

Biodiversity Monitoring For Natural Resource Management

An Introductory Manual

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LIST OF ABBREVIATIONS

ANSAB	Asia Network for Sustainable Agriculture and Bioresources
BBOP	Business and Biodiversity Offset Programme
BM	Biodiversity Monitoring
CBD	Convention on Biological Diversity
CITES	Convention on International Trade in Endangered Species of Wild Fauna and Flora
CMS	Convention on the Conservation of Migratory Species of Wild Animals
COP	Conference of Parties
EMAN	Ecological Monitoring and Assessment Network
ENV	Education for Nature Vietnam
FAO	The Food and Agriculture Organization of the United Nations
GBIF	Global Biodiversity Information Facility
GIZ	Gesellschaft für Internationale Zusammenarbeit
ITPGRFA	International Treaty on Plant Genetic Resources for Food and Agriculture
IUCN	International Union for the Conservation of Nature
LIDAR	Light Detection And Ranging
M&E	Monitoring and Evaluation
METT	Management Effectiveness Tracking Tool
NGO	Non-Governmental Organisation
NBSAP	National Biodiversity Strategy and Actions Plan
NTFP	Non-timber forest product
OECD	Organisation for Economic Cooperation and Development
PA	Protected Area
PPP	Public-Private Partnerships
PSR	Pressure-State-Response
PSBR	Pressure-State-Benefit-Response
REDD+	Reducing Emissions from Deforestation and Forest Degradation
SBIA	Social and Biodiversity Impact Assessment
SMART	Sensitive, Specific, Measurable, Achievable, Time-bound
SMART	Spatial Monitoring and Reporting Tool
SNRD	Sector Network Rural Development
TEEB	The Economics of Ecosystems and Biodiversity
TRA	Threat Reduction Assessment
UNEP	United Nations Environment Programme
UNFCCC	UN Framework Convention on Climate Change
WHC	World Heritage Convention



1. INTRODUCTION

1.1. Scope of this Document

The monitoring of biological diversity (biodiversity) is in increasing demand in the international development sector, as the key role of biodiversity in securing livelihoods through the provision of basic goods and ecosystem services is increasingly acknowledged. Meanwhile, the rapid global growth of conservation schemes designed to incentivise communities and other local stakeholders to effectively conserve natural resources has placed new importance on the role of biodiversity monitoring in assessing whether agreements and targets linked to payments are being met [Danielsen et al. 2014].

Practitioners in the sectors of sustainable forestry, agriculture, fisheries and conservation who are confronted with the task of biodiversity monitoring often do not have a background affinity with biodiversity sciences. The internet offers them an overwhelming amount of information, the filtering and gleaning of which can be a time-consuming way of getting a grip of the topic. This brief introduction to biodiversity monitoring aims to provide practical guidance for professionals working towards sustainable management of natural resources, especially in developing countries. It addresses some of the principal questions, issues and pitfalls in biodiversity monitoring and offers carefully selected references for further reading.

1.2. Defining Biodiversity Monitoring

Biodiversity has long been a buzz-word throughout a range of fields, and notions of what biodiversity actually means diverge widely. While some use the term very narrowly to refer to single species or groups of species of outstanding conservation concern or economic significance, others (including most ecologists) relate biodiversity to a much more general and comprehensive context. This is relevant, since diverging definitions often give rise to misconceptions and misunderstandings. Setting clear definitions of biodiversity and of related key terms is therefore an important first step in ensuring that stakeholders efficiently find common ground regarding the objectives and concepts of their biodiversity monitoring. To date, biodiversity is generally defined broadly as including three dimensions: *'diversity within species (genes), between species and of ecosystems'* (CBD, Art. 2), including domesticated plants and animals.

Monitoring, defined as the collection and analysis of repeated observations or measurements to evaluate changes in conditions and progress towards meeting a management objective [Elzinga et al. 2001], can be applied to all three dimensions of biodiversity. However, especially the monitoring of genes has some practical limitations. For example, the measuring of alleles (alternative forms of genes) requires sophisticated and expensive detection systems. It is also now widely recognised that it is not simply numbers of alleles but how they combine in forming multi-locus genotypes that determines effective genetic diversity. Ecosystems are often non-discrete



(with continuous transitional zones, 'ecotones'); hence their definition, number and area are arbitrary to some extent (Boyle 2001). Biological species are somewhat more palpable: they are natural and (mostly) intuitive units that constitute the elementary building blocks of ecosystems and can be assessed relatively easily in the field. Traditionally, measures of species diversity and ecosystem structure are the principal dimensions of biodiversity as such (biodiversity 'state') assessed by many biodiversity monitoring projects, and are also covered here in some more depth (see Appendices). Yet, as outlined below, monitoring programmes should not only consider quantifying biodiversity state but should also include related drivers, pressures, and also managerial, governance and policy responses.

1.3. Why and When Monitor Biodiversity?

Besides the obvious provisioning services (e.g. food, medicine), biodiversity provides a wealth of regulating (e.g. climate regulation, crop pollination), cultural,

and supporting services (maintaining ecosystem functioning; Kumar 2010). Although many of these ecosystem services are not tied to individual species, and many ecosystems may appear richer in species than necessary to sustain ecosystem functioning, individual species do count. Species-rich ecosystems have higher productivity and stability, are more resistant to invasive species and more resilient to global climate change and to natural disasters (e.g. Peterson et al. 1998, Gamfeldt et al. 2013). Importantly, they have higher potential for ecosystem-based adaptation to climate change, which can mitigate immense economic losses. Moreover, the impact of biodiversity loss is believed to be gradual only to a certain critical threshold of ecosystem stress (the 'tipping point') at which ecosystem functions and services collapse.

Monitoring measures of biodiversity and related parameters allows the detection, quantification and forecasting of trends in the state of biodiversity, and to measure compliance with standards and effectiveness of management. It also allows the improvement of understanding of causal relationships between human actions and biodiversity. By **allowing informed decision-making**, monitoring provides a fundamental basis for effective management and governance of biodiversity.

1.4. International Biodiversity Monitoring Commitments

The **Convention on Biodiversity (CBD)** has set a number of targets approved by the states that have signed the convention (Contracting Parties). E.g., at the CBD's 11th Conference of Parties (COP) in Hyderabad (2012), donor countries agreed to double the total biodiversity-related international financial resource flows by 2015 and pledged to maintain or increase these levels until 2020. CBD Art. 6 requires states to develop National Biodiversity Strategies and Actions Plans (NBSAPs) that outline how they intend to fulfil the objectives of the Convention in the light of specific national circumstances. Based on the CBD 2011-2020 Strategic Plan for Biodiversity, which includes the 20 so-called [Aichi Biodiversity Targets](#), each Contracting Party is committed to monitoring and reviewing the implementation of its NBSAP, making use of the set of indicators developed for the Aichi Biodiversity Targets, and to reporting to the COP. Any NBSAP should therefore include actions aimed at measuring the progress toward the Aichi targets. Commitments



pledged in other international conventions likewise demand or suggest national-level biodiversity monitoring, including:

- **Convention on Wetlands ([Ramsar Convention](#)):** identification and monitoring of wetlands of international importance based on clear criteria;
- **Convention on International Trade in Endangered Species of Wild Fauna and Flora ([CITES](#)):** monitoring of international wildlife trade;
- **Convention on the Conservation of Migratory Species of Wild Animals ([CMS](#) or 'Bonn Convention'):** monitoring of populations and trends of selected migratory species;
- **International Treaty on Plant Genetic Resources for Food and Agriculture ([ITPGRFA](#)):** monitoring of genetic impoverishment in agricultural plants (backed by an international database: [Global Information System](#));
- **UN Framework Convention on Climate Change ([UNFCCC](#)):** most notably regarding forest biodiversity co-benefits under REDD+);
- **World Heritage Convention ([WHC](#)):** identification and monitoring of sites of outstanding cultural and natural value.

Most of these conventions have developed specific monitoring guidelines and protocols (e.g. for [Ramsar wetlands](#)). For further information, see the [CBD website](#) or Latham et al. (2014).

Biodiversity monitoring schemes, often developed following commitments made at international level, are ultimately obligations of national governments. This is because biodiversity monitoring aims to inform decision making by agencies of national and local governments. Data gathering is often coordinated by the national statistical agency, with the collaboration of the Ministry of Environment and the input of other governmental agencies (forestry, fishery, agriculture, land use planning, etc.). Alongside governmental bodies, national and international NGOs and research institutions often produce indicators or gather raw data. Developing a biodiversity monitoring scheme therefore often requires good knowledge of a large number of stakeholders and the capacity to engage and cooperate with them.



2. SELECTING SUITABLE INDICATORS

An indicator is commonly defined as a measure based on verifiable data that conveys information about more than itself. In very general terms, the appeal of biodiversity indicators is thus to provide information of broader relevance to biodiversity in a technically and financially feasible fashion. Indicators are routinely linked to specific criteria, especially in forest management ('criteria & indicators'). Criteria define the range of management targets and the essential elements or principles of management. Each criterion thus relates to a key element of management success, and tying indicators to specific criteria helps set up a comprehensive and efficient (targeted) set of indicators.

Any discussion on biodiversity monitoring needs to begin with the question '**what are the ultimate goals**

of our monitoring?'. The choice of suitable indicators is made only *after* agreeing on clear and specific monitoring objectives among key stakeholders.

2.1. Considering Different Indicator Categories

Indicators of biodiversity *state* can be categorised usefully into functional, structural or compositional and according to their organisational levels (**Fig. 1**). However, the classical approach of monitoring biodiversity itself (its *state*, e.g. species abundance or composition, habitat quality or quantity) alone is rarely sufficient to inform management or policy decisions. This is partly because such indicators of state, while documenting changes in biodiversity, rarely yield useful information about the driving factors behind these trends. Monitoring the state of biodiversity is also a costly and long-term task. Given the assumed causal relationship between management targets, specific pressures (or threats, stressors) and the management responses (interventions) designed to mitigate these pressures, the monitoring of pressures and responses allows measurement of progress towards management goals over shorter periods, albeit with lower confidence (Rao et al. 2009; **Fig. 2**).

