LETTER

Linking Public Participation in Scientific Research to the Indicators and Needs of International Environmental Agreements

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Abstract

Different monitoring approaches collect data that can measure progress toward achieving global environmental indicators. These indicators can: (1) Audit management actions; (2) Inform policy choices; and (3) Raise awareness among the public and policy makers. We present a generic, empirically based, framework of different environmental monitoring approaches, ranging from scientist-driven to those undertaken by local people. This framework is used to assess monitoring possibilities for the Convention on Biological Diversity "2020" indicators, and those of 11 other international environmental agreements. Of the 186 indicators in these 12 environmental agreements, 69 (37%) require monitoring by professional scientists, whereas 117 (63%) can involve community members as "citizen scientists." Promoting "community-based" and "citizen science" approaches could significantly enrich monitoring progress within global environmental conventions. It would also link environmental monitoring to awareness raising and enhanced decision-making at all levels of resource management.

Introduction

There is broad international agreement that a better understanding is required of global status and trends in species, habitats, and ecosystem services (Butchart *et al.* 2010; Intergovernmental Platform on Biodiversity and Ecosystem Services 2013). Similarly, decision makers—from international to local—require a better understanding of progress in environmental initiatives and agreements (Mace & Baillie 2007). Moreover, because knowledge alone is insufficient to affect environmental change (Walker *et al.* 2009), changes in human attitudes and behavior are required to facilitate the achievement of environmental goals (Ehrlich & Kennedy 2005).

In response to the global environmental crisis, several hundred international environmental agreements have been adopted by countries around the world (Mitchell 2003). These induce countries to change policies, and some have delivered major improvements by reducing environmental problems such as acid rain in Europe, the frequency of oil spills, the release of ozone depleting gases, and international trade in threatened wildlife (Kanie 2007). One key environmental agreement is the Convention on Biological Diversity (CBD), which is intended to encourage governments to reverse declines in species and habitats and maintain the benefits to people from wild nature (Convention on Biological Diversity 2013). Failure of countries to achieve the CBD 2010 targets led the 10th Conference of the Parties to the CBD (October 2010) to adopt a revised plan for tackling biodiversity loss, which included 20 stronger, more comprehensive, more explicit, and more measurable targets for 2020 (Aichi biodiversity targets; United Nations Environment Programme [UNEP] & CBD 2010).

The new targets require indicators that can be monitored to track progress, and the process to develop these indicators has been initiated (UNEP, CBD 2010; Pereira *et al.* 2013). Structured frameworks of indicators assist the interpretation and presentation of results (Walpole *et al.* 2009), with the most widely used indicator framework being the "pressure, state, and response" framework of the Organization for Economic Cooperation and Development (OECD 1998). A slightly modified version has been proposed to organize indicators and reporting on the achievement of the 2020 targets to the CBD (Sparks *et al.* 2011).

Most indicators are developed assuming that data will be collected, interpreted, and analyzed by professional scientists. Involving local people in the collection and even interpretation of environmental data could, however, have many positive benefits, as demonstrated by the schemes known as "citizen science" (Shirk *et al.* 2012) or "community-based monitoring" (Fry 2011). Local stakeholder involvement would not only leverage effort in data collection (Possingham *et al.* 2012) but also enhance public engagement in addressing shared global concerns. The process of engaging many actors in the collection of monitoring data to measure different indicators could transform international agreements to instruments *of* change and processes *for* change (Walker *et al.* 2009).

Our past work used expert opinion to suggest that environmental monitoring approaches range from scientist-executed—with no involvement of local stakeholders—to autonomous local schemes with no involvement of scientists (Danielsen *et al.* 2009). Here, we evaluate whether different types of monitoring approaches, undertaken by a variety of stakeholder groups, can assist in measuring environmental indicators within major international conventions. We develop a framework of approaches to environmental monitoring, using multivariate statistical analysis to segment published monitoring schemes. To test the utility of this framework, we use it to assess data gathering possibilities for all indicators of 12 major international environmental agreements. Finally, we discuss how monitoring approaches that include local people might augment scientist-dominated methods, while also raising environmental awareness among the general public and policy makers.

Methods

Grouping monitoring approaches

We develop a statistically defined typology of environmental monitoring schemes based on 3,454 papers that present monitoring results, published between 1987 and 2012. From these, we identified 126 different schemes that focused on monitoring either species or populations, habitats or ecosystems, or resource use (Appendix S1). For each scheme, we coded 25 clearly distinct parameters that contributed to characterizing the type of scheme and which could be extracted from publications (Table 1). Each scheme was independently coded by two team members; in the few cases where their evaluations disagreed, they reached a conclusion on scoring through discussion. After coding, parameters or schemes with missing data and parameters not logically representing a span of numerical values were excluded from the cluster analysis. Seventeen of the parameters and 107 of the schemes had complete data (Appendixes S2 and S3). We then grouped these schemes using cluster analysis in the Programme R (Appendix S4).

