A framework for monitoring biodiversity in protected areas and other effective area-based conservation measures

Concepts, methods and technologies

Daniel Dalton, Vanessa Berger, Hanns Kirchmeir, Vanessa Adams, Judith Botha, Stephan Halloy, Robbie Hart, Vid Švara, Katia Torres Ribeiro, Sunita Chaudhary, Michael Jungmeier

IUCN WCPA Technical Report Series No. 7

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A framework for monitoring biodiversity in protected areas and other effective area-based conservation measures

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Created in 1948, IUCN is now the world's largest and most diverse environmental network, harnessing the knowledge, resources and reach of more than 1,400 Member organisations and around 16,000 experts. It is a leading provider of conservation data, assessments and analysis. Its broad membership enables IUCN to fill the role of incubator and trusted repository of best practices, tools and international standards.

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www.iucn.org
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IUCN World Commission on Protected Areas

IUCN's World Commission on Protected Areas (WCPA) is the world's premier network of protected and conserved areas expertise. The Commission has over 2,500 members spanning 140 countries who provide strategic advice to policymakers and work to strengthen capacity and investment for protected areas establishment and management. The Technical Reports series is one of the Commission's flagship products, providing timely guidance on aspects of protected area planning, management and assessment.

iucn.org/wcpa

Carinthia University of Applied Sciences

Carinthia University of Applied Sciences is a leading institute of higher education in southern Austria and is home to the UNESCO Chair on Sustainable Management of Conservation Areas. Providing high quality educational offers, international partnerships and practical work experiences, the university has five campus locations featuring areas of expertise in Civil Engineering & Architecture, Engineering & IT, Health Sciences & Social Work and School of Management. Many faculty specialise in high-tech fields, including using state-of-the-art technologies for environmental analysis and monitoring. About 40 degree programmes are offered at the Bachelor's or Master's level, including the distinguished Master of Science programme Management of Conservation Areas.

cuas.at/en

UNESCO Chair on Sustainable Management of Conservation Areas

The UNESCO Chair on Sustainable Management of Conservation Areas is one of about 950 UNESCO Chair programmes worldwide and was established at Carinthia University of Applied Sciences, Austria in 2020. Our integrated programme is part of the UNITWIN Network, combining research, teaching, community engagement and training to advance UNESCO's role as a global observatory and source of innovative ideas. Our UNESCO Chair is composed of international scientists and a robust network of collaborators that bring diverse experiences and perspectives to the table, resulting in strong global partnerships.

unesco.org/en

ICIMOD

The International Centre for Integrated Mountain Development (ICIMOD) is an intergovernmental knowledge and learning centre working in eight regional member countries of the Hindu Kush Himalaya (HKH) region – Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan. ICIMOD works to improve the lives and livelihoods of men, women and children of the HKH and protect mountain environments and cultures.

icimod.org

E.C.O. Institute of Ecology

E.C.O. Institute of Ecology is an Austrian company that is a world leader in planning, consulting, research and training for nature conservation, certified regions and protected areas since 1997. The company has a permanent staff of around 20 highly qualified professionals, supported by an international network of cooperating professionals and organisations. E.C.O. provides consultancy, research, training and project design services specifically for protected areas and for organisations or authorities concerned with conservation, natural resources, land-use planning or ecology. Based on many years of practical experience, E.C.O. develops ecological solutions in close cooperation with different stakeholders and projects.

e-c-o.at

ICMBio

The Chico Mendes Institute for Biodiversity Conservation (ICMBio) is a Brazilian federal institution linked to the Ministry of the Environment and Climate Change. It is in charge of 336 protected federal areas, in the most diverse IUCN categories, including areas of shared management with traditional communities. ICMBio is also responsible for articulating conservation strategies for endangered fauna and protecting the country's speleological heritage, through national conservation action plans. The main lines of action are promoting public use, strengthening biodiversity production chains, promoting research and monitoring. In addition, the institution supports activities such as enforcement and land regularization, having social participation as a transversal axis of action.

gov.br/icmbio

Missouri Botanical Garden

The Missouri Botanical Garden's mission is "To discover and share knowledge about plants and their environment in order to preserve and enrich life". Founded in 1859, the Missouri Botanical Garden is the USA's oldest botanical garden in continuous operation and a National Historic Landmark. The Garden is a centre for botanical research and science education, as well as an oasis in the city of St. Louis. The Garden offers 79 acres of beautiful horticultural display, including a 14-acre Japanese strolling garden, historic architecture, and one of the world's largest collections of rare and endangered flora. The Garden's Science and Conservation division is dedicated to exploring, conserving, and restoring global plant life and ecosystems while amplifying impact through collaboration to ensure a sustainable future for biodiversity and people.

missouribotanicalgarden.org

South African National Parks

South African National Parks (SANParks) is based in South Africa and is mandated to conserve both natural and cultural heritage through the network of protected areas that they manage. The bulk of the biophysical and social science monitoring and research is conducted by the Scientific Services division. The generated knowledge informs park management and promotes the conservation of biodiversity. Biophysical monitoring and research span the terrestrial, aquatic and marine domains and includes current threats such as climate change, invasive alien species and many more.

sanparks.org

University of Tasmania

Since its beginnings in 1890, the University of Tasmania has established a strong foundation in research excellence. The University of Tasmania strategy focuses on place-based but globally significant research, world-leading for Tasmania and from Tasmania to the world. Environmental research is central to this. The School of Geography, Planning, and Spatial Sciences builds on and advances the University's strategic pursuit of academic and applied multi-disciplinarity, encompassing and integrating human geography, physical geography, spatial sciences, planning, and environmental management. The School seeks to leverage its collective expertise in geography, planning, and spatial sciences to contribute to a sustainable and equitable future. We believe in the power of scientific inquiry, systems thinking, and community collaboration to generate solutions that address complex social and environmental challenges.

utas.edu.au

Bahir Dar University

Bahir Dar University (BDU) is situated in the beautiful city of Bahir Dar, Ethiopia at the southern shore of Lake Tana Biosphere Reserve. Lake Tana is the largest freshwater body protected by UNESCO. The establishment of BDU is associated with the beginning of Bahir Dar Polytechnic Institute and Bahir Dar Teachers' College in 1963 and 1972, respectively. Currently, BDU is one of the largest universities in Ethiopia enrolling more than 40,000 students in its 434 programmes (115 undergraduate and 297 postgraduate programmes, 16 specialty and subspecialty and six certificate programmes). Nationally, BDU has been ranked first in the higher education differentiation scrutiny by the Ethiopian Ministry of Education. It has also been ranked in the top 20 Sub-Sahara African universities. BDU aspires to be one of the leading research-intensive universities in Africa and the first choice in Ethiopia by 2030. It aligns its operational and educational priorities with relevant Sustainable Development Goals.

bdu.edu.et

Observatoire des Forêts d'Afrique Centrale

Created in 2007, the Observatoire des Forêts d'Afrique Centrale (OFAC) is a specialised unit of the Commission des Forêts d'Afrique Centrale (COMIFAC) that provides up-to-date, relevant data on the region's forests and ecosystems, aimed at informing political decision-making and promoting better governance and sustainable management of natural resources. OFAC collaborates with several international partners (IUCN, UNEP-WCMC, FAO, JRC, ATIBT, etc.). Its information system is organised around an online interactive analytical platform (https://www.observatoire-comifac.net/analytical_platform), and the observatory publishes numerous analyses through maps and flagship publications such as the State of Forests and the State of Protected Areas. OFAC is supported by the RIOFAC project, financed by the European Union.

