences of the loss of the service can readily be detected and characterized. Measuring the intact service is most easily done by noting the absence of the consequences of the service being degraded – essentially using "avoided change" as a metric. When seeking to assess the positive contributions of ecosystem services, the challenge of this approach is now to characterize degradation, that has not happened (a "counterfactual") due to the contribution of a regulating service?

4.3. Positive trends for ecosystem service indicators

The increased awareness of ecosystem services by policy-makers holds promise for development of ecosystem service indicators. Among the patterns noted in the analysis of MA global indicators is that indicators are stronger for services that are traded or subject to government regulation (Layke, 2009). As governments and international agreements around climate change explore and begin to implement policies like nutrient trading (Selman et al., 2008) and payment for carbon sequestration that make use of regulating services, demand for ways to measure the contributions of these services will increase. Some examples of how markets and regulation of ecosystem services has contributed to ecosystem services are presented below.

4.4. Economic markets for ecosystem services

This analysis found that ecosystem services which have economic markets are supported by stronger indicators than those without. Most provisioning services are traded, and have the strongest overall metrics and indicators. Within cultural services, recreation and ecotourism, which are often paid for, had comparatively strong indicators. Similarly, a number of regulating services are beginning to be integrated in economic markets, such as water purification and waste treatment. Mechanisms to enhance global climate regulation by paying to manage ecosystems for carbon sequestration are being implemented (Hamilton et al., 2009). Those regulating services that are being integrated into economic markets appear to have more developed metrics than those that are not.

4.5. Government regulation

In addition to economic markets, ecosystem services subject to laws, regulations and incentives by governments appear to have stronger indicators than those that are not been regulated (Layke, 2009). Some services such as water purification and waste treatment, global climate regulation, and erosion regulation have been recognized by governments as important contributors to human well-being, as evidenced through legislation to encourage or require management of these services. For example, numerous countries have incentives to plant and harvest crops in ways that maintain erosion regulation. Similarly, limits on logging exist in certain areas to protect water purification, erosion regulation, and natural hazard regulation services. These kinds of government interventions are less common for other services like disease regulation, air quality regulation, and pest regulation. Those services noted above as being the subject of government regulation received aggregate indicator scores of *high* or *medium* for ability to convey information at both global and sub-global scales. In addition, these services tended to have more indicators than for other regulating services. 10 of 28 total regulating service indicators compiled from the global MA were for global climate regulation and water purification and waste treatment (no erosion regulation indicators were identified). For sub-global assessments, 36 or 50 total indicators compiled for regulating services were for global climate regulation, water purification and waste treatment, and erosion regulation.

5. Improving and applying ecosystem service metrics and indicators

This study illustrates the gaps that exist in ecosystem service metrics and indicators, especially regulating, cultural and supporting services. Work to improve these indicators is urgently needed and should be undertaken on multiple fronts. The first is to develop conceptual approaches to fill the gaps identified in this analysis. To complement that work, existing ecosystem service indicators need to be applied. Since indicators are tools to inform policy and management decisions, effective development of metrics and indicators will require an iterative process of conceptual development and applying indicators with diverse audiences to identify what works, where gaps are being filled, and where they remain. Fortunately, work on both fronts is being undertaken. Analyses like The Economics of Ecosystems and Biodiversity (EC, 2008, second iteration forthcoming), supported by the relatively rich data provided by the European national and common statistical offices, universities and research institutions, and the European Environmental Agency, illustrate the strength of analysis that is possible by adapting existing metrics and approaches. Efforts to develop approaches that can efficiently measure ecological functions are also underway (see for example Willamette Partnership et al., 2009).

Some ideas for steps on both fronts are laid out below.

5.1. Start with existing indicators

While existing ecosystem service metrics and indicators have many gaps and limitations, applying those existing indicators in diverse policy processes and further assessments should be a priority. This will help introduce ecosystem services concepts to policy-makers in a tangible way, and can help drive demand for data to expand application of the metrics. The process of identifying which metrics and indicators work and which do not will help focus conceptual research to develop new metrics.

To help facilitate application of existing indicators, the indicators compiled for this study are being made available on an online database (http://www.ecosystemserviceindicators.org). This practical resource is intended to help future work build on the foundation provided by the MA. New assessments started since the MA such as the pilot assessments conducted in East Africa, did not have a ready resource of metrics and indicators that had previously been applied to rely on as a reference point. By making the compiled metrics and indicators readily available, parishioners will be able to refer to the concepts that have already been applied, and assess whether they are relevant for their purposes.

As indicators are applied over time and in diverse situations, it will become possible to identify which ones are best for various purposes. This compilation can help build consensus around which ecosystem service metrics and indicators are useful, and for what. For example, which are helpful for ecosystem assessments, landscape management, weighing trade-offs in policy decisions, economic valuation and cost–benefit analysis, and other applications?

5.2. Develop integrated databases

Beyond a database that compiles indicators, databases that can store data needed to apply the indicators are also needed. This will require the ability to store information for ecosystem service metrics and indicators themselves, but also integrating those data with information on human well-being, direct and indirect drivers of ecosystem change, and policy responses. Villa et al. (2007), for example, notes that integrated databases will be necessary for efficiently applying valuation at large scales. Such integrated databases should support the ability to store data across multiple scales and relate to both ecological and administrative boundaries.

5.3. Develop indicator frameworks

Closely related to the process of establishing databases to help develop and apply ecosystem service indicators is the need to conceptualize and apply frameworks designed to organize these indicators. How metrics and indicators of ecosystem condition and biodiversity can usefully be organized to inform the capacity of regulating services and delivery of provisioning services is an important question for helping policy-makers apply these concepts. Similarly, how these indicators can be integrated with indicators of other elements of the ecosystem services framework published in the MA, including human well-being, policy strategies and interventions, and direct and indirect drivers, need to be addressed to support the application of ecosystem services concepts in policy processes.

5.4. Test frameworks and indicators with policy-makers

To test how well ecosystem service metrics and indicators work, along with the frameworks and databases developed to help apply them, intentional engagement with policy-makers should be a high priority. Testing should be done in varied locations, with populations at different levels of development and facing different challenges, and at multiple scales. In addition, indicators should be tested with different kinds of decision-makers including public officials, businesses, agencies responsible for managing natural resources, and others.

5.5. Support research to develop ecosystem service indicators

Efforts intentionally focused on the application of ecosystem services concepts in policy-making are helping to drive the development and refinement of improved indicators. While these activities are impressive in their scope and diversity, additional efforts are needed to fill indicator gaps for some services. It will be important to enlist scientific and policy research organizations from outside the MA follow-up or biodiversity research communities to help. The diverse and novel approaches these organizations bring to bear could be helpful in identifying ecosystem service indicators which can support policy-making with low-cost data. Supporting these organizations should accelerate progress, particularly in the less well understood areas of regulating and cultural services.

5.6. Ecosystem assessments

Ecosystem assessments provide an important testing ground for ecosystem service indicators. These efforts typically compile data from many sources and would benefit from integrated databases, once developed. In the meantime, sub-global assessments will compile and, in some cases, collect new data. Such sub-global assessments may also conceptualize new indicators to fill existing gaps. Ideally, each will also communicate their findings to policy-makers and help identify which indicators are effective and which are not. By applying ecosystem service indicators and engaging government agencies, sub-global assessments will play an important role in influencing governmental indicator compendia and data-gathering regimes, and in mainstreaming ecosystem service concepts.

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