Applying classification of monitoring schemes to international environmental agreements

To examine the utility of the classification of monitoring schemes identified using cluster analysis, we mapped different types onto indicators of 12 major international environmental agreements (see Table 2). The indicators were placed within the seven thematic areas (shown in Table 3) of the CBD work program before 2010, based on the topic of the indicators.

Assignment of monitoring scheme types to indicators was undertaken independently by F.D. and N.D.B. Where we disagreed, consensus was reached through discussion (data in Appendix S5). For each indicator, we assessed if it could be measured: (1) By professional scientists without involving local stakeholders; (2) By professional scientists with involvement of local stakeholders as data collectors; (3) By local stakeholders who collect, process, and interpret the data and present findings to indicator initiators or decision makers based on an original initiative to set up monitoring that was undertaken by outsiders; or (4) By

Table 1 Parameters assessed for each published environmental monitoring scheme in order to develop the statistically defined framework of environmental monitoring approaches

	Topic of parameter	Options
	Before the monitoring	
a1	Initiative to monitor taken by	Who took the initiative[a]
a2	Objective of the monitoring: money or livelihood value?	Was the monitoring intended to increase the provision of food, water or income? 1) Yes 2) No
a3	Objective of the monitoring: ethical or esthetic value?	Was the monitoring intended to increase ethical or esthetic values? 1) Yes 2) No
a4	Climate of the area of the monitoring scheme (if the scheme covered >1 climatic zone, we listed the dominant climatic zone, in terms of area)	1) Polar 2) Temperate 3) Tropical
a5	Biome of the area of the monitoring scheme (if the scheme covered >1 biome, we listed the dominant biome, in terms of area)	1) Marine 2) Limnic 3) Terrestrial
a6	Continent of the area of the monitoring scheme	1) North America 2) Central/South America 3) Europe 4) Africa 5) Asia 6) Pacific 7) Australia 8) Antarctica
a7	Gross national income (GNI) per capita of the country of the monitoring scheme at the time of the assessment[b]	1) GNI per capita USD 2,570 or more[c] 2) GNI per capita <USD 2,570
a8	Land-tenure system of the area of the monitoring scheme (if the scheme was undertaken in an area with >1 land-tenure system, we listed the dominant land-tenure system, in terms of area or time)	1) Protected area under government authority 2) Protected area managed (partially or fully) by the local communities 3) Outside of protected areas
a9	Number of community members involved, or believed to be involved, in the monitoring scheme	1) >100 2) 50–100 3) 10–49 4) 1–9 5) 0
a10	Total size of area monitored by the monitoring scheme	1) 100,000 ha or more 2) 50,000–99,999 ha 3) 10,000–49,999 ha 4) 5,000–9,999 ha 5) 1–4,999 ha
a11	How much equipment was used to collect the data in the monitoring scheme?	1) People with >1 piece of mechanical scientific equipment 2) People with 1 piece of mechanical scientific equipment (e.g., binoculars, professional hand net, measure string) 3) People with no scientific equipment
a12	Attributes monitored by the monitoring scheme	1) >1 taxonomic group/resource 2) One taxonomic group/resource (e.g., fish)
a13	Spatial sampling scale of the monitoring scheme	1) International or largely international 2) Country or largely country 3) Village/catchment/protected-area, or largely village/catchment/protected-area
	During the monitoring	
b1	The monitoring scheme was funded by (recurrent costs; not including training)	Who paid for the monitoring[a]
b2	The monitoring scheme was designed by	Who designed the monitoring[a]
b3	The data collection in the monitoring scheme was undertaken by	Who collected the data[a]
b4	The data processing in the monitoring scheme was undertaken by	Who prepared the data for analysis[a]
b5	The data interpretation in the monitoring scheme was undertaken by	Who interpreted the results[a]
b6	The presentation of the findings from the monitoring scheme was presented to decision makers by	Who presented the findings to decision makers[a]

Continued

Table 1 Continued

	Topic of parameter	Options
	After the monitoring	
c1	Decision-making	Who took (or were expected to take) decisions on the basis of the findings from the monitoring scheme[a]
c2	Implementation of decisions	Who carried out (or were expected to carry out) the management interventions emanating from the monitoring scheme[a]
c3	Scale of management impact	On which spatial scale did the management interventions impact[a]
c4	Policing	Who checked (or were expected to check) that the management interventions were being undertaken[a]
	Other information	
d1	Number of years of monitoring at the time of the assessment	1) >10 2) 5–10 1) <5
d2	Start year of the monitoring scheme (year)[d]	1) <1940 2) 1940–49 3) 1950–59 4) 1960–69 5) 1970–79 6) 1980–89 7) 1990–99 8) 2000–2009

[a]One of the following four options was used: (1) entirely external (national or international level); (2) more than 50% external (national or international level); (3) more than 50% internal (village or district level); and (4) entirely internal (village or district level).
[b]Source: World Bank (2012).
[c]Monitoring schemes in Antarctica were included in this category.
[d]For monitoring schemes that started a century or more ago, we used "<1940."

local stakeholders who set up the monitoring schemes and undertake the whole monitoring process, from design, to data collection, to analysis, and finally to use of data for management decisions on their own without any involvement of professional scientists. The criteria are not mutually exclusive and some indicators received multiple scores. To assess our own scoring, we also asked 13 experts from around the world (Appendix S1) to independently assign the monitoring scheme types to a random sample of 12.5% of the 186 indicators (Appendix S6). For every indicator, we also assessed the main constraints, if any, to the involvement of local stakeholders (Appendix S5). Finally, we determined for each indicator whether we knew of specific examples of monitoring schemes in which the indicator had been populated with data, as a measure of our certainty in the coding assigned.