A useful and widely applied conceptual framework for selecting biodiversity indicators that considers the shortcomings of these approaches is the Pressure-State-Response (PSR) model (OECD 1994). The core message of the PSR framework is that monitoring programmes should never monitor conservation targets in isolation, but should always include the

positive and negative influences on those targets (Richards & Panfil 2011), thus combining indicators of pressures, state and responses wherever feasible. An additional category of biodiversity indicators worth considering are indicators of benefits (CBD 2011; **Box 1**).

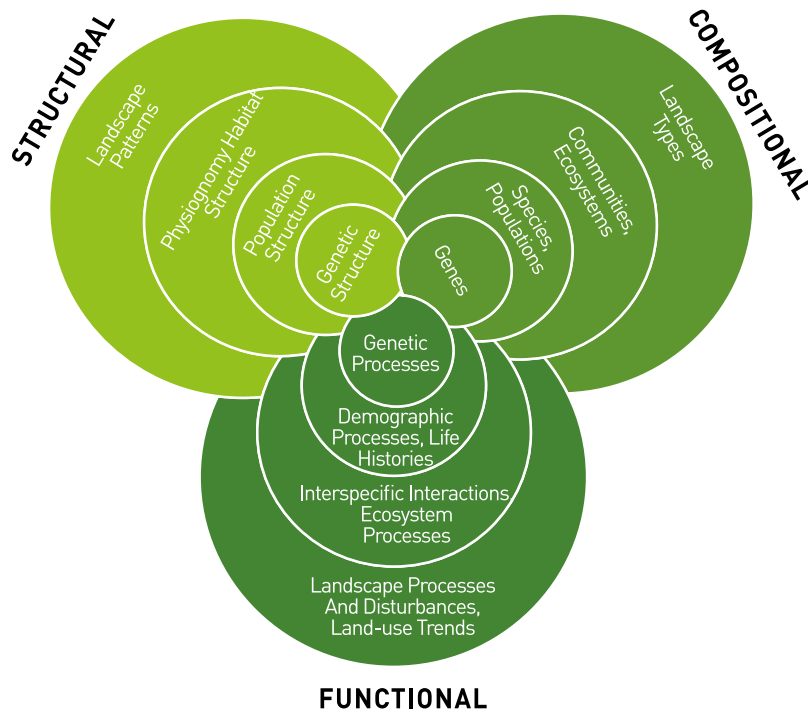


Fig.1. Compositional, structural, and functional components of biodiversity state, each encompassing multiple levels of organisation. This conceptual framework facilitates the selection of state indicators. Structural parameters can often be resource-efficient; e.g. the amount of deadwood of a forest is easy to measure, tends to be well correlated with many biodiversity measures and therefore can serve as a good, simple proxy for ecosystem health. Functional aspects tend to be important for an understanding of processes and cause-effect relationships, and play an important role in basic research and validation monitoring, but less so in implementation and effectiveness monitoring. Source: redrawn after Noss 1990.

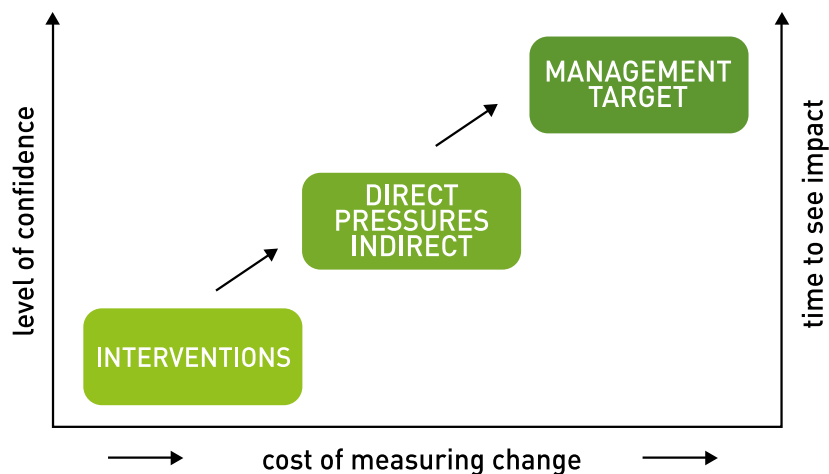


Fig. 2. Trade-offs in costs, time and level of confidence when monitoring project interventions (management responses), pressures or management targets (biodiversity state) themselves. Indirect pressures here refer to ultimate socioeconomic drivers (e.g. population growth) behind direct (proximate) pressures (e.g. overfishing). Source: modified after Rao et al. 2009.

Box 1. Indicator Categories for Adaptive Management

Management strategies and plans are invariably based on assumptions (risks, threats, opportunities, cause-and-effect relationships) that may or may not be correct under certain circumstances, and which change over time. Adaptive management facilitates tackling these inherent uncertainties through an iterative process of informed questioning and readjustment of management strategies based on the results of monitoring. The straightforward concept of adaptive management is thus a regular cycle of planning, implementing and monitoring, ensuring that management is continuously and effectively improved by learning. Closely tied to this concept is the PSR/PSBR framework, which assists in maximising the practical value of indicator sets (Fig. 3).

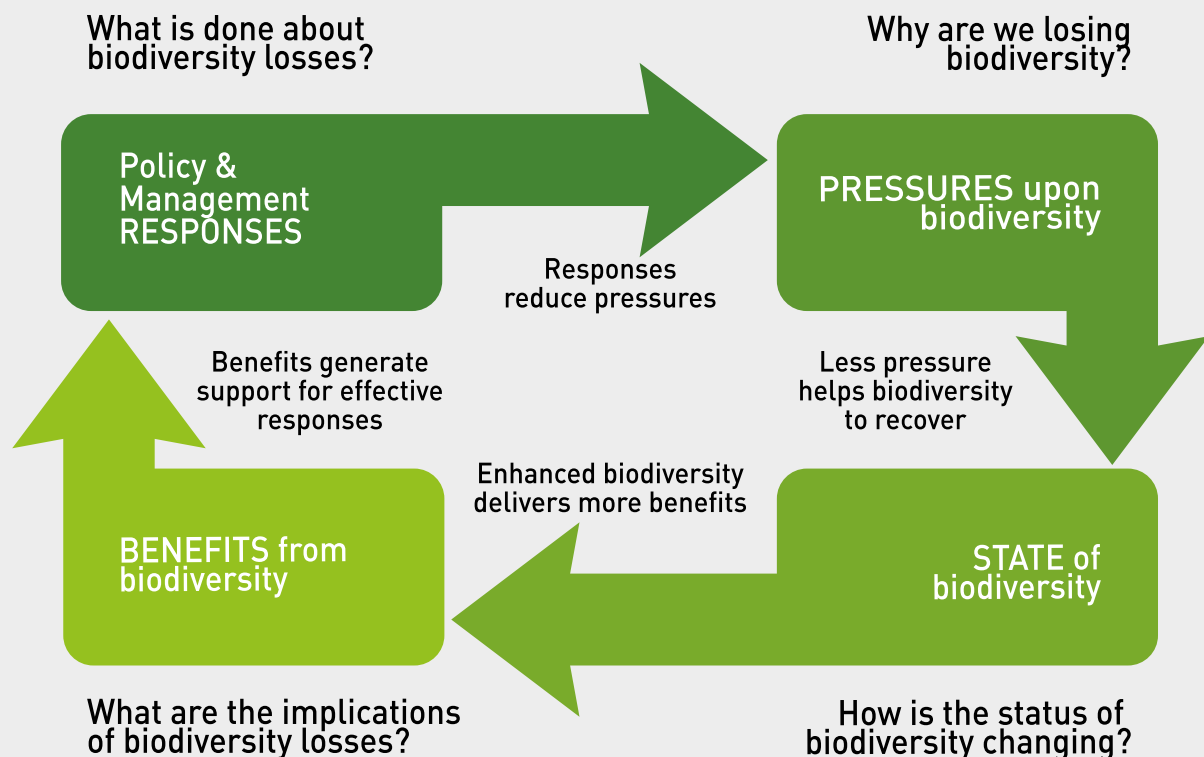


Fig.3. Pressure-State-Benefit-Response (PSBR) model of biodiversity indicator types (modified after Sparks et al. 2011). Indicators include, e.g., **pressures**: socio-economic drivers of land-use change and resulting direct pressures (habitat conversion, degradation, fragmentation), invasive species, extractive activities, climate change, pollution, including also *potential* pressures (threats) (compare Fig. 4); **state**: species population sizes/ranges, species richness, community composition, forest carbon stocks, habitat extent and condition, etc.; **benefits**: provisioning (e.g. food, raw materials, energy, medicine), regulating (e.g. climate regulation, water purification, crop pollination), supporting (maintaining ecosystem functioning, e.g. nutrient cycling), cultural ecosystem services (e.g. spiritual, recreational), as level of services provided (e.g. volume of water or wood), a monetary or derived value (e.g. jobs in forestry), etc.; **responses**: e.g. resource investment into sustainability, law enforcement/management efforts, laws and policy.

Note that single indicators may match more than one category; e.g. forest cover can be indicative of pressure, state, response and benefits. Because they are challenging to assess, indicators of pressure, benefit and response are often based on existing information (e.g. from national statistics offices). Benefit indicators help highlight and communicate the value of biodiversity and are of increasing practical use in incentivisation schemes. However, they tend to be more challenging than indicators from the other categories. A yet more complex variant of the PBR concept is the Driver-Pressure-State-Impact-Response (DPSIR) model (<http://www.epa.gov/ged/tutorial/>).