observatoire-comifac.net

Centre for Biodiversity Conservation Research

The Centre for Biodiversity Conservation Research (CBCR) is an autonomous research institution hosted by the University of Ghana. CBCR's mission is to promote the conservation of biological diversity for the benefit of current and future generations of people. The Centre's strategies for achieving its mission include, knowledge generation, training/capacity building, networking, policy analysis and research dissemination. CBCR's current programme focus includes: wetlands, a most vulnerable ecosystem in Ghana and globally; protected areas, a key tool for biodiversity conservation; species conservation to stem the tide of biodiversity losses and ecosystem services to demonstrate the value of biodiversity and highlight the nexus between nature conservation, livelihoods and development.

cbcr-ug.org

DivjaLabs

DivjaLabs, a spin-out company of the University of Ljubljana, Slovenia, was founded in 2022. Its diverse, international and multi-disciplinary team of scientists leverages state-of-the-art eDNA-based molecular and computational tools to tackle challenges in biodiversity conservation and wildlife management. With its dedication to innovation and appreciation of nature and wildlife, the DivjaLabs team has rapidly emerged as a frontrunner in European biodiversity and wildlife monitoring and research.

divjalabs.com

EarthRanger

EarthRanger is a data visualisation and analysis software platform that gives conservationists the real-time information they require to keep wildlife, habitats and communities safe. Easy to use and free for conservation missions, the platform collects, integrates, and displays all historical and available data and combines it with reports from the field to provide one unified view of collared wildlife, rangers and any other assets whether on land or sea. The EarthRanger programme has been in place for over nine years and has reduced threats to biodiversity and habitats in over 500 protected areas across more than 60 countries and on six continents. It has facilitated the reintroduction and restoration of diverse species and ecosystems that deliver global environmental and socioeconomic benefits. The programme is a philanthropic initiative by the Allen Institute for Artificial Intelligence (AI2), a non-profit founded by the late Paul Allen, co-founder of Microsoft.

EarthRanger.com

GEO BON

The Group on Earth Observations Biodiversity Observation Network (GEO BON) is a flagship of GEO and is hosted by the Quebec Centre for Biodiversity Science at McGill University in Montreal, Canada. GEO BON is a rapidly growing global research network and community of practice of nearly 3,000 members, from more than 1,700 organisations and 144 countries, dedicated to improved monitoring of Earth's biodiversity. GEO BON's mission is to improve the acquisition, coordination and delivery of biodiversity observations and related services to users including decision-makers and the scientific community. GEO BON initiates and coordinates efforts to design and implement interoperable national and regional biodiversity monitoring programmes with a vision of a global biodiversity observing system that contributes to effective management policies for the world's biodiversity and ecosystem services.

geobon.org

National Institute for Environmental Studies

The National Institute for Environmental Studies (NIES) was established in Japan in 1974 as the National Institute for Pollution Studies and was renamed in 1990. NIES focuses on research related to societal, social changes, and environmental challenges. The relationship between climate change and natural disasters, which have become increasingly common in recent years both in Japan and globally, has become a matter of major public concern, prompting Japanese government declarations that set goals for adaptation to climate change and achievement of carbon neutrality. The next decade will be a crucial period for achieving these goals and building a new society. At NIES, the primary mission is to study the many issues related to these challenges and provide scientific knowledge to inform the decisions of the Japanese government and the public. Since 2013, NIES has also collaborated with the International Union for Conservation of Nature-Japan (IUCN-J) to enhance biodiversity conservation efforts.

nies.go.jp/index-e.html

Universiti Teknologi MARA

Founded in 1956, Universiti Teknologi MARA (UiTM) is a mega public university in Malaysia. With its main campus in Shah Alam, the university has 34 campuses spread throughout the nation. UiTM is not only the largest university infra-structurally, but also demographically with 187,551 local and international student enrolment supported by 18,983 academic and non-academic staff. The university currently offers 510 academic programmes, and providing innovative education within four colleges of study, 14 faculties and seven academic centres across Malaysia. UiTM campuses are well equipped with modern facilities to accommodate its community's academic and research needs. The university has earned a reputation for teaching and research excellence over the last six decades.

uitm.edu.my

Stellenbosch University

Based at a world-class South African tertiary institution, Stellenbosch University, the School for Climate Studies is focused on developing and implementing an Africa-relevant research programme that responds to existing and emerging issues in climate change impacts, adaptation and mitigation responses, thus supporting human climate resilience on the continent. By working across all faculties in the university, it is developing new academic capacity, career paths and infrastructure for climate studies, creating opportunities for students to develop the skills required to work in leading national and international public and private entities engaged in fundamental and applied climate studies. The School consolidates and integrates current disciplinary and transdisciplinary thinking on climate, conducts and coordinates primary research, publishes and makes accessible research results, and creates or supports the required platforms for data-intensive research and innovation.

climate.sun.ac.za

University of Florence

The University of Florence is a leading European research and higher education institution, including on biology and biodiversity science. The University offers 126 Degree courses (Bachelor and Master Degrees) to a population of approximately 50,000 students, and each year awards around 9,000 diplomas. The Department of Biology is one of the 24 departments and carries out research mainly on conservation biology, functional and structural biology, and evolutionary biology. The various research groups that focus on biodiversity include the laboratory of animal ecology and biodiversity conservation.

ecologyandbiodiversity.unifi.it

University of Ljubljana

The University of Ljubljana, founded in 1919, stands as Slovenia's premier higher education and research institution. With over 40,000 students and 6,000 faculty and staff across 23 faculties and three arts academies, our rich tradition and modern facilities are central to Ljubljana's academic landscape. Consistently ranked among the top 500 universities globally by multiple analytics firms, University of Ljubljana is an important hub of academic and research activity.

uni-lj.si/

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IUCN WCPA Technical Report Series No. 7

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Contents

List of figures

List of tables

List of annex figures

List of annex tables

List of checklists

List of boxes

High-elevation arid plateau featuring giant lobelia (*Lobelia rhynchopetalum*), Bale Mountains National Park, Ethiopia.
© *Michael Jungmeier*

Preface

The growing pressures on Earth's natural environments threaten biodiversity and the functioning of ecosystems. Protected areas and other effective area-based conservation measures provide areas of land and water to safeguard species populations. As their numbers and expanse increase, these landscapes play a key role in conservation. Yet, management of our protected areas requires a strategic and evidence-based approach. Accurate information is gained through monitoring the right indicators at the right time. Maintaining a balance between ecological and cultural elements is a major challenge to site management, especially in the absence of sufficient resources or when monitoring programmes are not performed consistently. To make the best use of limited resources, systematic monitoring of management outcomes that affect biodiversity is critical.

This Technical Report Series guideline provides a decision-making framework for managers to develop biodiversity monitoring programmes in protected areas and other effective area-based conservation measures. The guideline is organised into eight chapters and contains several workshop tools to assist in programme conceptualisation.

Chapter 1 introduces the road map for a four-step framework that will guide managers in the development of efficient and meaningful long-term biodiversity monitoring programmes.

Chapter 2 details the information required to complete the first step of the decision-making framework, the preparatory phase. Managers identify international conventions that require monitoring and gather all background information and site conservation objectives. This step helps to plan and prioritise management activities, leading to documentation of a monitoring statement of purpose.

Chapter 3 defines the six questions that guide the conceptual phase of a new biodiversity monitoring programme. Managers and site employees address the questions together to identify why monitoring is needed, what indicators are most appropriate to monitor, where the programme will take place, when monitoring will occur, who will be involved in the programme and what their responsibilities are, and how many resources are needed to accomplish the programme. This dialogue reveals a meaningful and realistic scope of monitoring.

Chapter 4 describes the implementation phase of the biodiversity monitoring programme. In this phase managers define how the decisions from the conceptual phase are put into action, including developing a statistically robust sampling design and determining which tools to use. Field monitoring cycles are outlined with consideration towards data management and analysis.

Chapter 5 briefly expresses the value of periodic programme re-evaluation to determine whether the programme should be continued in its original state, whether and how it should be modified to address site management, or whether it should be terminated.