For the assessment of the indicators of international environmental agreements, we defined monitoring as "the process of gathering information about state variables at different points in time for the purpose of drawing inferences about changes in state" (Yoccoz *et al.* 2001). Indicators, then, are "a metric that represents that state" (Jones *et al.* 2011). We defined local stakeholders as "local resource users, local government staff or amateur naturalists." We defined citizen science as "scientific research that use volunteers in data collection," and community-based monitoring as "monitoring of natural resources undertaken by local stakeholders using their own resources and in relation to aims and objectives that make sense to them."

Results

Our cluster analysis of 17 parameters among 107 monitoring schemes with complete data identifies a framework of monitoring approaches with five major types of monitoring schemes (Figure 1; Appendix S4). The most distinct monitoring schemes are within monitoring scheme type A (Figure 1) and have two unique characteristics: (1) Local stakeholders took the initiative to set them up and (2) They are fully financed locally: scientists are not involved. These schemes include, for example, monitoring in "customary" (Cinner & Aswani 2007) management regimes in the Pacific (Johannes 1998). The second most distinct group is monitoring scheme type B (Figure 1). In these schemes, the original initiative was taken by scientists but local stakeholders collect, process, and interpret the data. An example is the fishermen's and hunters' monitoring of coastal resources in Greenland (Danielsen *et al.* in press). The third most distinct group is monitoring scheme type C (Figure 1). These schemes were designed by scientists who also analyze the data, but

Table 2 Proportion of indicators across 12 international environmental agreements that are suitable for monitoring using monitoring schemes of type A, B, C-D, and E of our framework. The table also shows the proportion of indicators that, for different reasons, are constrained in involving local stakeholders in their measurements, and, in addition, our confidence in the coding

		[b]Suitable monitoring approach				Constraints to local stakeholder involvement					
International agreement[a]	Indicators (*n*)	E, Scientist-executed monitoring[c] (%)	C-D, Collaborative monitoring with external data interpretation/externally driven monitoring with local data collectors[d] (%)	B, Collaborative monitoring with local data interpretation[e] (%)	A, Autonomous local monitoring[f] (%)	Area-based data required[g] (%)	National overview required[h] (%)	Legislative knowledge required[i] (%)	Data required from museums and herbaria (%)	Technically difficult[j] (%)	Certainty[k] (%)
AEWA	13	100	69	46	15	8	62	85	0	38	100
CBD	20	95	75	60	30	30	45	50	25	85	100
CBMP[l]	19	100	79	68	37	32	32	16	0	79	95
CITES	20	100	35	10	0	0	95	80	0	35	93
CMS	2	100	0	0	0	0	0	0	0	100	100
IOSEA	17	94	94	82	41	6	12	18	6	47	97
OECD	15	100	67	40	27	13	27	33	0	87	100
Ramsar	10	100	60	50	10	10	50	30	0	70	100
SEBI	26	100	81	62	35	15	27	35	12	69	83
UNCCD	28	100	29	21	14	25	64	68	0	25	98
UNFCCC	9	100	56	11	11	11	0	0	11	100	39
WHC	7	100	71	14	14	0	86	43	0	29	79
Total	186	99	63	44	23	16	45	44	5	59	92

[a]AEWA, Agreement on the Conservation of African-Eurasian Migratory Waterbirds; CBD, Convention on Biological Diversity; CBMP, Circumpolar Biodiversity Monitoring Program; CITES, Convention on International Trade in Endangered Species; CMS, Convention on Migratory Species; IOSEA, Indian Ocean—South-East Asian Marine Turtle Memorandum of Understanding; OECD, Organization for Economic Cooperation and Development; Ramsar, Convention on Wetlands of International Importance; SEBI, Streamlining European 2010 Biodiversity Indicators; UNCCD, United Nations Convention to Combat Desertification; UNFCCC, United Nations Framework Convention on Climate Change; and WHC, World Heritage Convention.

[b]The nomenclature for the subgroups of environmental monitoring schemes is modified from Danielsen *et al.* (2009).

[c]By professional scientists without involving local stakeholders.

[d]By professional scientists with involvement of local stakeholders as data collectors.

[e]By local stakeholders who collect, process, and interpret the data and present findings to indicator initiators or decision makers.

[f]By local stakeholders on their own without involving professional scientists.

[g]Requires area-based or remote sensing-based data.

[h]Requires a national or supranational overview.

[i]Requires knowledge of administrative, legislative, policy, regulatory, or managerial aspects.

[j]Difficult to monitor technically or analytically.

[k]The proportion of indicators (averaged between the two evaluators) where we personally knew of specific, or closely related, examples of monitoring schemes in which the indicators had been populated with data. This was used as a measure of our confidence in the coding we had provided.