2.2. What Makes a Good Indicator?

For delivering useful results, biodiversity monitoring needs to be tailored for specific objectives. It is therefore critical to define monitoring objectives clearly at an early planning stage.

The SMART criteria are crucial in the selection of indicators. A good biodiversity indicator should be:

- **Sensitive** and **Specific** for the environmental condition (state), pressure or response under question. Sensitivity refers to rapid detectability of fine changes;
- **Measurable**, if possible quantitatively, so as to allow a measure of confidence in results;
- **Achievable** with the resources at hand, and economic (cost-efficient); see also [Appendix 3](#) specifically respective species monitoring;
- **Relevant** to agreed monitoring goals, natural resource management and policy; any monitoring scheme should further provide clear linkages to the NBSAP and its objectives (see example in **Fig. 4**);
- **Time-bound**, because results must be accessible within a defined time frame and yield information on changes over time.

Further practical considerations include:

- Choice of **indicators responsive to both positive and negative changes**;
- Choice of **multiple indicators** whenever possible. Natural systems are complex and even a carefully chosen indicator may fluctuate unpredictably; e.g. a species population due to disease or extreme climatic events (Richards & Panfil 2011) or may be affected by factors outside the monitoring area (e.g. migratory species, water quality in a shared basin);
- **Intuitiveness**. Is the indicator easily enough understood to be effectively communicated to local stakeholders and decision-makers? Does it relate to something that people can use or does it have emotional value?
- **Information availability**. Historical data may serve as a valuable baseline (e.g. land-use change, distribution or abundance of species), while present-day data (e.g. socio-economic indices from national statistics) can complement many monitoring schemes;
- **Sustainability**. Can the monitoring scheme be institutionalised (i.e. included in the duties of government agencies) in order to ensure its long-term implementation?

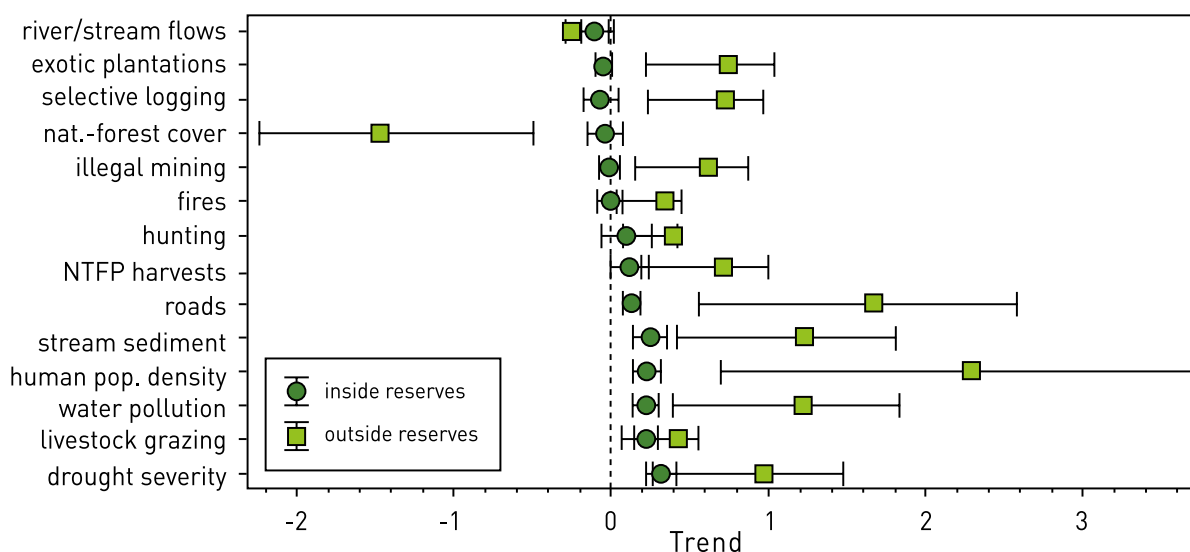


Fig.4. Common pressures on tropical forest biodiversity. This figure shows temporal trends (means and 95% confidence intervals) in selected pressures inside (green circles) and outside (red squares) of 59 tropical forest reserves worldwide. Trends are displayed as a relative index based on a semi-quantitative questionnaire (Laurance et al. 2012). Threat Reduction Assessment (TRA; Margoluis & Salafsky 2001) offers a well-established tool for designing studies involving pressure indicators; the Management Effectiveness Tracking Tool (METT; Stolton et al. 2007) provides another, even broader tool for an assessment of indicators relevant to conservation management through questionnaires.

3. ENGAGING PARTNERS

3.1. Stakeholder Engagement

Early identification and thorough consultation of relevant stakeholders from international down to local level is critical to ensure the success of monitoring initiatives. This helps ensure that misunderstandings are avoided and support is maximised, allows common monitoring goals and objectives to be defined, suitable indicators to be subsequently selected, and methodologies to be optimised. Stakeholder involvement is also vital for securing the sustainability of monitoring arrangements (e.g. long-term financing, institutionalisation). Relevant stakeholders include all entities and people that can provide the necessary capacity, data and technical expertise and those affected by or benefiting from monitoring activities and outcomes.

Objectives and indicators need to be tailored to the stakeholders' needs. In practice, however, stakeholders tend to ask for too much. It is therefore important to question initial ideas and wishes, e.g. *'What are you going to do with this information? Might it instead be sufficient to have only ...?'* Drafting result models and product matrices helps identify real needs and limit costs. Fewer but meaningful and well-assessed parameters will be more informative than numerous but poorly assessed indicators. Stakeholder consultation is an iterative process that can often require a lot of mediation to find practical compromises.

3.2. Opportunities and Challenges in Participatory Biodiversity Monitoring

The term 'participatory monitoring' is usually applied to monitoring activities that involve local people (Evans & Guariguata 2008). While the involvement of local expertise from governmental institutions or NGOs for biodiversity monitoring is already common practice, the involvement of local communities remains widely underused.



Opportunities in Participatory Biodiversity Monitoring

Irrespective of their educational background, committed local people can collect high-quality data at low cost (see Danielsen et al. 2014). Including local communities, residents and institutions in biodiversity monitoring can bring about a number of important benefits such as:

- Raising awareness, reflection and sense of ownership of their biodiversity among local communities and other local stakeholders;
- Increasing conservation support among local communities and other local stakeholders;
- Improving local livelihoods through additional income;



- Blending of extensive traditional indigenous knowledge with scientific rigour;
- Promoting local human capacities;
- Making labour-intensive monitoring feasible and affordable (e.g. when continuous field data collection is necessary). Participatory monitoring approaches can reduce costs immensely (see e.g. Holck 2008);
- Improving sustainability of monitoring schemes through low running costs and permanent local structures.

Challenges and limitations of Participatory Biodiversity Monitoring

- Many indicators and sampling protocols require extensively trained professionals, and costly and delicate equipment; training locals for such tasks may not be realistic;
- Higher likelihood of limited, variable (between persons) or uncertain data quality compared to that collected professionally; one measure for cross-checking data quality in participatory biodiversity

monitoring is to have different individuals or teams occasionally repeat the collection of each others' data;

- Reliably identifying suitably prepared, self-motivated and dependable personnel is critical and may be challenging;
- Initial investments for training may be high and may bring about dependence on long-term commitment of staff;
- Results obtained may more easily be influenced by expectations or desired outcomes;
- Rotation and work time splitting of local staff can be detrimental to monitoring results, yet tensions frequently arise when only a few community members benefit from employment.

How much local participation is feasible or ideal depends strongly on project contexts. However, while well-trained, non-specialist locals may often be a good choice to actually gather data, it is wise to have at least one trained scientist overseeing the monitoring (Pitman 2011).

3.3. More Partners?

Citizen science

'Citizen science', the involvement of *volunteers* from the general public into research, is a participatory approach to data collection that offers many new opportunities through web-based tools (Bonney et al. 2014). Voluntary contributions by members of the public may range from opportunistic reporting to full-time volunteering, and often also involves non-locals.

Besides providing valuable information at lowest possible cost, the involvement of citizens is also an effective outreach and education tool. Good examples include e.g. [ebird](#), an online database that taps into the immense expertise and activities of the birdwatching community; the Vietnamese NGO ENV employs a [web based reporting system](#) that facilitates citizens' reporting of wildlife crimes via smart phones; Australia's Great Barrier Reef National Park asks visitors to help take and upload imagery taken from fixed points which then serve for [monitoring mangroves](#). Refer also to the [Cornell Lab](#) for more information.

Academia

Linking with individual scientists and/or universities or other research institutions is an underused opportunity for increasing the cost-efficiency, outcomes and impact of a survey.

Assuming good quality and documentation of collected plant and animal material, many international **taxonomic experts** will readily help identify voucher specimens (plant or animal samples collected for identification and reference); many of them will be happy to advise further on preparation and documentation of specimens or on preliminary species recognition in the field.

National and international **research scientists in ecology, remote sensing or related fields** may often be available for helping design and advise during the study, or to recruit and supervise thesis students from their own institution or elsewhere. Their involvement can greatly increase impact through professional planning, analysis and publication of results in scientific journals. Often interested in long time series they can help ensure further sustainability by providing momentum and resources for continuing monitoring.

Well-supervised **thesis students** can provide substantial help with coordination, data collection and analysis at comparably low costs (coverage of expenses commonly sufficing for Bachelor or MSc students). National thesis students offer excellent opportunities for developing professional in-country capacity. Carefully selected, they will help ensure success through high motivation and skills and a very real interest in high quality results.

Scientists employed by research institutions will often charge comparably low fees, if any, given the prospect of obtaining and getting to publish interesting results. On the down-side, planning and implementing a collaboration with academic partners will often require more preparatory time than the classical consultancy (e.g. permit requirements for specimen shipment, availability of thesis students). Identifying possible academic partners at an early stage of planning is therefore vital for successful coordination.