Chapter 6 details the many general considerations that help make effective biodiversity monitoring programmes.

Chapter 7 provides an overview on the methods and technologies available today for biodiversity monitoring. Expert monitoring tips are provided for diverse species groups. These are followed by a review of the suitability of different types of monitoring tools and techniques for monitoring target species. Advanced data analytical techniques are introduced.

Chapter 8 provides a synthesis of the guideline and a vision of hope as we face the growing challenges to biodiversity.

To complete the guideline, a series of annex figures and tables is provided, followed by checklists to help prepare for efficient field work and data collection. These materials are designed to be used in a workshop setting to effectively communicate ideas and decisions to involved staff and stakeholders.

We express in this guideline that the value of consistent design and good methodological and technical preparation is fundamental for effective biodiversity monitoring. In addition, we show our enthusiasm for technologies and approaches that are currently transforming biodiversity monitoring. We cast a wide net to gain the perspectives of protected area managers, research scientists, IUCN scientists and other stakeholders.

Each monitoring programme is a commitment to describe our planet's rich biodiversity. May this publication empower and guide all those dedicated to managing our natural wonders.

Executive summary

Protected areas and other effective area-based conservation measures (OECMs) are important to stop the global decline in biodiversity. Systematic site-based monitoring of the state of biodiversity and conservation outcomes is necessary for evidence-based adaptive management in protected areas and OECMs. Biodiversity monitoring is also important to inform managers if they are meeting their conservation goals.

The framework described in this publication will help managers and site planners to consider all relevant details to develop effective biodiversity monitoring programmes for improved management outcomes (Box 1). A step-by-step approach is provided on how to establish biodiversity monitoring programmes as components of biodiversity monitoring systems in conservation areas including protected areas and OECMs, Key Biodiversity Areas and UNESCO sites including biosphere reserves, Global Geoparks and Natural World Heritage Sites. More than 295,ooo protected areas and OECMs are represented on the World Database on Protected Areas (UNEP-WCMC, 2023a), indicating the great need for utilising standardised monitoring frameworks whilst meeting local objectives. Today's monitoring technologies are undergoing a rapid evolution, and this publication also provides a snapshot of the state-of-the-art of monitoring tools.

Box 1

Scope of monitoring, biodiversity monitoring systems and monitoring programmes

Monitoring is the process of regular data collection and analysis that is then used by managers to determine whether project objectives are being met. Monitoring may occur at multiple points within the framework cycle of drivers, pressures, state, impacts and responses and is the main tool for managers to determine overall management effectiveness at their sites. Multiple monitoring programmes are contained under a comprehensive biodiversity monitoring system, supporting management objectives of protected areas and OECMs.

A biodiversity monitoring programme is an ongoing module of the biodiversity monitoring system. It is designed to deliver benefits to the organisation that are aligned with its objectives (Weaver, 2010). Programmes may or may not be time-limited, as determined by the organisational structure of the protected area or OECM.

A biodiversity monitoring project is an activity that is usually limited in time and funding. A project is designed to deliver a specific output. Efficiency of the work is key to a successful project (Weaver, 2010). Monitoring projects serve as opportunities for protected areas and OECMs to showcase effective monitoring methods and their unique biodiversity.

The schematic shown in Figure 2 describes the different purposes of monitoring. If information on the indicator is missing, and management activities have not been determined, typically a research project will generate basic site information. If the state of the indicator is unknown, but management activities have already been determined, monitoring is conducted as a baseline study. If the status of the indicator is known, and the management activities are not decided, monitoring is most suitable for regional documentation. If information on the indicators is available and the desired management techniques are known, monitoring to support site management may proceed. This guideline focuses on this last scenario, monitoring for management purposes.

Source: Compiled by the report authors

The framework for developing biodiversity monitoring programmes is introduced in a step-by-step manner consisting of four phases: a) preparatory phase; b) conceptual phase; c) implementation phase with periodic interim evaluation guiding adaptive management; and d) periodic re-evaluation (Figure 1). We conclude with a discussion on the level of technology that is required for adequate monitoring, considering that monitoring is a long-term activity and the state-of-the-art is continually improving. We point out the importance of data continuity given the different methodologies and monitoring tools worldwide. Developing a good biodiversity monitoring system requires using different forms of knowledge, ethical issues, scientific evaluation and effective communication.

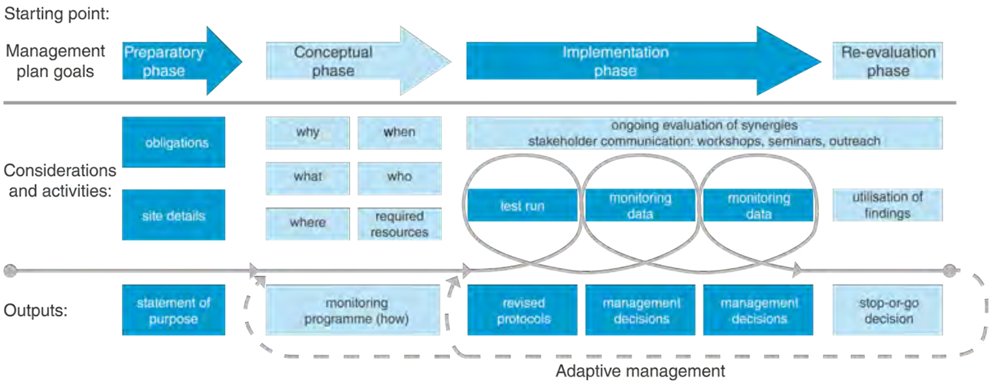

Figure 1 Key phases of developing a biodiversity monitoring programme in protected areas and other effective area-based conservation measures Effective biodiversity monitoring programme planning will correspond with site management goals. In the preparatory phase, a review of the site details and obligations should be conducted, resulting in a monitoring statement of purpose. The conceptual phase follows, where a series of basic questions are addressed about the intended monitoring programme. The result is an understanding of how the monitoring programme will be implemented. To verify the protocols, test runs are conducted in the implementation phase prior to the repeating cycles of the programme. Data analysis will guide management decisions based on findings. Detailed re-evaluation of the programme occurs after a predetermined number of cycles, providing opportunities for adaptive management. *Source: Compiled by the report authors*

All site-based monitoring programmes should be well-integrated into the biodiversity monitoring system. Within individual protected areas or OECMs, several types of monitoring programmes may be established, contributing to protected area management effectiveness (PAME), law enforcement, threat assessment and resource use efficiency. Biodiversity monitoring programmes must produce accurate data supporting site management, and multiple sites will ideally be included in a programme for conclusions on long-term trends. Effective management will in turn help develop policy recommendations to remedy the loss of biodiversity and restore damaged ecosystems.

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All opinions, findings, conclusions and recommendations expressed in this Technical Report Series guideline are those of the authors and do not necessarily reflect the view of the funding agencies or the IUCN WCPA. All textual errors are the responsibility of the authors.

Primeval beech forest, Poloniny National Park, Slovakia, part of the Serial World Heritage Site "Ancient and Primeval Beech Forests of the Carpathians and Other Regions of Europe".
© *Hanns Kirchmeir*

Glossary

Adaptive management. A systematic process of continually improving management policies and practices by learning from the outcomes of existing programmes (IUCN, 2022b).

Area of interest. Area representing a habitat, environment or ecosystem where biodiversity monitoring takes place.

Biodiversity monitoring. Regular, statistically designed counts of a population in order to watch its numbers, composition and distribution (IUCN, 2022b).

(Biodiversity) monitoring programme. An ongoing component of the site management framework that addresses site objectives (e.g. vegetation monitoring, bird monitoring).

Biodiversity monitoring system. Framework that considers management objectives, conceptual elements and best practices to support multiple biodiversity monitoring programmes.

Conservation goal. An identified target that is intended to be reached in conservation planning, including species, habitats, landscapes, biodiversity or ecosystem services (Lacher, 2018).