[l]For this study, we consider CBMP an international agreement.

Table 3 Proportion of indicators among 12 international environmental agreements across seven thematic areas that are suitable for monitoring schemes of type A, B, C-D, and E. The table also shows, for each thematic area, the proportion of indicators which, for different reasons, are constrained in involving local stakeholders in their measurements, and our confidence in the coding

		Suitable monitoring approach[a]				Constraints to local stakeholder involvement					
Thematic area	Indicators (*n*)	E, Scientist-executed monitoring[b] (%)	C-D, Collaborative monitoring with external data interpretation/externally driven monitoring with local data collectors[c] (%)	B, Collaborative monitoring with local data interpretation[d] (%)	A, Autonomous local monitoring[e] (%)	Area-based data required[f] (%)	National overview required[g] (%)	Legislative knowledge required[h] (%)	Data required from museums and herbaria (%)	Technically difficult[i] (%)	Certainty[j] (%)
Status of and trends in the components of biodiversity	28	100	68	46	21	32	54	32	14	93	100
Sustainable use	17	100	71	59	41	29	41	47	0	76	97
Threats to biodiversity	8	100	63	63	50	13	0	38	38	88	88
Ecosystem integrity and ecosystem goods and services	17	100	94	76	35	29	18	0	0	88	94
Status of traditional knowledge, innovations, and practices	3	67	100	100	33	0	0	33	0	33	83
Status of access and benefit-sharing	2	100	50	50	0	0	50	100	50	50	50
Status of resource transfers	10	100	50	30	10	0	70	60	0	0	95
Other thematic area	101	99	56	34	17	9	50	52	2	47	90
Total	186	99	63	44	23	16	45	44	5	59	92

[a]The nomenclature for the subgroups of environmental monitoring schemes is modified from Danielsen *et al.* (2009).
[b]By professional scientists without involving local stakeholders.
[c]By professional scientists with involvement of local stakeholders as data collectors.
[d]By local stakeholders who collect, process, and interpret the data and present findings to indicator initiators or decision makers.
[e]By local stakeholders on their own without involving professional scientists.
[f]Requires area-based or remote sensing-based data.
[g]Requires a national or supranational overview.
[h]Requires knowledge of administrative, legislative, policy, regulatory, or managerial aspects.
[i]Otherwise difficult to monitor technically or analytically.
[j]The proportion of indicators (averaged between the two evaluators) where we personally knew of specific, or closely related, examples of monitoring schemes in which the indicators had been populated with data.

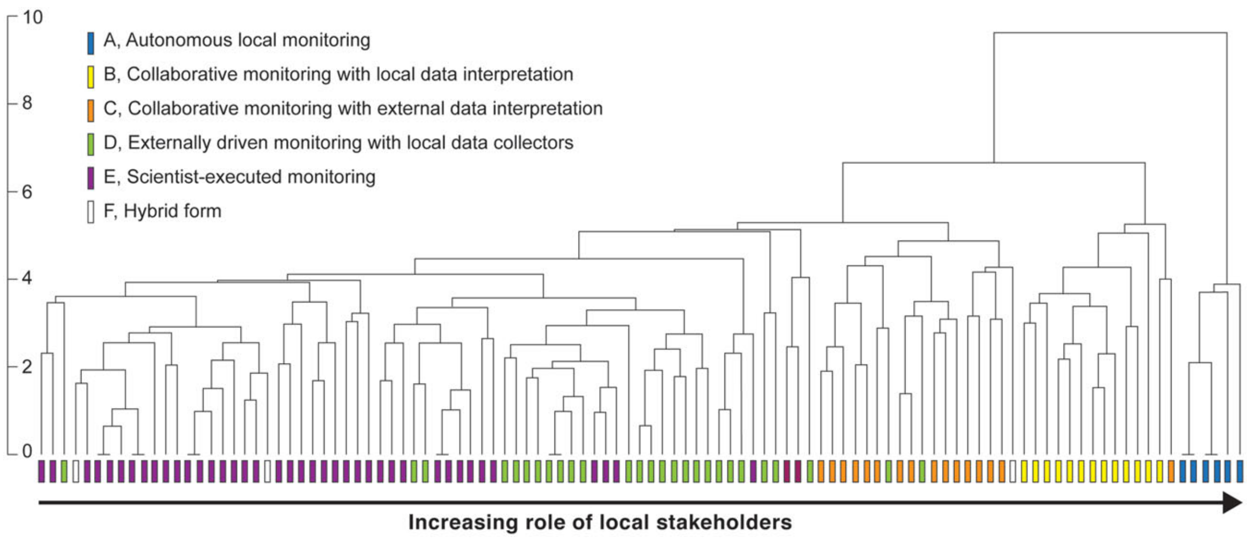

Figure 1 Dendrogram of environmental monitoring schemes, based on a cluster analysis of 17 parameters among 107 schemes published between 1987 and 2012. The relative role of local stakeholders in the monitoring schemes increases from left to right between the five types of monitoring schemes. The nomenclature for the types of environmental monitoring schemes is modified from Danielsen *et al.* 2009.