Private sector

Private companies are becoming more and more interested in contributing to biodiversity conservation and monitoring. This is the result of a growing appreciation of three main reasons: the economic value of biodiversity and its ecosystem services; improved national legislation requirements for economic development planning; and a more prominent and widespread appreciation of biodiversity in society.

As a result, **Public-Private Partnerships (PPP)** offer attractive opportunities for sustainable financing of biodiversity monitoring. Notably the Business and Biodiversity Offset Programme ([BBOP](#)) offers an opportunity for both biodiversity monitoring and conservation in the context of economic development projects. It provides a useful framework ('mitigation hierarchy') and detailed best-practice guidelines and standards for biodiversity-friendly economic development projects.

The establishment of Conservation Trust Funds, often created by cooperation between governmental and private contributions is also increasingly popular and effective in delivering important resources for biodiversity conservation and monitoring in all parts of the world (see e.g. World Bank 2013). Refer also to the CBD's [Global Platform on Business and Biodiversity](#) for a variety of approaches and best practices.



4. PLANNING MONITORING ACTIVITIES

4.1. Types of Monitoring

Conceptually, it is useful to distinguish between four different categories of biodiversity monitoring according to their objectives:

- **Surveillance monitoring:** focuses on detecting long-term changes of biodiversity (number of species, species composition, etc.). Surveillance monitoring programmes must be representative for the area under consideration (single habitat, landscape, region or country) and tend to cover a broad range of species or species groups and functional types (both mobile and sessile species, herbivores and carnivores, etc.). In general, surveillance monitoring aims at detecting changes in state parameters but is not hypothesis-driven or management-oriented, is poor at resolving cause-and-effect relationships and relatively costly. It is sometimes referred to as 'omnibus' monitoring for the large (and vague) variety of possible applications, such as: providing data for strategic planning, reporting and information sharing in compliance with legislation or international agreements (e.g. CBD); generic early warning (e.g. response to climate change); documenting and/or modelling global change effects on biodiversity (e.g. for climate change adaptation, conservation planning); gathering of baseline information (e.g. for projecting trends). The [Swiss Biodiversity Monitoring Programme](#) is a classic example of surveillance monitoring;
- **Implementation monitoring ('operational monitoring')**: used to evaluate the compliance of management activities against a management plan, guidelines or agreed standards (e.g. following of stakeholder engagement procedures for REDD+ certification; reporting to line agencies, donors or certifying bodies);
- **Effectiveness monitoring ('impact monitoring')**: focuses on measuring the effects of interventions on management targets (e.g. impact of the construction of a motorway, effects of incentives to farmers, effects of groundwater management). Typical applications include the monitoring of management effectiveness (e.g. law enforcement or sustainable resource extraction in protected areas) and related compliance- or results-based incentive schemes (e.g. through evaluation and rewarding of staff or communities; REDD+ verification);

- **Validation monitoring:** used to determine whether the accomplishment of specific objectives was actually a consequence of management activities. This is the most challenging category of monitoring because it involves establishing causal relationships between some management action(s) and an environmental response (Lindenmayer & Franklin 2002). Validation monitoring therefore needs to include a wider range of indicators and may not always be feasible.

Importantly, the latter three monitoring categories are **complementary, applied ('targeted') monitoring types** which should ideally be **combined for adaptive management**. While combining surveillance monitoring with these applied types of monitoring is theoretically possible, they generally exclude each other for methodological and financial reasons.

One-off biodiversity assessments share many methodological similarities and challenges even though they are not monitoring in the sense of *repeated* data collection. Such assessments may provide valuable baseline information for future monitoring programmes, e.g. gathering information on biodiversity patterns for environmental impact assessment (EIA), land-use and conservation planning (e.g. gap analysis or zoning for protected areas).

4.2. Forms of Data Acquisition

Three broad categories of data can be distinguished according to the method of their collection:

- **Systematically collected data:** a) **remotely sensed** (aerial photography, satellite imagery, radar, LIDAR, etc.) or b) **field-collected** data (e.g. plots, questionnaires) gathered systematically following a rigid study design so as to maximise their value. See section 4.3 for more information.
- **Opportunistically collected data:** consequent recording of observations made during routine work can create valuable information where extensive inspecting or patrolling is carried out by project staff or collaborators (e.g. in forestry or protected area management), especially regarding parameters that are difficult or tedious to record in systematic fashion (e.g. records of selected animals, human presence, traps or other illegal activities). Data are typically processed into simple indices to make up for the lack of systematising of sampling efforts (e.g. incidents per person day or per km patrolled). This is a cost-efficient option with high potential for sustainability, and



is frequently a most valuable addition, if not a starting point for monitoring programmes.

- **Third-party data:** provided by state agencies (e.g. national offices of statistics), international bodies (e.g. FAO, IUCN), initiatives (e.g. [globalforestwatch](https://www.globalforestwatch.org/)), NGOs or others, and which can be used as is or processed to serve as indicators.

4.3. Study Design and Survey Methodology

Project conditions are invariably too unique to allow existing study designs to be adopted without major adjustments. Sound study planning is therefore an important investment towards resource efficiency and success (see also **Box 2**). As self-evident as this sounds, innumerable biodiversity monitoring initiatives have underachieved or failed due to poorly adapted or flawed study designs. Changing a sampling strategy *after* the onset of monitoring activities comes at a high cost (data comparability, resources). Moreover, many pitfalls of study design such as pseudoreplication, sampling bias or undersampling will go unnoticed

Box 2. Checklist for Biodiversity Monitoring

Checklist for planning of a biodiversity monitoring cycle (not strictly sequential, and numerous steps are worth repeating).

1. Identify and involve stakeholders, define common terms and needs;
2. Conceptualise the project context in terms of result chains/impact models of system response to pressures and management;
3. Agree common and specific monitoring objectives and priorities with key stakeholders, define spatial and temporal scope of activities;
4. Define *testable* and management-oriented *a priori* hypotheses where possible to assure effective and efficient resource use (see e.g. Nichols & Williams 2006);
5. Consider involvement of local and external (e.g. academic) partners, and paths towards institutionalisation;
6. Screen for existing data and indicators that can be built upon;
7. Decide on and prioritise suitable indicators. Consider inherent trade-offs in breadth, precision, confidence and cost for setting priorities. Focusing on fewer parameters may yield more valuable results;
8. Choose methodology that, based on previous studies and experience, ensures accuracy, quality and efficiency. Note in particular sample sizes used and the variability in results as a guide for choosing appropriate replication (Coe 2008). Consider confounding factors and, in particular, which environmental factors may add substantial variability and how this can be minimised or estimated;
9. Assess how and to what extent participatory approaches can be included;
10. For draft sampling design and analysis strategy, consider pilot sampling for testing feasibility. If relying on random sampling make sure you have enough statistical power to ensure that the sampling methodology is practical and effective (consider power analysis);
11. Develop M&E and reporting systems: clarify financial, logistical and technical responsibilities for the entire duration of proposed monitoring;
12. Approximate costs vs. budget: clarify financial, logistical and technical responsibilities for the entire duration of envisioned monitoring. This is often challenging due to the low priority given to monitoring and the need for monitoring to extend far beyond typical budget cycles. Assess whether the objectives are achievable or whether the scope of the proposed monitoring scheme should be reduced. Develop a detailed monitoring plan including a detailed, illustrated description of methods fit to serve as a manual;
13. Critically re-evaluate sampling methods early after onset of survey and modify where necessary. Later changes will often affect comparability of sampling runs and can be very costly;
14. Periodically collect, archive, analyse and interpret data, entering and quality-checking data as early as possible;
15. Work towards institutionalisation of the programme;
16. Customise results and channel them to specific target audiences;
17. Evaluate sampling strategy and indicator performance and consider refinement (back to top).



until it is too late to fix them—typically during data analysis. This is particularly tricky where only random sampling of small subsamples is possible (typical field monitoring; e.g. plot- or interview-based surveys) rather than wall-to-wall monitoring (e.g. remote sensing). Some relevant considerations are summarised in [Appendix 1 \(Study design in field monitoring\)](#). Furthermore, most ecosystems and project settings are highly complex, and strong data noise (scatter) due to resulting natural variability in space and time poses particular challenges to biodiversity monitoring. Options for mitigating such variability are discussed in [Appendix 2 \(Dealing with variability in random sampling\)](#).

Widely used **sampling protocols** (describing an exact methodology used to collect data) have many benefits. They are tried and tested, are likely to allow sound data analysis, and increase the value of data by facilitating comparison with other studies. However, the limited consensus on survey methodology for many types of biodiversity indicators also shows that a single method often cannot be ideally suitable for any situation, and that modifications may often be advisable.

Generally, the likelihood of success will be highest for *simple* monitoring schemes, which, while often elaborate and tricky to design, will be robust and require only limited resources and technical capacities to collect and analyse data. E.g., a rough index obtained with an easily replicable method not highly dependent on the observer's individual skills

may often outperform elaborate assessments.

References on methodologies for specific types and groups of indicators are given under [Further Resources](#).

Crucial to sustained success is to elaborate and keep available a *detailed*, unambiguous **documentation of sampling protocols** so as to ensure that methods remain truly replicable and as independent of staff continuity as possible.

The workload following data collection is easily underestimated. The time and resources required for data entry, management and analysis typically equal or exceed those involved in field collection of data (Gibbs et al. 1999).

4.4. Managing Raw Data

Sound data management is much more costly than often acknowledged. E.g., Lindenmayer & Franklin (2002) recommend that as much as 20-25% of the budget for long-term monitoring programmes should be allocated to data management.