Conservation outcome. The result of a management action.

Convention on Biological Diversity (CBD). International agreement effective from 29 December 1993 containing three main goals: conservation of biodiversity; sustainable use of biodiversity resources; and fair and equitable sharing of benefits from genetic resources (CBD, 1992).

Drivers, pressures, state, impacts and responses. Causal chain framework where driving forces such as economic development put pressure on the environment, changing its state. These changes lead to impacts on ecosystems, leading to a societal response that feeds back into the causal chain (Niemeijer & de Groot, 2008).

Flagship species. Popular charismatic species that serve as symbols to stimulate conservation awareness and action locally, nationally, regionally or globally (IUCN, 2022b).

Governance. Relating to seven principles of legitimacy, transparency, accountability, inclusiveness, fairness, connectivity and resilience that enable positive management outcomes (Lockwood, 2010).

Indicator (species). A species sensitive to environmental change, which can therefore provide a measure of health for the ecosystem (IUCN, 2022b).

Indigenous peoples and local communities. The CBD does not recommend a formal definition of Indigenous peoples and local communities. However, the IPBES Global Assessment Report on Biodiversity and Ecosystem Services provides the following definition: “individuals and communities who are, on the one hand, self-identified as indigenous and, on the other hand, are members of local communities that maintain inter-generational connection to place and nature through livelihood, cultural identity and worldviews, institutions and ecological knowledge” (Brondizio et al., 2019).

Key Biodiversity Area. Site contributing significantly to the global persistence of biodiversity (IUCN, 2016).

Kunming-Montreal Global Biodiversity Framework (GBF). Building on the CBD Strategic Plan for Biodiversity 2011–2020, the GBF calls for transformative changes in the world approach to conserving biodiversity by 2050, including placing at least 30 per cent of the Earth’s terrestrial surface under effective conservation, with emphasis on management effectiveness.

Marine Protected Area. Any area of intertidal or subtidal terrain, together with its overlying water and associated flora, fauna, historical and cultural features, which has been reserved by law or other effective means to protect part or all of the enclosed environment (Kelleher, 1999).

Minimum mapping unit. The size of the smallest unit that can be reliably detected or mapped.

Monitoring. The process of regular data collection and analysis that is then used by managers to determine whether project objectives are being met.

Monitoring concept worksheet. Strategic template worksheet used by managers and staff to identify the available resource base and appropriate scope of a proposed biodiversity monitoring system.

Monitoring cycle. Single monitoring interval that includes complete routine from securing field workers to data analysis and archiving.

National Biodiversity Strategy and Action Plan (NBSAP). Principal instrument for implementing the CBD at the national level. Signatories are required to prepare a national biodiversity strategy or equivalent instrument. NBSAPs provide important information on national targets and commitments and on the activities planned to achieve them (CBD, 2020).

Other effective area-based conservation measure (OECM). A geographically defined area other than a protected area, which is governed and managed in ways that achieve positive and sustained long-term outcomes for the in situ conservation of biodiversity with associated ecosystem functions and services and, where applicable, cultural, spiritual, socio-economic and other locally relevant values are also conserved (IUCN, 2022b).

Protected area. A clearly defined geographical space, recognised, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values (Dudley, 2008).

Protected Area Management Effectiveness (PAME). Assessment of biodiversity, social, cultural and economic outcomes as a result of protected area management. This evaluation also includes understanding the context of management, planning, inputs, processes, outputs and outcomes (Hockings, Leverington & Cook, 2015).

Proxy indicator. Something that might not be directly important but helps to get information about an indicator of interest.

Red List of Threatened Species™. Listing of the conservation status of the world's flora and fauna administered by IUCN. The IUCN Red List of Threatened Species™, known as the IUCN Red List, is the world's most comprehensive inventory of the global conservation status of plant and animal species. It uses a set of criteria to evaluate the extinction risk of species and subspecies. The IUCN Red List is recognised as the most authoritative guide on the status of biological diversity (IUCN, 2022b).

Simulated data. Realistic mock data that can be used during project development to assist developing a robust statistical design.

Stakeholder. Actor (such as but not limited to landowners) socially endowed with legal or customary rights with respect to land, water and natural resources who possesses direct or indirect interests and concerns about these resources but does not necessarily enjoy a legally or socially recognised entitlement to them (Borrini-Feyerabend et al., 2013).

Statement of purpose. Brief summary of the purpose of a biodiversity monitoring system or management programme.

Traditional ecological knowledge. Knowledge from Indigenous or local communities that plays a significant role in facilitating or discouraging collaboration between Indigenous and non-Indigenous stakeholders (Whyte, 2013).

Umbrella species. A species whose conservation is expected to confer protection to a large number of naturally co-occurring species (Roberge & Angelstam, 2004).

United Nations Educational, Scientific and Cultural Organization (UNESCO). Organisation that promotes international cooperation in education, sciences and culture. UNESCO's programmes contribute to the achievement of the Sustainable Development Goals defined in the 2030 Agenda (UNESCO, 2022).

World Heritage Site. Unique area of Outstanding Universal Value that requires long-term protection, is non-renewable and irreplaceable, as identified by UNESCO and the World Heritage Committee (Zhang et al., 2022).

Floodplain forest along the Isar River, Bavaria, Germany.
© *Vid Švara*

CHAPTER 1.

Introduction

1 Introduction

Biodiversity monitoring is the main tool to assess the state of biodiversity at a site. Long-term monitoring can show the effect of management actions and helps managers determine the outcome of conservation measures. It is also an approach supporting establishing baseline information, scientific research and regional documentation (Figure 2). This publication presents a consistent decision-making framework for designing biodiversity monitoring programmes that support biodiversity monitoring systems in protected areas and OECMs. It is beyond the scope of the guideline to consider monitoring for general scientific research or for establishing baseline inventories of habitats and species. Besides monitoring, additional features of a management programme will contribute to positive conservation outcomes, including governance and social engagement (Jungmeier et al., 2013). An IUCN Best Practices guideline is available that details the many components of governance that contribute to protected area management effectiveness (Borrini-Feyerabend et al., 2013).

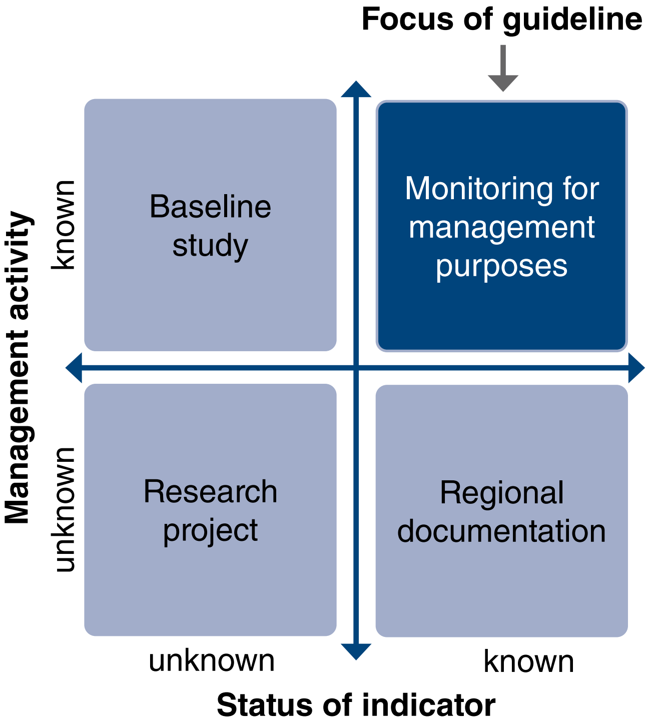


Figure 2 Scope of the framework for monitoring biodiversity in protected areas and other effective area-based conservation measures (OECMs) Biodiversity monitoring accomplishes many potential goals. The focus of the guideline is on achieving management objectives through monitoring of biodiversity in protected areas and OECMs. Monitoring for baseline data, scientific value and regional documentation are beyond the scope of the guideline. *Source: Compiled by the report authors*

Protected areas are sites where the main management objective is the conservation of biodiversity or the environment. By contrast, OECMs are sites where management activities should deliver positive conservation results even though such activities may not be the main purpose of site management. For OECMs, the most important biodiversity values may need to be identified in advance of developing a site-level biodiversity monitoring system. A three-step assessment tool requiring fulfilment of eight criteria is available for managers to determine whether their site qualifies as an OECM. After all criteria are satisfied, the assessment is transferred to the governing authority, who then reports the site through the World Database on Protected Areas (Jonas et al., 2023). Protected areas and OECMs are both considered important for achieving the targets established by the Kunming-Montreal Global Biodiversity Framework (see chapter 6.1).