the local stakeholders collect the data, take decisions on the basis of the findings, and carry out the management interventions emanating from the monitoring scheme. These schemes include, for example, monitoring of shallow tropical marine fisheries in Kenya (Obura 2001). The least distinct clusters are monitoring scheme type D and E (Figure 1). In type D, local stakeholders are involved in data collection, but other activities are carried out by professional scientists. Examples of schemes of monitoring scheme type D include volunteers' monitoring of coral reefs in the Gulf of Mexico (Pattengill-Semmens & Semmens 1998) and other "citizen science" schemes (Shirk *et al.* 2012). In monitoring schemes of type E, all aspects of the monitoring are undertaken by professional scientists, without involvement of local stakeholders. The five types of monitoring scheme outlined are not mutually exclusive, and hybrid models exist (Figure 1; Appendix S2). The most important parameters in the clustering were who took the original initiative to set up the monitoring schemes, who funded them, who collected the data, who processed and interpreted the results from the monitoring, and who carried out the management interventions emanating from the monitoring.

While monitoring scheme types A and E are easy to distinguish, types B, C, and D may superficially resemble each other as they all involve scientists and local stakeholders. They are different in practice, however. Monitoring schemes of type D are mostly long-running "citizen science" projects (34.6% >10 years; $n = 26$) from Europe and North America (70.4%; $n = 27$). In contrast, most of the schemes of type B and C have been in operation for a short time (<10 years; B: 100%, $n = 13$; C: 85.7%, $n = 14$), are located in the tropics (B: 92.3%, $n = 13$; C: 62.5%; $n = 16$), are more "participatory" (Chambers *et al.* 1989) in character, and typically developed as part of "adaptive management" (Berkes *et al.* 2000).

Regarding issues addressed by different monitoring approaches, the five types of monitoring schemes address different issues (Figure 2a, b). Monitoring scheme type A, B, and C generally monitor products that support local livelihoods (e.g., food, building materials, fuel, water, income) ($P < 0.01$). Conversely, monitoring schemes of type D and E collect data relevant to the conservation of threatened species or populations ($P < 0.01$). Governance also varies between different approaches (Figure 2c). Scientist-executed schemes are located in protected and nonprotected areas (type E schemes; $n = 42$), whereas autonomous local schemes are all located in nonprotected areas (type A schemes; $n = 6$). Monitoring schemes of type C and D are mainly located in nonprotected areas, and schemes of type B are equally distributed in nonprotected areas or in reserves managed by local communities or government (monitoring scheme types B, C, and D; $n = 13$, 16, and 27; respectively).

When applied to the indicators of international environmental agreements, almost all (99%) of the 186 indicators can be measured by professional scientists without involving local stakeholders (Table 2); our type E. At the other extreme, 23% of the indicators can be measured by local stakeholders autonomously without any involvement of professional scientists (Table 2); our type A. However, because type A schemes are self-established

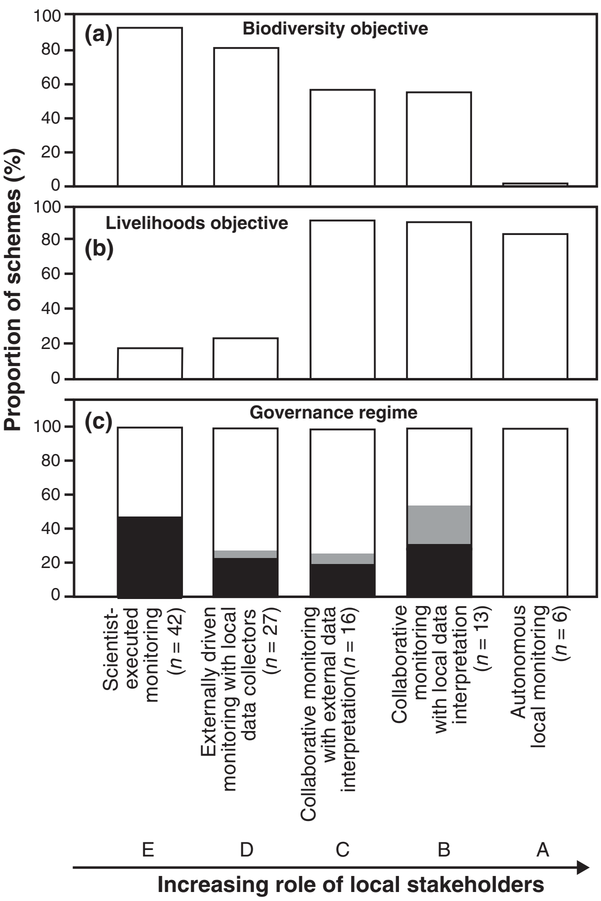

Figure 2 The proportion of published environmental monitoring schemes within each type of monitoring scheme that have a biodiversity (a) or livelihoods (b) objective; and the types of governance regime (c) they operate within, including areas without protection status (white), government-managed protected areas (black), and community-managed protected areas (shaded). The relative role of local stakeholders in the monitoring schemes increases from left to right.

and managed, they would be unlikely to provide data for tracking international environmental agreements.