Spreadsheets are familiar and handy tools for managing tabulated data. However, biodiversity data tend to be complex and, for analysis, often require compilation into sheets that quickly become excessively large and unhandy. More importantly, **spreadsheet** data can be entirely corrupted by a single sorting error and such errors often go unnoticed. This becomes likely when data are entered or handled by

several or inexperienced staff, a hazard avoidable by using **database software**. Ready access by various project staff is an important reason for user-friendliness being a key characteristic of database software. Manual data entry may nevertheless easily turn into a bottleneck. Reducing the workload of data entry is often achievable through sound customisation of a database (e.g. dropdown lists for quick, error-free entry) or by, as far as possible, replacing data recording on field forms by tablets, smartphones or GPS units from which data only needs to be imported (see 6.2 '[Software for Data Management and Analysis](#)').

Important early steps in data management are rigorous **quality control** (detecting and correcting erroneous data points, dealing with missing data) and thorough documentation (when/where/how exactly were data recorded and by whom). The experience of the BDM Switzerland programme suggests that as much as 10% of budget should be allocated for quality control.

Digital **photos** of organisms, signs or habitats can be of great value for documentation and identification, assuming that they are well-labelled (coded) and thus readily searchable. Short-coding of images may include information on taxonomy, specimen collection number and/or reference to sampling unit (e.g. plot identity). Software such as [Picasa](#) facilitates the use of image databases with rapid search options and custom-size thumbnail views.

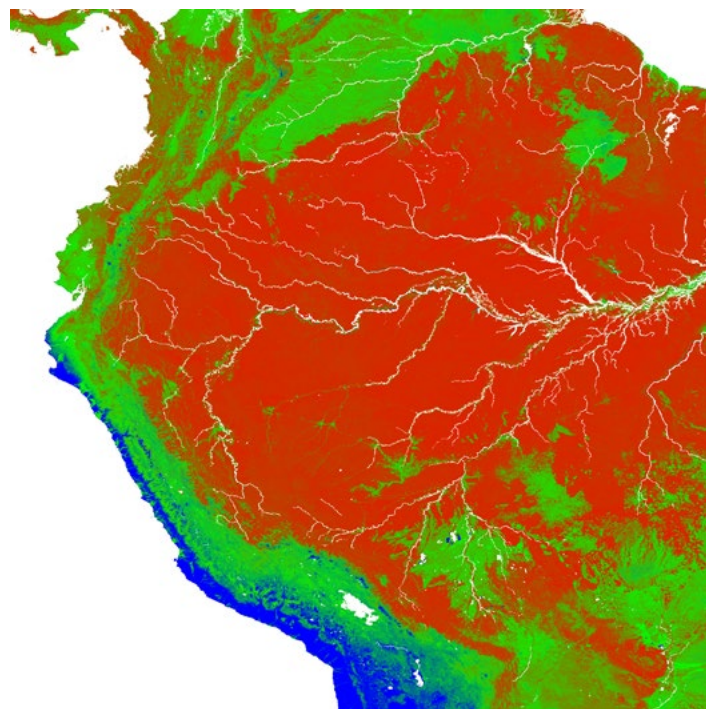
4.5. Data Analysis and Interpretation

Data analysis needs to be considered during study planning and *before* the beginning of sampling to avoid design flaws and maximise resource-efficiency. Critical questions include:

- Which analysis methods are suitable to obtain meaningful, reliable results for the smallest possible effort?
- How many sampling units need to be monitored, and where? Frequency of sampling?
- Who conducts analyses and interprets and writes up results?
- How are results to be shared (e.g. publicly via informal reports or following scientific standards)?

The **use of statistical methods** is worth careful consideration, since statistics provide a number of important advantages such as:

- **providing a reliable estimate of error probability** (statistical 'significance'; determining the likelihood of a trend being real or only coincidental). For indicators based on random samples (i.e. small sub-areas or sub-populations sampled rather than edge-to-edge, as e.g. in remote sensing) statistical significance can provide evidence for patterns or trends (e.g. in animal populations along transects) and a truly solid and objective basis for decision-making;
- **allowing detection of subtle trends** or trends that otherwise remain masked (concealed) by other factors;
- helping ensure that management decisions are based on **correct assumptions**;
- **providing evidence** on conservation trends for incentivisation, certification or legal measures;
- **helping convince decision-makers and the general public**;
- **allowing the sharing of widely acceptable results** with communities of scientists and practitioners;
- ultimately, **optimising the usefulness and efficiency of limited resources** for monitoring.





The main message of this section is that **study design and data analysis have immense influence on the success** of any biodiversity monitoring project and must not be neglected. Sound study design and data analysis are the best possible investment towards both resource efficiency and quality of outputs. Because the topic is complex it will pay to seek advice from a trained research ecologist for planning of monitoring schemes, supervision of collection and entry of data, help with data analysis, and interpretation and presentation of results. It should be borne in mind, however, that professional scientists often bring their own biases to monitoring projects. Ornithologists will favour birds whereas GIS experts will prefer remote sensing (Pitman 2011). One of the most important challenges for project coordinators is to consider and mediate these biases among stakeholders and technical staff, and to minimise their effects on project design.

4.6. How to Make the Best Use of Results?

Securing and sharing data

Raw, systematic biodiversity data are of lasting value and should be made freely and permanently available wherever possible. They allow a wealth of future analyses and serve as invaluable historical baselines for future monitoring efforts (Magurran et al. 2010). Given regular data back-up, stand-alone database systems (e.g. [BIOTA](#)) allow for professional data management and analysis but often cannot ensure permanence of data beyond the duration of a project cycle, nor their distribution among potential users. Web-based international biodiversity database networks offer free, searchable and reliably permanent data storage for species records (registers of a species in time and space) or simple checklists,

e.g. [GBIF](#). More complex ecological data (e.g. raw survey data on bird diversity ordered by sampling units and dates) can be permanently stored and made visibly available via the database [PREDICTS](#), the data repository [DataOne](#) or [other services](#). Adding detailed metadata (information that helps understand and use data; e.g. information on project setting, methods used) is key for preserving the value of data.

Feeding results back into management

Periodic review of indicator trends is essential for adaptive management. Challenges may often lie in the limited resources available for regularly (e.g. monthly, yearly) summarising and reviewing results in reports. Visualising results through accessible, simple graphs (e.g. bar charts, scatter plots) or maps facilitates ready, time-efficient interpretation of trends by decision-makers, while limitations in man power and technical capacity for producing such periodical summaries can often be compensated through automation. The software platform [R](#) has noteworthy potential for automating analysis and reporting. The Spatial Monitoring and Reporting Tool [SMART](#) can likewise be a useful software programme for many applications.

Monitoring itself also needs to be subjected to the adaptive management approach. Hence its progress, methods and the system in place need to be critically assessed on a regular basis through monitoring and

evaluation in order to ensure that the data are providing useful and reliable information in an efficient manner.

Sharing results through publication

Monitoring results must be shared regularly with major stakeholders. The weight, circulation and sustained impact of reports can be boosted greatly by **adhering to some minimum standards for scientific publishing**, allowing outcomes to be cited and built upon by others in particular: clear specification of authors, publication year and publishing body, detailed description of methods used (for 'replicability'), wide and permanent availability. At this point, again, the involvement of scientists can pay off for more ambitious monitoring projects through dissemination of major results in peer-reviewed scientific journals. Doing this will boost the acceptability and usefulness of monitoring outcomes, and thus expand and perpetuate the impact of a biodiversity monitoring project.

Because scientific publications are very technical, they invariably make poor advocacy materials. **Refining results for decision-makers and the general public** is a distinct process for which people other than scientists tend to be better suited. For these target groups, results also need to be communicated through entirely different channels (e.g. hardcopy and executive reports, leaflets, educational materials, press notes, public meetings, websites).



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6. FURTHER RESOURCES

Adaptive Management and Opportunistic Monitoring

Conservation Measures Partnership. 2013. Open standards for the practice of conservation. *Authoritative, compact manual outlining the open standards for adaptive management in conservation.* Available [here](#).

Margoluis R., Stern C., Swaminathan V., Brown M., Johnson A., Placci G., Salafsky N. & Tilders I. 2013. Results chains: a tool for conservation action design, management, and evaluation. *Ecology and Society* 18: 22. *Conceptual paper describing results chains as an important tool for helping teams clearly specify their theory of change in adaptive management.* Available [here](#).

Nyberg B. 1999. An Introductory guide to adaptive management. British Columbia Forest Service, Victoria. *Enjoyable compact manual on adaptive management.* Available [here](#).

Schmitt K. 2006. Ranger-based data collection. A reference guide and training manual for protected area staff in Cambodia. Ministry of Environment, Phnom Penh. *Practical introduction to opportunistic data collection in protected area management.* Available [here](#).

Stokes E.J. 2010. Improving effectiveness of protection efforts in tiger source sites: Developing a framework for law enforcement monitoring using MIST. *Integrative Zoology* 5: 363–377. *Concise paper on opportunistic, software-supported law enforcement monitoring.* Available [here](#).

Participatory Monitoring

ANSAB. 2010. Participatory biodiversity monitoring in community forests. ANSAB, Kathmandu. *Practical step-by-step guidance to community involvement in biodiversity monitoring.* Available [here](#).

Corrigan C. & Hay-Edie T. 2013. A toolkit to support conservation by indigenous peoples and



local communities: building capacity and sharing knowledge for indigenous peoples and community conserved territories and areas (ICCAs). UNEP-WCMC, Cambridge. *A wealth of useful references including short descriptions and links.* Available [here](#).

Evans K. & Guariguata M.R. 2008. Participatory monitoring in tropical forest management: a review of tools, concepts and lessons learned. CIFOR, Bogor. *Practical introduction to key concepts and issues around participatory monitoring. 50 pp.* Available [here](#).

Monitoring Matters. *Website offering many useful scientific references on participatory biodiversity monitoring for download.* Website [here](#).