The decision-making framework for biodiversity monitoring includes four phases (see Figure 1). The preparatory phase is designed to help managers identify the requirements of their sites to accomplish management objectives. In the conceptual phase, managers and staff evaluate the scope of individual biodiversity monitoring programmes. The outcome is a monitoring strategy that is applied in the implementation phase. The re-evaluation phase helps decision-makers determine whether the findings of the monitoring programme effectively guide adaptive management procedures, concluding with a decision to continue, modify or terminate the monitoring programme.

Preparatory phase. Site management activities are determined by management plan goals, protected assets, actual or potential threats, the demands of different stakeholders, and from changing uses of the protected area or OECM and surrounding areas. Site-specific conditions will impact the scope of the biodiversity monitoring programmes that make up the biodiversity monitoring system. In many cases, requirements on indicators and protocols already exist and should first be considered, such as the objectives of a country's National Biodiversity Strategy and Action Plan that is required by the Convention on Biological Diversity (CBD). Legal obligations from other national or international policies may also exist. Additional site-specific background information will reveal any knowledge gaps that can be improved in later phases. The output of the preparatory phase is a clear programme-specific statement of purpose that identifies priority questions for monitoring. Documenting the approaches used to address a particular monitoring question will help other sites in the network implement effective protocols.

Conceptual phase. With clearly defined biodiversity goals from the statement of purpose, the next step is to document the questions and answers that guide the specific biodiversity monitoring programme. This step is the conceptual phase. The conceptual phase is assisted by the use of the monitoring concept worksheet, a tool that helps to focus the many considerations of biodiversity monitoring programmes through a series of six basic questions: 'why' establish the monitoring programme, 'what' will be monitored, 'where' and 'when' will monitoring occur, 'who' are the stakeholders involved, and what 'required resources' are needed. We provide a printable poster-sized version of the monitoring concept worksheet to help managers and staff make the necessary considerations (Annex Figure 1). Example considerations of each part of the monitoring concept worksheet are provided (Annex Figure 2). Questions can be considered in any order and can be revisited at any time. It is recommended to review all questions at least two times. After the questions have been considered, the framework of 'how' monitoring will be conducted and the synergies with other monitoring programmes will complete the monitoring concept worksheet. A key output of the conceptual phase will be to document supporting decisions on which tools and methods will be used in the next phase of the monitoring programme, implementation. Working through the six questions will identify how monitoring will be conducted and potential synergies with the larger management programme or national network.

Implementation phase. The actual monitoring occurs during the implementation phase of the monitoring programme. This phase involves specific steps for performing field work and data collection. The necessary materials should be acquired, and a preliminary manual describing the details of the field work should be produced. When finalised, field workers should be trained according to the manual. After training, at least one test run should occur at an easily accessible site. Any changes should be recorded in the manual, and training and test run cycles should be repeated until the workflow functions as planned. Data collection can then begin at field sites through monitoring cycles that are repeated at appropriate intervals, depending on the indicators. Statistical analysis of the collected data should occur periodically during the implementation phase. Presentation of the results should be given transparently and in appropriate formats to different stakeholder groups. Findings should support adaptive management decisions, provide the basis for PAME reporting, and can be valuable for outreach.

Re-evaluation phase. The fourth phase is the re-evaluation phase. The timing of this phase is typically defined through funding cycles or reporting requirements to comply with biodiversity treaties. Findings are given to decision-makers to identify strengths and weaknesses of the biodiversity monitoring programme. Effective components can be transferred to other site monitoring programmes, or within national and regional biodiversity monitoring networks. Sharing findings can maximise synergies with other programmes because successful elements may serve as templates for further use in other protected areas and OECMs. The outcome of the re-evaluation phase is the decision to continue, adjust or terminate the monitoring activities.

Many general considerations are relevant to developing a biodiversity monitoring system and its many biodiversity monitoring programmes. The following points are applicable to most situations:

- **Obligations: International conventions and policies (see chapter 6.1)**

  Biodiversity monitoring programmes in protected areas and OECMs should be guided by international agreements and must contribute in a meaningful way to national reporting requirements.

- **Art of omission: Daring to simplify (see chapter 6.2)**

  To obtain high-quality data despite potential budgetary or resource restrictions, simplifying monitoring to the lowest number of indicators and technologies possible should be a key feature of a biodiversity monitoring programme.

- **Biodiversity monitoring systems: Designing modular, multi-scale and multi-purpose monitoring systems (see chapter 6.3)**

  Biodiversity monitoring systems should utilise known effective methods and synergies to guarantee that the results are comparable between sites.

- **Combining forms of knowledge (see chapter 6.4)**

  Indigenous and traditional ecological knowledge should be utilised in combination with scientific data for the best understanding of the state of biodiversity in the protected area or OECM.

- **Continuity risks: Avoiding disruptions and gaps in data (see chapter 6.5)**

  Data are most valuable when they are supported by an appropriate statistical design.

- **Detecting trends and correlations: The value of time series (see chapter 6.6)**

  Well-timed and regular collection of data provides strong evidence of trends of the selected indicators.

- **Maintaining ecological balance: Establishing baselines and thresholds (see chapter 6.7)**

  The baseline condition of an indicator is required knowledge to develop meaningful thresholds of change, at which point management activities may be necessary for adaptive management.

- **Setting up monitoring systems: Costs and outcomes (see chapter 6.8)**

  Biodiversity monitoring programme costs are highest at the beginning of the programme, whilst knowledge gain occurs in later cycles.

- **Protected Area Management Effectiveness evaluation tools (see chapter 6.9)**

  Protected area management programmes are evaluated using PAME evaluation tools that are harmonised across protected area networks or National Biodiversity Strategies and Action Plans.

The processes to develop effective biodiversity monitoring programmes are outlined in the following chapters. The **preparatory phase is introduced in chapter 2**, followed by a detailed breakdown of the **conceptual phase in chapter 3**. The **implementation phase is addressed in chapter 4**. Key components of ongoing monitoring cycles are illustrated, with particular emphasis on data management and feedback to facilitate adaptive management (Caughlan & Oakley, 2001). Considerations of the **re-evaluation phase are addressed in chapter 5**. In re-evaluating the programme, reflection is given on appropriate ways to guide future monitoring cycles. In **chapter 6, greater detail is provided on the general considerations listed above. In chapter 7, a brief review of past and current tools for biodiversity monitoring** is provided. The guideline concludes in **chapter 8 with a synthesis and future outlook** of biodiversity monitoring in protected areas and OECMs.

With this road map, it is now time to develop site-specific biodiversity monitoring programmes that will contribute to meeting the overall protected area or OECM management objectives.

Stand of cacti surrounding epiphyte-covered tree *Eriotheca ruizii*, Refugio de Vida Silvestre Laquipampa, Lambayeque, Peru. © *Tobias Fremout*

CHAPTER 2.