Our assessment suggests that 63% of the indicators could benefit from local stakeholder involvement in data collection (type C-D schemes; $n = 186$), whereas for 44% of the indicators, local stakeholders might contribute data *and* analysis (type B schemes; $n = 186$; see Table 2). For 92% of the indicators, we could name specific or closely related examples of monitoring schemes ($n = 186$; Table 2), which we interpreted as supporting our results. Thirteen experts, who also assigned our monitoring scheme types to a random sample of the indicators, were in fair agreement with our assignments of suitable monitoring approaches (Kappa coefficient $\kappa = 0.39$; $n = 92$; Appendix S6).

Our assessment of the main constraint to local stakeholder involvement in monitoring international agreements is that much of the work is technically difficult, or requires analytical skills; this relates to 59% of the indicators (Table 2). Another common constraint is that the indicator requires a national overview (45%), or a detailed knowledge of administrative or regulatory aspects in the country (44%). Less frequent constraints are dependence on area-based or remote sensing approaches (16%), or data from museums or herbaria (5%). Our 13 independent experts were in fair agreement with our identification of main constraints to local stakeholder involvement in monitoring the indicators of international agreements ($\kappa = 0.27$; $n = 115$; Appendix S6).

Comparing indicators of environmental agreements with our empirically derived monitoring framework reveals one topic that is particularly suitable to local stakeholder involvement: "ecosystem integrity and ecosystem goods and services" (Table 3). Almost all (94%) indicators of this topic are suitable for local stakeholder involvement in data gathering and most (76%) are suitable for local involvement in data analysis ($n = 17$; Table 3). Making the indicators more appropriate for local stakeholder involvement would require adjusting them to address the challenges: (1) they are technically or analytically demanding (88%; $n = 17$) and (2) they cannot be measured without area-based or remote sensing-based data (29%; $n = 17$; Table 3).

Organizing the 186 indicators of the 12 environmental agreements within the "pressure, state, response" framework (Sparks *et al.* 2011) suggests that indicators of "status" and "pressure" are particularly suitable for data gathering by local stakeholders (80%; $n = 61$; and 71%; $n = 31$; respectively; Appendix S7). Most are also suitable for local stakeholder involvement in data analysis (61%; $n = 61$; and 52%, $n = 31$; respectively; Appendix S7).

Discussion

Our analysis shows that published environmental monitoring schemes range from entirely local efforts—with all the work undertaken by local people—to efforts where monitoring and analysis are undertaken solely by professional researchers. Within this range, schemes fall into five categories defined by the degree of scientist and local participation in scheme design, data collection, data analysis, and implementation of management interventions. Other characteristics, such as the Gross National Income of the country concerned, are not defining parameters.

Despite strong efforts to be objective in this work, some areas remained subjective. These included our selection of parameters for clustering, and the accuracy of data extraction from publications. We also relied on the peer-reviewed literature, which may underestimate small-scale local and volunteer-based efforts and are probably biased toward large, well-funded schemes.

Our empirically based, statistical analysis corroborates all five categories previously identified by "experts" (Danielsen *et al.* 2009). The five categories of environmental monitoring schemes show similarities with categories of public participation described in the literature on "community development" (Arnstein 1969; White 1996; Pretty & Hine 1999). Such classifications tend to range from fully local stakeholder-driven approaches to externally led interventions with very little or no local participation. Most monitoring schemes are established to achieve either social or environmental objectives, but schemes of category B and C often aim at attaining both objectives. A major difference exists between the categories of monitoring schemes in terms of why the information is being sought and who are the end-users of the information (Staddon *et al.* 2012). Schemes of the participatory categories (A, B, and C) are mainly "monitoring for participants" to improve their livelihoods (Figure 2). Conversely, scientist-led schemes (type D and E) are "monitoring for others" to protect biodiversity. A clear focus on who and what the monitoring is for may help to avoid establishment of schemes that fall apart when scientists depart by ensuring that the monitoring is of specific value to specific people (Staddon *et al.* 2012).

Jones *et al.* (2011) proposed that the most important global environmental monitoring objectives are: (1) To evaluate conservation management actions; (2) To inform policy choices; and (3) To raise awareness among the public and policy makers of sustainable development. Meeting these objectives requires careful choice of environmental indicators and a clear understanding of the best ways of collecting data to populate them. A major challenge for delivering international environmental agreements is that of linking the agreements to decision-making on the management of natural resources in the "real world." Past lessons suggest that use of "lay" knowledge can help governments and civil society address environmental problems at early stages (Harremoës *et al.* 2001). Empirical studies and reviews of the scientific literature also suggest that involving local stakeholders in monitoring the environment can not only raise awareness among the public and policy makers about sustainable development (e.g., Funder *et al.* in press) but also—crucially—enhance management responses and improve the speed of decision-making to tackle environmental trends at operational levels of resource management (Danielsen *et al.* 2010; Tidball & Krasny 2012).