Participatory Monitoring and Management Partnership. *A platform for participatory monitoring.* Website [here](#).

General Standard References for Monitoring

BDM Coordination Office. 2014: Swiss Biodiversity Monitoring BDM. Description of methods and indicators. Environmental Studies no. 1410. Federal Office for the Environment, Bern. *A comprehensive description of the exemplary Swiss national surveillance monitoring programme. This and many related publications can be found [here](#).*

Eymann J., Degreef J., Häusler C., Monje J.C., Samyn Y. & Vanden D. (eds.). 2010. Manual on field recording techniques and protocols for all taxa biodiversity inventories. ABC Taxa Vol. 8. *A broad range of up-to-date standard techniques and protocols for monitoring*



a large variety of organism groups (e.g. all classes of vertebrates, invertebrates, plants, fungi) in a broad variety of habitats, plus useful chapters on specimen preservation and data management. Available [here](#).

Gardner T.A. 2010. Monitoring forest biodiversity. Earthscan, London. *Comprehensive 390-pp. monograph on biodiversity monitoring for conservation, tailored to a scientific and advanced conservation practitioners' readership, with a focus on the monitoring of species assemblages for forest management. Introduces a wealth of relevant concepts and provides ample references.*

Hill D., Fasham M., Tucker G., Shewry M. & Shaw P. (eds.). 2005. Handbook of biodiversity methods and monitoring: Survey, evaluation and monitoring. Cambridge University Press, Cambridge. *Thoroughly covering planning of monitoring projects, habitat monitoring and survey techniques for a wide range of organism groups in 580 pp. Since the book is tailored for the UK, some of the proposed methods will not be ideally suited for tropical environments, but many other sections (notably planning) are of very general usefulness.*

Latham J., Trivedi M., Amin R. & D'Arcy L. (eds.). 2014. Biodiversity monitoring for REDD+: A sourcebook of why, what and how to monitor. ZSL, London. *Providing a practical introduction to key concepts and cornerstones of biodiversity monitoring such as relevant international initiatives, agreements, indicator*

selection, and monitoring methods with emphasis on vertebrates and remote-sensing, and many useful references. Available [here](#).

Newton A. 2007. Forest ecology and conservation: a handbook of techniques. Oxford University Press, Oxford. *Exceptionally broad introduction to a wide range of techniques (both remotely sensed and field data) for assessing forest extent, condition, structure, composition and dynamics at different scales. Particularly useful regarding structural and functional parameters.*

Richards M. & Panfil S.N. 2011. Social and Biodiversity Impact Assessment (SBIA) Manual for REDD+ Projects: Part 1 – Core Guidance for Project Proponents. Version 2. Climate, Community & Biodiversity Alliance, Forest Trends, Fauna & Flora International, and Rainforest Alliance. Washington, DC. *Excellent starting point for planning biodiversity monitoring in tropical forests; also offering good guidance on study planning and indicator selection following the Open Standards for the Practice of Conservation. Available [here](#).*

Sutherland W.J. (ed.). 2006. Ecological census techniques: A handbook. Cambridge University Press, Cambridge. *Outlining methods for surveying all major groups of vertebrates, invertebrates (both aquatic and terrestrial) and plants in compact, practically oriented chapters, plus general chapters on study design and environmental variables. Excellent starting point for biological monitoring. Available [here](#).*

Selection of Monitoring Indicators

Biodiversity Indicator Partnership. 2011. Guidance for national biodiversity indicator development and use. UNEP World Conservation Monitoring Centre, Cambridge. *An authoritative, concise manual on indicator selection and use, offering close step-by-step guidance for selecting and monitoring national biodiversity indicators that is likewise helpful for smaller-scale monitoring.* Available [here](#). Many other useful resources via the BIP [website](#).

CIFOR. 2009. Criteria & indicator toolbox. Guidelines for developing, testing and selecting criteria and indicators for sustainable forest management. CIFOR, Bogor. Available [here](#).

Pereira H.M., Ferrier S., Walters M., Geller G.N., Jongman R.H.G., Bruford M.W., Brummitt N., Butchart S.H.M., Cardoso A.C., Coops N.C., Dulloo E., Faith D.P., Freyhof J., Gregory R.D., Heip C., Höft R., Hurtt G., Jetz W., Karp D.S., McGeoch M.A., Obura D., Onoda Y., Pettorelli N., Reyers B., Sayre R., Scharlemann J.P.W., Stuart S.N., Turak E., Walpole M., Wegmann M. 2013. Essential biodiversity variables. *Science* 339: 277–278. *Still roughly hewn classification of elementary biodiversity state indicators by the Group on Earth Observations Biodiversity Observation Network (GEO-BON), with more detailed indicators to follow soon.* Available [here](#).

Pomeroy R.S., Parks J.E. & Watson L.M. 2004. How is your MPA doing? A Guidebook of Natural and Social Indicators for Evaluating Marine Protected Area Management Effectiveness. IUCN, Gland. *Strong conceptual and practical guidance for planning and conducting monitoring in adaptive resource management exemplified for the case marine protected areas, yet of much more general applicability. Includes thorough treatment of a broad array of useful indicators (organized into biophysical, socio-economic and governance indicators) to choose from. 232 pp.* Available [here](#).

Study Design and Data Analysis

Elzinga C.L., Salzer D.W. & Willoughby J.W. 2001. Measuring and monitoring plant populations. Bureau of Land Management, Denver. *Excellent, freely available and accessible tome on biodiversity monitoring, giving practical advice on the whole cycle of biodiversity monitoring, from rationale over study planning and design, data collection and analysis to feeding results*



back into management. The geographical context (Colorado) is peculiar, so that field methods will not be complete or ideal for some settings. Available [here](#).

Feinsinger P. 2001. Designing field studies for biodiversity conservation. Island Press, Washington, DC. *Engaging, clear, practically oriented and succinct book on designing, planning and implementing biodiversity surveys, with an emphasis on the fundamentals of study design.* Available [here](#).

Fowler J., Cohen L. & Jarvis P. 1998. Practical statistics for field biology. Wiley, London. *Focuses on study design, principles and fundamental methods of statistical analysis and the presentation of results. Among the most clearly-written and encouraging introductions to this scary topic, the book focuses on the fundamentals and ends where many statistics books for advanced scholars begin (ANOVA).*

Horning N., Robinson J.A., Sterling E.J., Turner W. & Spector S. 2010. Remote sensing for ecology and conservation: A handbook of techniques. Oxford University Press, Oxford. *Sound, broad introduction to remote sensing for biodiversity monitoring. 470 pp.*



Survey Methods for Specific Groups of Organisms

Dodd K. (ed.). 2009. Ecology and conservation of amphibians. A handbook of techniques. Oxford University Press, Oxford. *Comprehensive volume thoroughly covering the broad range of methods for monitoring amphibians across all life stages and habitats.*

Gerwing J.J., Schnitzer S.A., Burnham R.J., Bongers F., Chave J., DeWalt S.J., Ewango C.E.N., Foster R., Kenfack D., Martínez-Ramos M., Parren M., Parthasarathy N., Pérez-Salicrup D.R., Putz F.E., Thomas D.W. 2006. A standard protocol for liana censuses. *Biotropica* 38: 256–261. *Authoritative guidelines for liana sampling.* Available [here](#). See also Schnitzer S.A. et al. 2008. *Supplemental protocol for liana censuses.* *Forest Ecology and Management* 255: 1044–1049. Available [here](#).

Lawesson J.E. (ed.). 2000. A concept for vegetation studies and monitoring in the Nordic countries. TemaNord Vol. 517. Nordic Council of Ministers, Copenhagen. *Very useful despite its focus on cold temperate environments, offering excellent chapters on a variety of topics such as study design, sampling methods, data treatment, analysis and interpretation for remotely sensed as well as field-collected data.* Available [here](#).

McDiarmid R.W., Foster M.S., Guyer C., Gibbons J.W. & Chernoff N. (eds.). 2012. Reptile biodiversity: Standard methods for inventory and monitoring. University of California Press, Berkeley. *Comprehensive tome stretching from study design over survey techniques to data analysis.*

New T.R. 1998. Invertebrate surveys for conservation. Oxford University Press, Oxford. *A 240-pp.-summary of techniques for surveying both terrestrial, freshwater and marine invertebrates.*

Roberts-Pichette P. & Gillespie L. 1999. Terrestrial vegetation biodiversity monitoring protocols. Ecological Monitoring and Assessment Network (EMAN) Occasional Paper Series Report No. 9. Burlington, Canada. *Clear guidance for monitoring vegetation in plots or transects structured as four independent sections (1. trees, 2. shrubs/treelets and 3. herb layer in plots, and 4. vegetation transects). Designed for Canada but likewise useful elsewhere; incl. good illustrations.* Available [here](#).

Sutherland W., Newton I. & Green R.E. (eds.). 2004. Bird ecology and conservation: A handbook of techniques. Oxford University Press, Oxford. *Authoritative book on bird survey techniques, but also a host of related topics.*

Software for Data Management and Analysis

BIOTA. *Free, well-tested database system for professional management of complex survey data (by sampling units or lot batches), voucher specimens, etc. based on 4D engine. Allows for reference to photos, batch print-out of specimen labels and generous customisation. Comes with a detailed manual.* Available [here](#); see also [here](#) for a list of many alternative database software options.

EstimateS. *Freely available, user-friendly software for estimating (extrapolating) species richness, calculating biodiversity indices (alpha diversity, species turnover), individual- and sample-based rarefaction for comparing different-sized samples.* Available [here](#).



MARK. Widely used and freely available software for mark-recapture analysis of animal populations. Available [here](#).