Preparatory phase: Setting the frame

2 Preparatory phase

Setting up a biodiversity monitoring programme is a strategic decision-making process that will have long-term effects on protected area or OECM site management. Therefore, enough time should be spent in the preparatory phase to make sure that the programme is properly conceptualised. Site-specific goals and main conservation challenges should be reviewed through a basic site investigation if they are not present in the pre-existing management plan.

In the preparatory phase, all background materials on management of the protected area or OECM should be collected and analysed for their relevance in the subsequent phases. This will indicate the major site threats – and where they are most serious – prior to developing the supporting biodiversity monitoring programmes. Decisions affecting the design of a programme will reference the materials gathered in the preparatory phase. The key output of the preparatory phase is to produce a monitoring statement of purpose to identify and prioritise the main objectives of each monitoring programme in the biodiversity monitoring system (Figure 3).

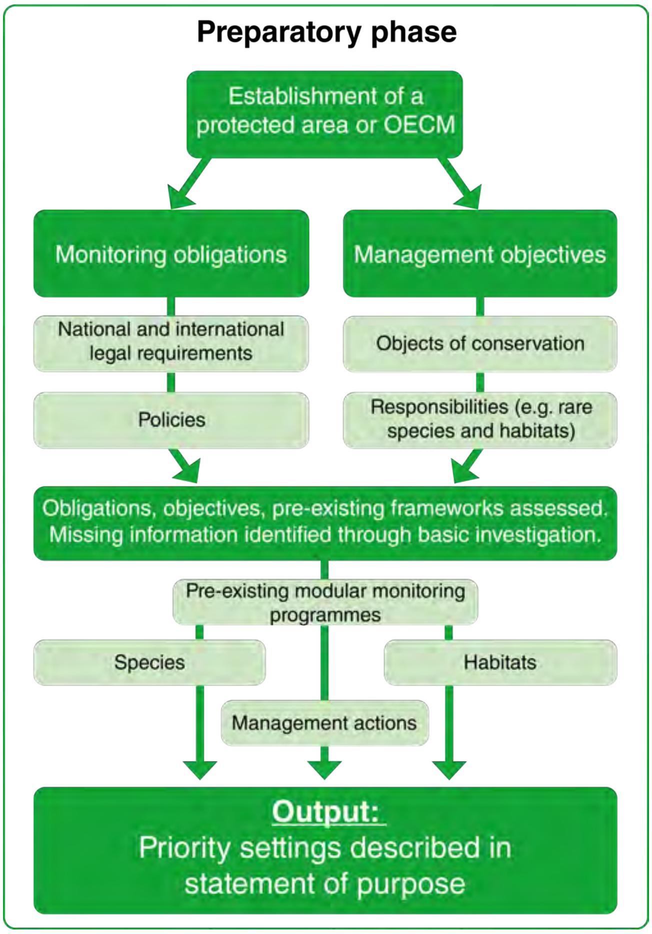


Figure 3 Ontology of the preparatory phase Development of effective biodiversity monitoring programmes requires consideration of management objectives as components of the larger management plan. The previous establishment of a protected area or other effective area-based conservation measure (OECM) is the starting point for filling any knowledge gaps through a basic site investigation. Managers should become familiar with relevant outstanding features, ecological characteristics, threats and site conservation goals. This includes identifying frameworks such as the cycle of drivers, pressures, state, impacts and responses (see Figure 4). With all available information, a list of priority monitoring objectives will be described in a monitoring statement of purpose. *Source: Compiled by the report authors*

2.1 Conventions and standards

Many international conventions and national programmes have reporting obligations on species or habitats of particular value. These requirements should be the first considerations for developing or revising a biodiversity monitoring programme. Sources for this information include formal paperwork, previously surveyed indicators, appropriate monitoring intervals and legal agreements. The information will establish a binding basis for monitoring. To compensate for incomplete information, administrators may consult pre-existing standards and frameworks applicable to similar sites as a guide to develop site-specific approaches. This step is only necessary if the information is not already available in the protected area or OECM management plan.

2.2 Basic investigation and site assessment

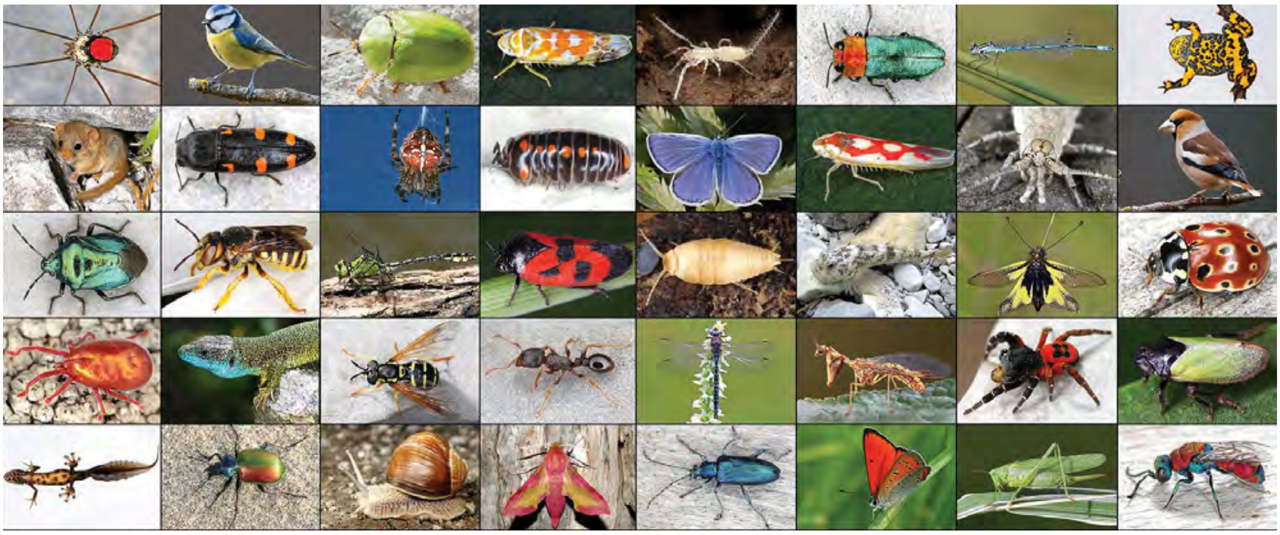
The basic requirement for establishing a biodiversity monitoring programme is good knowledge of the baseline conditions of the protected area or OECM. Existing data, documents, Indigenous and traditional ecological knowledge, and descriptions should be assessed early on to identify the most important biodiversity assets and indicators of the site. If available, assessment should be based on the IUCN Red List of Threatened Species™ (IUCN, 2022c) for species that have historically lived at the site. Data from previous programmes, national and regional catalogues, or other institutions may be helpful. For example, data of climatological or hydrological relevance may improve understanding of the pre-existing site conditions. Depending on the site, cultural or natural heritage considerations may also be important. Land use history may be revealed through examining archive satellite data, historical maps and other past records. Basic investigation and site assessment are only necessary if a management plan does not already provide this information.

2.3 Specifying conservation objectives

Desired conservation outcomes are usually listed either in the text of the nomination or in the legal document establishing the protected area or OECM. However, based on national and international standards and obligations, managers must have a comprehensive site overview of key species and habitats and their protection status. Indicators may be of biological, geological, ecological or cultural significance. Species monitoring can track abundance, distribution, diversity, conservation status and biological characteristics, as described by the Essential Biodiversity Variables developed by GEO BON (Box 2). A site will have elevated conservation responsibility for rare or endangered species and habitats if it meets the criteria for Key Biodiversity Area designation (IUCN, 2016). Comprehensive site planning is beyond the scope of regular management activities. If the management plan does not provide a detailed description of the conservation objectives, administrators should invest sufficient resources for comprehensive site planning, at least to the extent that is reasonably achievable.