To inform discussions on investments in effective monitoring of environmental agreements, we compared the

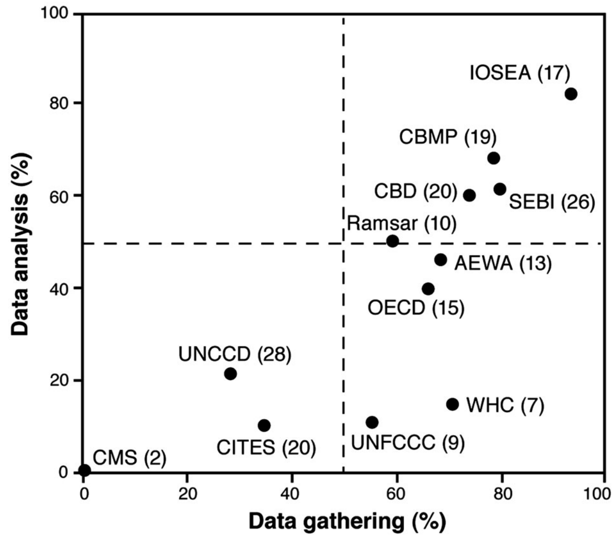

Figure 3 Proportion of indicators from 12 international agreements that are suitable for local stakeholder involvement in data gathering (*x*-axis) and data analysis (*y*-axis). For each agreement, the *x*-axis plots the proportion of indicators that can be measured by professional scientists with the involvement of local stakeholders as data collectors. This indicates the extent to which the agreement is amenable to being monitored by monitoring schemes of type C-D of our framework. The *y*-axis plots the proportion of indicators that can be measured by local stakeholders, who not only collect data but also process and interpret the data and present the findings to decision makers. This indicates the extent to which the agreement is amenable to being monitored by monitoring schemes of type B of our framework. The dashed cross lines indicate 50% values for each axis. Environmental agreements with high values on both axes are most amenable to monitoring approaches with local stakeholder involvement. The number of indicators of each agreement is shown in brackets. For the abbreviations of the international agreements, see Table 2.

proportions of indicators suitable for monitoring schemes of type B and C-D. We classified the environmental agreements into three categories (see the quadrants in Figure 3). Agreements in the upper right quadrant are those that are most suited to involving local stakeholders in *both* collecting and analyzing monitoring data. These agreements are on marine turtle conservation (IOSEA, for abbreviations, see Table 2) and on monitoring biodiversity in Europe (SEBI), the Arctic (CBMP) and globally (CBD). Despite the suitability of these four agreements for local stakeholder-led monitoring, some of their indicators are technically or analytically demanding (Table 2). Environmental agreements in the lower right quadrant are suited to involving local stakeholders in collecting but *not* in analyzing data. These agreements are WHC, AEWA, OECD, Ramsar, and UNFCCC although, for UNFCCC, our assessment is subject to uncertainty (Table 2). Environmental agreements in the lower left quadrant are least suited to involving local stakeholders in collecting or

Table 4 Examples of indicators of international environmental agreements that are either amenable or not amenable to involvement of local stakeholders in their monitoring

		Examples of indicators	
International agreement[a]	Coverage	That are amenable to involvement of local stakeholders in their monitoring	That are *not* amenable to involvement of local stakeholders in their monitoring
AEWA	Old World	"Trends in waterbird populations"	"€100,000 annually disbursed to developing countries to help implement AEWA"
CBD	Global	"Anthropogenic pressures on coral reefs"	"Biodiversity values have been integrated into poverty reduction strategies"
CBMP	Arctic	"Human Well-being Index"	"Land Cover Change Index"
		"Trends in availability of biodiversity for traditional food"	"Trends in extent of biomes, habitats, and ecosystems"
		"Trends in incidence of pathogens and parasites in wildlife"	"Coverage of protected areas"
		"Trends in phenology"	"Extent of seafloor destruction"
CITES	Global	"Number of cases where CITES regulation has had positive impact on conservation status of species"	"Number of annual export quotas based on population surveys"
IOSEA	Indian Ocean[b]	"Marine turtle population trends, and debris near turtle habitats"	"Genetic identity of marine turtle populations"
OECD	Global	"Fish catch"	"Ozone layer depletion"
		"Intensity of use of water and forest resources"	"Acidification via NOx and SOx emission"
		"Urban environmental quality"	"Toxic contamination by heavy metals and organic compounds"
Ramsar	Global	"Status and trends of waterbird biogeographic populations"	"Status and trends in wetland ecosystem extent"
SEBI	Europe	"Freshwater quality"	"Ecosystem coverage"
		"Forest deadwood"	"Critical load exceedance for nitrogen"
		"Invasive alien species in Europe"	"Ecological Footprint of European countries"
		"Marine Trophic Index of European seas"	"Patent applications based on genetic resources"
UNCCD	Global	"Area of forest under sustainable management"	"Number of countries implementing action plans"
UNFCCC	Global	"Biomass" (e.g., above-ground woody biomass of tropical forests)	"Leaf Area Index"
		"Ocean colour for biological activity"	"Fraction of absorbed photosynthetically active radiation"
		"Sea ice, and snow cover"	"Upper air temperature"

[a] Abbreviations in Table 2.
[b] Africa, Asia, and Australia.

analyzing data for measuring their indicators. These are CITES, UNCCD, and CMS (although CMS has only two indicators). For the agreements in the two lower quadrants, the main constraint to involving local stakeholders is that many of the indicators require a national overview and detailed knowledge of legislative aspects in the countries concerned to be effectively monitored (Table 2).