MIRADI. Freely available software for adaptive (result-based) management following the Open Standards for the Practice in Conservation. Assists in defining project scope, designing conceptual models and spatial maps of project sites, prioritising threats, developing objectives and actions, selecting monitoring indicators and developing work plans and budgets. Available [here](#).

PAST. Free, very compact and easy-to use package with a wide range of statistical and graphical analysis options for biodiversity data including standard multivariate techniques but also some truly fancy tricks (e.g. NPMANOVA). Customising and graphics layouting options are limited. Available [here](#).

PC-Ord. Affordable package for analysing multi-species (multivariate) biodiversity data. Offers a wealth of ordination techniques, multivariate significance testing, indicator analysis. More user-friendly than R while offering more options than PAST. Available [here](#).

QGIS. This open-source software sticks out among free GIS packages as being user-friendly and rapidly growing in functionality and support. Many more advanced analysis functions are available through plug-ins for other packages such as SAGA, GRASS or R. Available [here](#).

R. Free open-source platform rapidly growing in popularity. An immense and fast-growing range of statistical and graphical techniques can be downloaded and installed as packages (e.g. SPACECAP for mark-recapture analysis, MODIS for MODIS satellite imagery acquisition and processing, odfWeave for automated reporting). Commands are made through code, which is why getting familiar with this software, on the down-side, is significantly more arduous than with traditional general statistical packages such as SPSS or STATISTICA. [R-Studio](#) offers a freely available, user-friendly graphical user interface for R. Available [here](#).

SMART ('Spatial Monitoring and Reporting Tool'). For opportunistic data collection and analysis towards efficient site-based conservation management. Recently developed based on the functionality of and experiences with the software [MIST](#) ('Management Information System') this free open-source software combines a database with a GIS module as to allow keeping track of pressure, state and response indicators (threats, selected species, patrolling efforts). The reporting module allows the 1-click generation of summary analyses (maps, graphs, tables) as standard format reports. A plug-in also integrates functionalities of the software [Cybertracker](#), which facilitates field-recording GPS-linked data using smartphones or tablets. An application that permits centralised management of core functions (such as data storage or analysis, supervision 'SMART Connect') is scheduled to be available soon. Available [here](#).

APPENDICES

Appendix 1. Study Design in Field Monitoring

Important considerations during planning for a field study that (as usual) relies on random sampling include (among others):

- Carefully avoid **pseudoreplication**. Pseudoreplication means that sampling units (e.g. survey transects) are not spatially independent and therefore not true replicates (but rather double-counting of the same place). This happens when sampling units are too closely spaced to each other and leads to unreliable or even misleading results;
- **Sampling bias** has many faces and is one of the commonest major flaw in quantitative surveys based on random sampling. Sampling bias leads to unrepresentative survey results which do not accurately represent the area, conditions or populations under study. For example, if the exact positions of sampling plots are selected by the field team, difficult situations (e.g. dense underbrush, difficult terrain, distant sectors) will often be avoided and their underrepresentation will lead to unrepresentative results. Randomising the layout of sampling locations or even laying them out in a systematic grid would be measures to avoid this specific source of bias;
- **Replicability**. In essence this means meticulously defining and describing work procedures and materials used to the point that someone entirely unfamiliar with the project could repeat (replicate) the study and get to the same results;
- **Edge effects**. Be aware of and avoid proximity to habitat edges (or ecotones) unless edge effects are the subject of study. Edge effects can be physical (e.g. climate) or biotic (e.g. biodiversity) changes that can often be detected up to several hundred metres into the forest interior (Laurance et al. 2011). Related to this is the 'spill-over effect': degraded habitats show higher biodiversity near intact habitat because even many sensitive species will visit or pass through (spill over) into unsuitable

habitats ('source-sink dynamics') where they often cannot be distinguished from true (constantly present and successfully reproducing) residents;

- **Species richness is strongly scale-dependent ('scale effects')**. As an example, a single square metre of forest burned the previous year may easily hold more plant species than intact forest, but this picture changes drastically as the sampling area is increased;
- **Defining a meaningful baseline or reference ('control')** as a point of reference for monitoring results. E.g. it is very difficult to evaluate the effects of overgrazing without having the vegetation in a naturally grazed state for comparison. Controls further help distinguish the effects of target activities (e.g. selective timber harvest) from effects of unrelated environmental variability (e.g. climate). Bear in mind that smaller habitat fragments cannot offer ideal controls (see Laurance et al. 2011);
- **Defining hypotheses**. The formulation of working hypotheses (a priori predictions) on patterns, trends or relationships of interest helps in the elaboration of a suitable study design (including adequate number and distribution of sampling units) and methods of analysis. Later statistical testing of these hypotheses allows the objective assessment of whether and to what degree monitoring results confirm expectations and thus, ultimately, provide hard evidence for advising on policy and management decisions;
- **Critically re-evaluating sampling strategy and methodology early** after beginning of field work, and readjusting to match unforeseen challenges.

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Appendix 2. Dealing with Variability in Random Sampling

Most field-recorded indicators are work-intensive and require random sampling of small subareas or subpopulations. Variability is a particularly big challenge in analyzing such data. E.g., the likelihood of encountering a species in such a sub-sample (e.g. plot, transect) strongly varies with a wealth of natural (biotic and abiotic) and man-made parameters (e.g. patterns in socioeconomics and resulting land-use). This is the principle reason why the especially high spatial complexity and biodiversity of many tropical ecosystems poses challenges to ecological monitoring. As a more specific example, the density of fruit-eating birds is naturally highly variable in space and time due to the perpetually changing patchiness of fruiting trees. Limiting such unexplained variability ('data noise') is key because it allows for more reliable results at *lower* sampling efforts and thus costs. Measures worth considering in this regard include e.g.:

- **Stratification** should be considered whenever the area of study is not homogenous, because habitat heterogeneity will typically translate into high variability in many response parameters. Stratification can greatly reduce this uncontrolled variability. This is done by distributing (and analyzing) sampling units more strategically according to pre-defined (separated) habitat types ('strata'; e.g. according to terrain or land-use). See Kindt & Coe 2005;
- **Restricting sampling** focusing on thorough sampling of central parameters to obtain meaningful results, despite limited resources (e.g. by omitting other parameters, reducing sampling area, taking absence-presence data rather than abundances). See **Fig. 5**, Ward & Larivière 2004;
- **Recording of environmental parameters.** Many important environmental parameters such as altitude, slope inclination and exposure, topographic position (from ridge crest to valley bottom) or vegetation structure (e.g. canopy height and closure, tree basal area) can be measured easily, and the resulting data are usually of great value during analysis and interpretation of results (e.g. allowing quantification of their effects or explanation of variability). Robust, affordable data

loggers already allow automated recording of key climate variables such as rainfall, temperature or air humidity (e.g. [Testo](#) or [Onset](#)), which will often prove invaluable, especially in the case of extreme climate events;

- **Controlling temporal variation** by taking into account different seasons (e.g. dry vs. rainy season) and day times, and/or controlling for sampling time (e.g. by surveying different habitat types simultaneously rather than sequentially);
- **Plot versus transect sampling.** Thanks to their compact shape, sampling plots are less affected by spatial habitat variability than transects. The strength of transects, on the other hand, lies in maximising detection rates of low-density parameters (e.g. in the monitoring of large mammals or illegal activities, rapid biodiversity assessments);
- **Permanent survey units.** Species are distributed patchily due to environmental heterogeneity of habitats and resources. Permanently marking

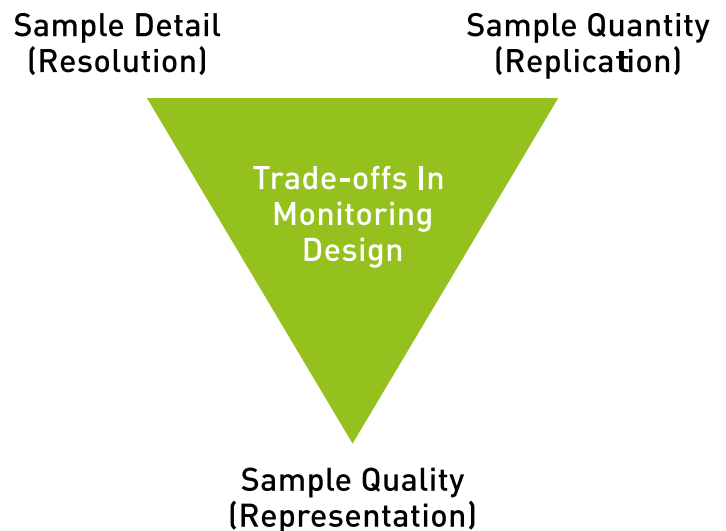


Fig. 5. The inherent trade-offs in any biodiversity monitoring between sample detail (the number and resolution of species and environmental measurements taken at a site), sample quality (the number of sub-samples collected to achieve satisfactory representation) and sample quantity (replication across space). Source: redrawn after Gardner 2010.

and repeatedly surveying the same sampling units (plots, transects, trap points) allows reduction of this large source of 'random' variability in data ('noise') and, in sessile (immobile) organisms such as plants or corals, the fate of individuals can be followed, further reducing noise. Similarly, marking individuals of mobile species allows much more precise estimates of population sizes, densities and trends ('mark & recapture');

- **Pilot sampling and power analysis** during study design allow for a quantification of the actual variability in the data and the determination of an adequate number of sampling units, and thus avoid both undersampling (monitoring too few sampling units to obtain clear results) and oversampling

(spending more effort than necessary and inefficient). This measure will pay off especially for more ambitious (costly) monitoring projects;

- **Quantitative ('numerical') data** (counts, measures, if unavoidable even estimates) should be collected rather than qualitative data such as 'categorical' (e.g. classes) or 'ordinal' (e.g. rankings) because they allow more powerful and meaningful analyses; they are also less susceptible to personal judgment (bias) and thus much more replicable and comparable.