Box 2

A global concept: Understanding indicators through the Essential Biodiversity Variables



By definition, biodiversity includes genes, species, traits, community composition and ecosystems. Data on one or more of these dimensions over time and space support biodiversity assessments. Information on how biodiversity changes in these environments is necessary for policy-making. In order to detect change, systematic biodiversity observations are collected using standard formats and methods, together with environmental monitoring. These observational data are moved to open databases. Ensuring that data are interoperable across databases will make efficient use of biodiversity information for guiding conservation and sustainable development strategies.

Essential variables to understand climate, biodiversity and other environmental changes have already been developed (e.g. Essential Climate Variables, Essential Ocean Variables). The concept of Essential Biodiversity Variables (EBVs) was introduced to advance the collection, sharing and use of biodiversity information (Navarro et al., 2017; Pereira et al., 2013), providing a way to aggregate the many biodiversity observations collected through different methods such as in situ monitoring or remote sensing. EBVs can be visualised as biodiversity observations at one location over time, or in many locations, aggregated in a time series of maps.

Aggregation requires collecting biodiversity observations by people and groups, depositing raw data into databases using standard formats and metadata, and processing the data. This information helps to detect and model biodiversity change for science, policy and sustainable development applications. Completing the whole procedure is important for protected area and OECM management activities because the analysis shows changes in biodiversity across large spatial scales. The underlying drivers and pressures of biodiversity change can then be identified (Mace & Baillie, 2007) and modelled (Oliver et al., 2015). Validation of modelling can then feed into global and regional policy processes to explain observations, to improve forecasting of biodiversity change and to produce global assessment reports.

EBVs are scalable, meaning the underlying observations can be used to represent different spatial or temporal resolutions required for the analysis of trends. For example, ecological community data collected at a location from different sampling events or methods can be combined into a single time series. The aggregated data may indicate the change in ecological communities across the region.

When combined with social or economic information from human or environmental pressures, EBVs can be used to identify indicators for biodiversity that reflect responses, for example change in the proportion of habitat in protected areas and ecosystem service benefits to humans. Essential Ecosystem Service Variables have been defined as a type of EBV to support the monitoring of ecosystem services (Balvanera et al., 2022).

Developing and applying EBVs requires local, national and international adoption of standard approaches to collect, store and share biodiversity and environmental observations. This is fundamental to address the pressing societal and economic needs of today and in the future.

Source: GEO BON, Canada. Picture: Animal collage. © Gernot Kunz

2.4 Management planning

Biodiversity monitoring is just one of many components allowing effective site-based management (Stephenson, 2019). Information from monitoring campaigns will help guide adaptive management decisions, resulting in improved conservation outcomes. An effective management plan must address social, cultural, economic and ecological factors (Jungmeier et al., 2013). These factors are best considered through including the perspectives of the full range of regional stakeholders. This involves understanding how burdens and benefits are distributed amongst local communities, clearly defining the management decision-making processes, and recognising the cultural identities of local and Indigenous groups (Zafra-Calvo et al., 2017). A protected area or OECM management plan is most effective when it includes collaboration with stakeholders to achieve goals of common interest (Karadeniz & Yenilmez Arpa, 2022b). A smart management plan will not only conserve biodiversity, but will also encourage local engagement. By including diverse values in management planning, governance of protected areas and OECMs can become transformative. This approach is necessary for sustainable management (Kelemen et al., 2023).

A well-considered management plan will involve Indigenous peoples and local communities in all phases of development and will include legal obligations, site characteristics, and local and regional conservation objectives. A management plan should already be in place in advance of establishing a new biodiversity monitoring programme (Box 3). It is important to have a clear picture of the main pressures, impacts and interactions on site-level biodiversity (Figure 4). Understanding these factors will guide management activities to address specific goals. This information will expedite the conceptual phase (see chapter 3). If some information is missing, additional assessment will be required.

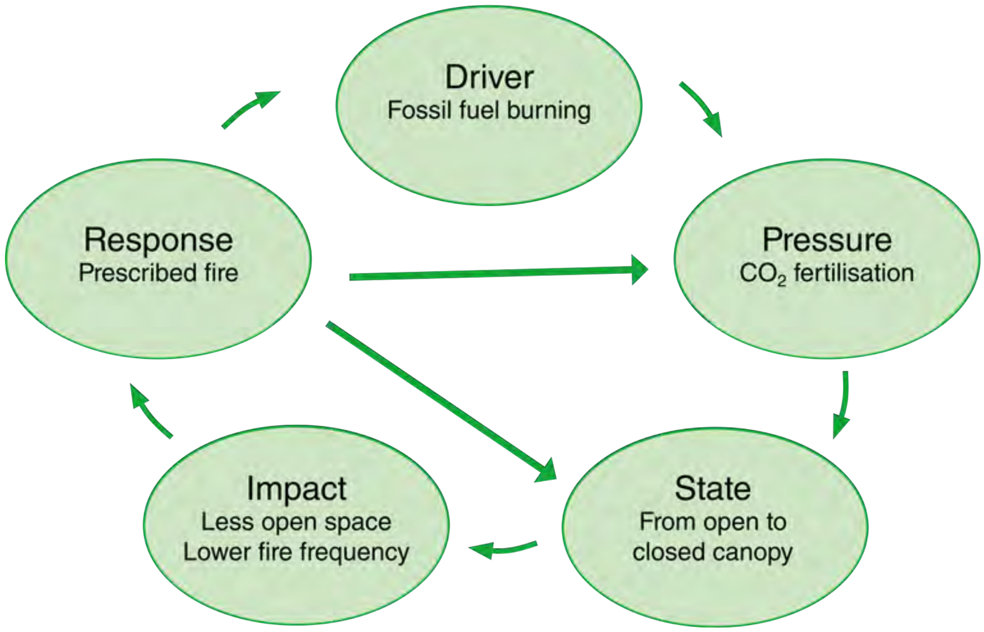
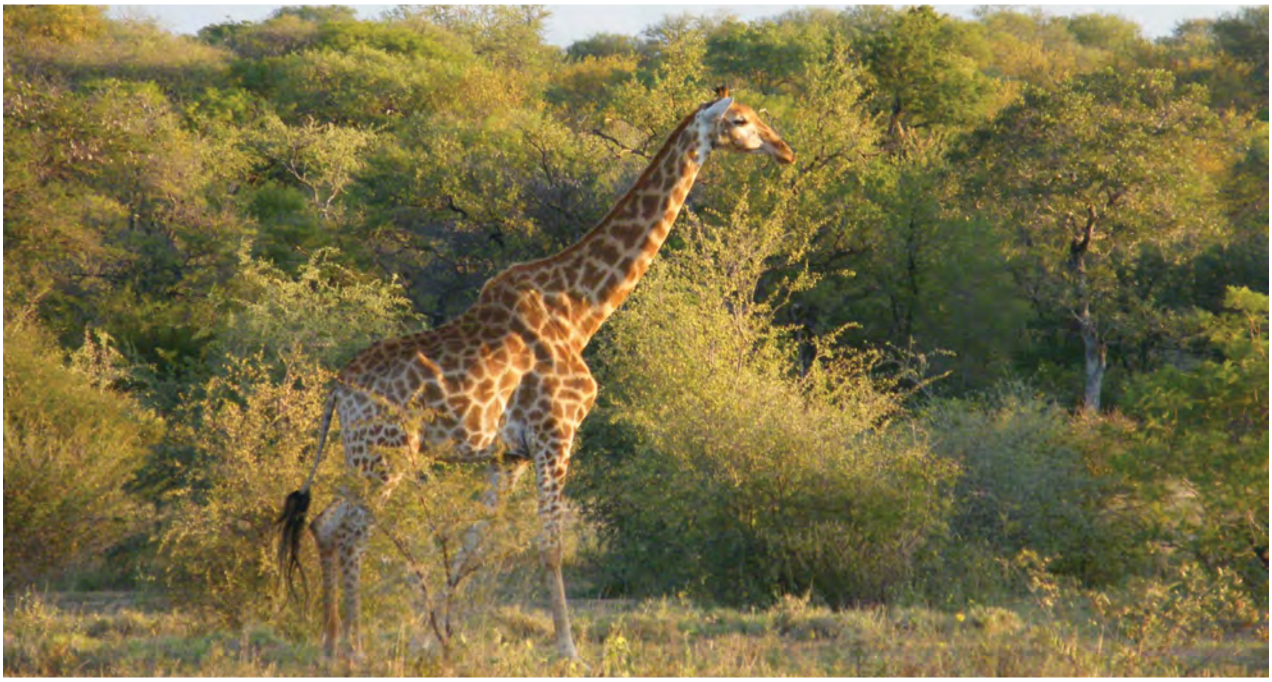