Our analysis of indicators from environmental agreements suffers from the flaws of using experts to think of examples (Sutherland *et al.* 2004). Although our own assessment of a sample of the indicators obtained the highest Kappa coefficient and thus was the most representative of all the expert assessments, there was only fair agreement between our assessment and the 13 independent assessments, suggesting that individual interpretation of the indicators may have influenced how we coded them (Appendix S6). We found the greatest divergence in individual interpretation for those indicators that were not clearly formulated. In many cases, the indicators are broad headlines without specified metrics. We also assume that the 12 international environmental agreements we examined are representative of international agreements, although other agreements may be more "bottom-up" (e.g., Partnership for the East Asian-Australasian Flyway 2013). We did not evaluate local or subnational environmental policies, which might have more potential for public involvement. Finally, for most of the indicators that are amenable to local stakeholder involvement in monitoring, local stakeholder measurements would be unlikely to stand alone. In most cases, they would need to be used in conjunction with scientist-executed measurements. Nevertheless, our findings demonstrate that, under the present work plans of many international environmental agreements, there is considerable opportunity for involving local stakeholders in collecting relevant data. Table 4 provides examples

Table 5 Recommendations for NGOs, government agencies, and scientists to help link public participation in scientific research to the indicators and needs of international environmental agreements

Proposed responsible	Proposed action
NGOs and the "citizen science community"	Identify what types of data are not being collected by "citizen science" and "community monitoring" initiatives. Identify what projects the field would need for more comprehensive monitoring of international environmental agreements. Develop list of needed projects for potential donors.
Government agencies and multilateral organizations	When selecting and developing environmental indicators, make sure you have a clear understanding of how the indicators are going to be measured and by whom. Undertake cost-benefit analyses of local stakeholder engagement versus expert approaches to monitoring of indicators. If you aim for local stakeholder involvement in monitoring indicators, avoid indicators that require a national overview or detailed knowledge of administrative or legislative aspects. See examples in Table 4.
Scientists	Develop a new field of research that predicts, and test predictions about, the benefits of environmental monitoring with varying degree of local participation (Possingham *et al.* 2012).

of indicators that are amenable and not amenable to involvement of local stakeholders in their monitoring. The topic "ecosystem integrity and ecosystem goods and services" is probably particularly suitable to local involvement because in many areas, the local communities heavily depend on tangible products like food provided by the natural ecosystems.

As 63% of the existing indicators we examined are suitable for some form of "citizen science" (Shirk *et al.* 2012) or "community-based monitoring" (Fry 2011), this has potential to help international environmental agreements to raise awareness among participants at local, national, and international scales. Efforts to mobilize and maintain a large "citizen science" or "community-based" initiative can, however, be costly and time-consuming. Some indicators are best suited to expert-driven assessment. Great care is therefore needed when developing indicators. To aid this process, we propose a series of recommendations (Table 5). A few agreements, such as the Ramsar Convention on Wetlands of International Importance, already use thousands of volunteers around the world to collect required data on bird populations (Kuijken 2006), which helps to populate the "status and trends of waterbird biogeographic populations" indicator (Appendix S5). In addition, eBird, a project managed at the Cornell Lab of Ornithology, now collects more than 3 million checklists of birds from observers around the globe each month that can be used in a variety of indicators focused on bird populations (Cornell Lab of Ornithology & National Audubon Society 2013). Similarly, a network of volunteers monitors coral reefs worldwide to collect the data required to populate the CBD indicator "anthropogenic pressures on coral reefs [. . .] are minimized, so as to maintain their integrity and functioning" (WordFishcenter 2008).

In conclusion, our findings suggest that promoting "community-based" and "citizen science" approaches could significantly enrich the monitoring of progress toward the indicators of the CBD and many other global conventions. It would also link environmental monitoring to awareness raising and enhanced decision-making at all levels of resource management.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Appendix S1. Description of the methods.

Appendix S2. Matrix of the 107 published environmental monitoring schemes scored across 25 parameters.

Appendix S3. Reference list of the published environmental monitoring schemes that were used to develop our statistically defined typology of monitoring approaches.

Appendix S4. Dendrogram of environmental monitoring schemes, based on cluster analysis of 17 parameters among 107 schemes published between 1987 and 2012 showing the identity of each scheme.

Appendix S5. The data set of 186 indicators within the 12 international environmental agreements.

Appendix S6. Results of 13 experts' independent assignment of our environmental monitoring scheme types to a random sample of 12.5% of the indicators of the 12 international environmental agreements.

Appendix S7. Proportion of indicators among 12 international environmental agreements across the "pressure, state, and response" framework that are suitable for monitoring approaches of type A, B, C-D, and E.

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