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Appendix 3. Organisms as Indicators

Because most ecosystems are overwhelmingly complex, limited financial and human resources usually require the reduction of biodiversity monitoring to a very small subset of organisms ('taxa'; usually individual species or groups of related species).

Groups of organisms differ greatly in their sensitivity to specific natural or man-made environmental pressures (both among and within groups of organisms). Hence, the indicative power and suitability of an organism group depends strongly on the specific monitoring objectives and project context. For example, while the species richness or community composition of lichens is an excellent indicator of air pollution it is of little practical value to monitor forest degradation and entirely useless for assessing hunting pressure. Likewise, many hoofed mammals are sensitive to opportunistic hunting, yet tend to be tolerant or even appreciative of forest degradation. Careful **selection of suitable groups of organisms** for the specific monitoring objectives ('indicator species') is therefore a critical step **after monitoring objectives have been agreed on** among relevant stakeholders.

Some specific practical considerations for selecting suitable indicator organisms include:

- **Taking into account population fluctuations and generation lengths.** Some species populations naturally fluctuate much more strongly and unpredictably in size than others (e.g. due to predator-prey cycles, climate sensitivity); moreover, species with long generation cycles may respond too slowly to management intervention to be ideal indicators.
- In practice, **the most reliable indicator may often not be the most sensitive species** or those most threatened and/or of highest conservation concern, but rather other species sensitive to the given pressure (e.g. opportunistic hunting) that are still reasonably common, and easy to identify and quantify (see Gardner 2010, p.76 ff., for a discussion on the use of threatened species).
- **Can the indicator be easily and reliably identified?** Species identification can be very challenging and resource-intensive. Also consider that **exact species identification may not be necessary**. For many monitoring purposes, recognising species as being distinct without actually naming

them ('morphospecies') is often sufficient when many species are monitored. Even more coarse identifications may suffice: the abundance of 'all ungulate species' (typically comprising several families) or 'all primates' lumped together can be detailed enough for monitoring hunting pressure. Coarse segregation of aquatic macroinvertebrates into genera, families or even orders of organisms is often sufficiently exact to monitor changes in water quality (Beatty et al. 2006). Likewise, the diversity of higher taxa (families and orders) has been recognised as a good surrogate indicator for overall marine diversity (Mellin et al. 2011). An important consideration, however, is that the composition of species assemblages or communities is often much more sensitive an indicator of environmental conditions than species richness (e.g. Imai et al. 2014), which requires higher identification resolution and efforts. See also Ward & Larivière (2004) for a helpful review of four commonly used approaches to reducing effort when making rapid biological assessments.

- **Taxonomic or functional groups?** Put simply, taxonomic (or phylogenetic) groups are groups of organisms that share a common ancestry. Because species identification is often very challenging, most studies have traditionally been limited to one or few such taxonomic groups. The traditional use of entire taxonomic groups for biodiversity surveys today facilitates comparison of biodiversity among studies and sites. While members of single taxonomic groups often have the advantage of being identifiable fairly reliably to species level by a single expert, their members typically diverge greatly in their ecological requirements and thus rarely yield the strongest indicators for certain environmental drivers. Functional groups or 'guilds' comprise all species in an ecosystem that share certain central life history traits irrespective of their common ancestry and genetic relatedness. Such shared traits often invoke exceptional sensitivity to certain environmental parameters (more so than groups instead defined by genetic relatedness), and functional groups can therefore be powerful indicators. E.g., at the top of the food chain the guild 'apex predators' are highly sensitive to a variety of human pressures, as large frugivorous birds are to opportunistic bush meat hunting.

- **Cost efficiency varies widely among taxonomic or functional groups** of organisms, related not only to differences in their indicative power but also to great variability in types and amounts of resources required for sampling and identifying these organisms. E.g. dung beetles can offer an easily monitored, highly cost-efficient proxy for abundance and diversity of larger mammals and thus a more cost-efficient indicator for hunting pressure (**Fig. 6, Fig. 7**).
- **There is no ideal surrogate indicator for overall biodiversity.** The key objective of many biodiversity

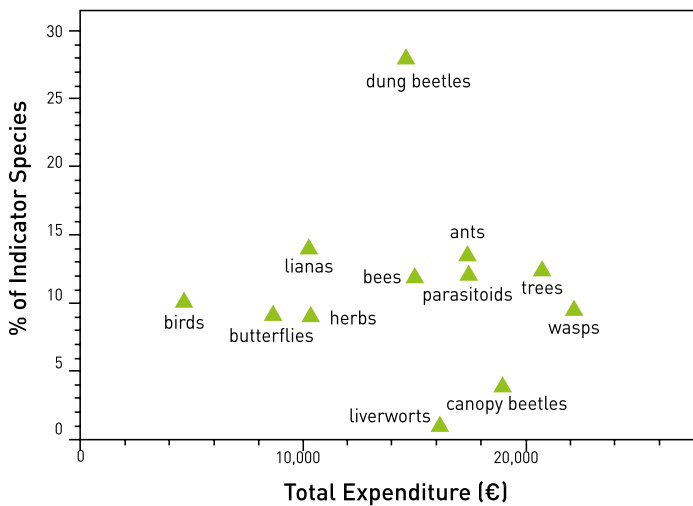


Fig. 6. Relationship between survey costs and the percentage of indicator species (as a proxy of indicative power) among different groups of organisms in old-growth rainforest and two agroforest habitats (high- and low-shade cocoa, respectively) in Sulawesi, Indonesia. Indicator species are given as the sum of species with significant indicator value for one of the three habitat types. Note that the different groups of organisms are not entirely comparable since sampling efforts and completeness were not standardised. In this particular study, dung beetles and birds show among the best cost-benefit ratios, liverworts and canopy beetles the poorest. In practice, the cost-efficiency of indicators is more complex. E.g. while monitoring trees is rather costly it often has many co-benefits (for differentiating vegetation types, estimating carbon stocks, management of sustainable resource use, etc.). Source: redrawn after Kessler et al. 2011

monitoring initiatives is to quantify trends in *overall* species richness of an area or habitat type. Biodiversity ‘surrogates’, single groups of organisms that reliably reflect general biodiversity, are a necessity to make this practically feasible. Unfortunately, ideal surrogates do not exist — virtually every group of organisms responds in an inherent and peculiar manner. Some groups do, however, make better surrogates than others. E.g. plants and birds are generally well-known, feasible to monitor, and usually correlate well with overall biodiversity.

- **Consider monitoring of ‘key species’.** Depending on the specific objectives, monitoring may not necessarily target species of maximum indicative value but species with other outstanding properties or values (‘key species’). Be aware that the term ‘key species’ is not clearly defined and can easily cause misunderstandings. Key species are often defined based on the following

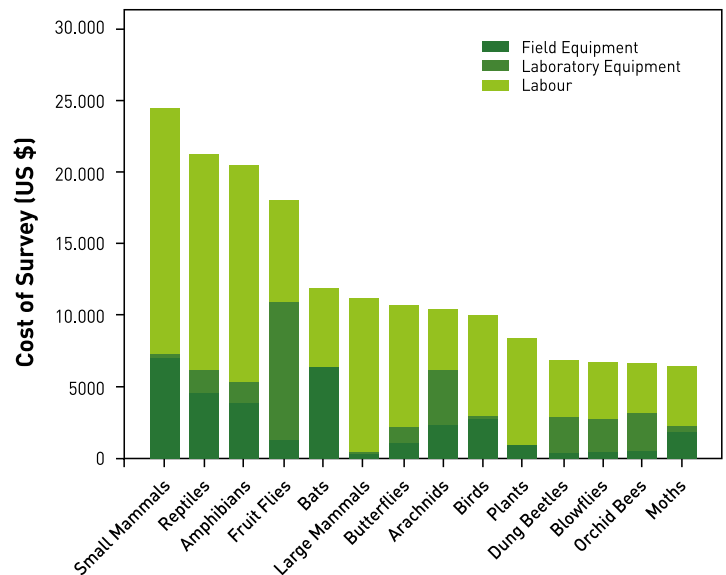


Fig. 7. Total survey costs for 14 groups of organisms in the Brazilian Amazon. In this study, dung beetles, birds and blowflies (scavenger flies) showed the highest returns in terms of indicative value for human alterations (or lack thereof) relative to expenses, small mammals and selected moths the lowest (not shown). Labour costs can occur mostly in the field (e.g. birds) or the lab (e.g. moths). Source: redrawn after Gardner et al. 2008.

concepts: **Umbrella species** are species with high requirements regarding habitat size and quality, the conservation of which almost consequentially secures the conservation of the bulk of other species sharing their habitat (e.g. tiger). **Flagship species** are ambassadors of conservation initiatives selected for being charismatic (to attract support) and usually rather large in size to promote the conservation of extensive areas (e.g. tiger, panda). **Keystone species** are named for their paramount importance for ecosystem stability and/or functioning (e.g. top carnivores, giant armadillo or fig trees). The related term **ecosystem engineers** is commonly applied to keystone animal species that strongly shape their habitat, especially through mechanical action (e.g. beaver building dams, elephants maintaining forest clearings). The IUCN Red List is authoritative regarding the national or global conservation status of species ([IUCN threat categories](#) e.g. being **vulnerable**, **endangered** or **threatened** with extinction). **Restricted-range species** are of particular conservation concern because their naturally narrow geographical distributions make

them particularly prone to extinction. Restricted-range species are often termed **endemics** (= endemic species) where their range coincides with geographical or political entities (e.g. limited to a biogeographical region, country, a province, mountain range or catchment).

- **Don't get carried away.** Simple approaches are usually the most cost-effective, feasible and sustainable and may be entirely sufficient. E.g. a simple index of relative abundance for a given target species based on opportunistic data (e.g. catch per effort) may often suffice to replace a resource-intensive setup that yields actual (absolute) population size.

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