Figure 4 The framework cycle of drivers, pressures, state, impacts and responses is the main tool for managers to determine overall management effectiveness at their sites. This example shows bush encroachment in a savanna ecosystem (see Box 3). *Source: Compiled by the report authors*

Box 3

Bush encroachment in an African savanna: An application of the framework cycle of drivers, pressures, state, impacts and responses in Kruger National Park



Since the pre-industrial era, global mean temperatures have increased by 0.8°C to 1.2°C. This global temperature increase is driven by human activity, and effects on ecosystems are already visible globally (Sala et al., 2000). The world has experienced increased frequency of extreme weather events, prolonged droughts, and heat. Global temperatures will continue to rise, with projected mean temperatures from 1.0°C to 3.5°C warmer by 2100 than the pre-industrial era (IPCC, 2021). Second only to land use change, climate change will have the greatest impact on biodiversity this century (Sala et al., 2000). Species across most ecosystems have already undergone range shifts and phenological changes (IPCC, 2022). Climate change has resulted in losses of critical habitat. In terrestrial ecosystems, warming of 1.5°C is expected to drive up to 14 per cent of species to extinction, with greater percentages at more extreme warming scenarios (IPCC, 2022). This represents a critical loss of biodiversity, even excluding direct impacts of human activities (Lenton et al., 2019).

Interactions between the biodiversity and climate crises are exemplified through ongoing bush encroachment in the savannas of Kruger National Park, South Africa. A major **driver** of bush encroachment is the globally high usage of fossil fuels. The increased atmospheric carbon dioxide (CO_2) levels are one of the **pressures** causing bush encroachment through CO_2 fertilisation that increases tree growth (Buitenwerf et al., 2012; Stevens et al., 2016). Large parts of the park are in a **state** of transition from a more open system characteristic of savannas to a more closed system. The resulting **impacts** include decreased grass abundance and biodiversity across the landscape, a lower carrying capacity for grazing animals, greater tree biomass, and lower fire frequency. In closed canopy systems many species become excluded, including cheetahs that need space to reach the speed to pursue prey, and vultures that need a certain level of open canopy to take flight (Bamford, Monadjem & Hardy, 2009). A possible management **response** includes applying targeted high-intensity controlled burning in some areas, allowing grasses to dominate in some regions and woody shrubs with old growth trees in others (Smit et al., 2016).

The role of protected areas and OECMs to mitigate the pressures caused by human activities is more important than ever. These pressures increase the vulnerability of ecosystems to climate change effects. More land must be conserved to allow species to respond to climate change, including movement of species through natural corridors in response to habitat loss or changes in climatic suitability. Managers must also develop stewardship plans to cope with climate change. Currently, protected area networks do not have enough coverage to ensure that species and ecosystems are resilient to human impacts and climate change. Conserving 30 per cent of land and limiting warming to 2°C could reduce species extinction risks by 50 per cent compared to a scenario where there is no global increase in conserved areas or control of climate change (Hannah et al., 2020).

Source: Kerry Grey, Stellenbosch University, South Africa. Picture: A closing canopy favours certain savanna species at the expense of others. © Clive Kaiser

2.5 Output: Statement of purpose

A statement of purpose should be produced as a brief explanation on the purpose and intent of the biodiversity monitoring programme. It should be focused on a narrow area of interest and should reference a prioritised list of indicator species or habitats. The statement of purpose should be in line with the overall vision and goals of the management plan and will serve to communicate the objectives of monitoring to employees, local residents, visitors and responsible authorities (Box 4). For clear direction, each monitoring programme should have its own statement of purpose, complete with relevant modular components. The statement of purpose will constitute the first element of the monitoring concept worksheet.

Box 4

South Georgia and South Sandwich Islands Marine Protected Area: Conservation objectives of a Marine Protected Area

The Southern Ocean is home to the South Georgia and South Sandwich Islands Marine Protected Area. This protected area was declared in 2012 and serves as a key research site to understand marine ecosystems. The islands are home to millions of seals and birds, whilst the surrounding waters are important for migratory whale species (Government of South Georgia & the South Sandwich Islands, 2016). The islands are uninhabited by people but face many pressures including climate change, tourism, fishing and introduction of invasive species.

The main objective of this protected area is to conserve marine biodiversity – with many specific objectives outlined for each of its management zones – and is supported by a comprehensive research and monitoring plan (Government of South Georgia & the South Sandwich Islands, 2021). The plan serves as a framework under which scientific research can be conducted given available funding and resources. Management activities are categorised under 10 research themes. Each theme has a clear statement of purpose with comprehensive lists of monitoring activities, research needs and relevant projects. The frequency of monitoring is prescribed for many activities. These themes thus represent the biodiversity monitoring system of the South Georgia and South Sandwich Islands Marine Protected Area.

Objective Research theme	Conserve biodiversity, habitats, ecosystems	Resilience to climate change	Sustainable fisheries management	Protect from trawling	Protect predators	Protect unique feature or area	Manage human activities	Prioritised monitoring activities	Prioritised research needs
Oceanography and biogeochemistry	X	X						yes	yes
Pelagic ecosystems	X	X						yes	yes
Higher predators	X				X	X		yes	yes
Benthic ecosystems	X		X	X		X			yes
Harvested fish	X		X			X		yes	yes
Harvested krill			X		X			yes	yes
Impact of fisheries – benthic habitats			X	X		X		yes	yes
Impact of fisheries – predator interactions	X		X		X	X		yes	yes
Climate change		X						yes	yes
Other human impacts							X		

Source: Government of South Georgia & the South Sandwich Islands, 2021, adapted by the report authors

CHAPTER 3.

Conceptual phase: Designing the monitoring concept worksheet

3 Conceptual phase

After the overall goals and purposes of the biodiversity monitoring programme are defined, the conceptual phase begins (Figure 5). The monitoring concept worksheet is a tool to help develop the logic of a new programme (see Annex Figure 1). It is designed to identify and structure its primary objectives within the larger protected area or OECM management plan. It can be completed together with partners, external experts and stakeholders. The first element of the monitoring concept worksheet is the statement of purpose that was developed at the conclusion of the preparatory phase (see chapter 2.5). The following elements make up the majority of the monitoring concept worksheet, addressing the questions: **Why** prepare the monitoring programme? **What** will be monitored? **Where** will monitoring take place? **When** will monitoring be conducted? **Who** will be involved in the monitoring programme? and What are the **required resources** to conduct monitoring? The questions are designed to be answered in an iterative way. Most importantly, the answers to the questions should interlink with one another. Different versions of the monitoring programme – for example different cost frames, areas of interest or technological approaches – can be proposed for internal debate. Working through the monitoring concept worksheet will help justify the need for monitoring in the context of management objectives. The monitoring concept worksheet is a key resource to draft a field manual for implementation of the monitoring programme (see chapter 4.3), including evaluation of synergies that can be built into the larger biodiversity monitoring system and national networks.

Figure 5 Ontology of the conceptual phase
Starting with the statement of purpose of the preparatory phase, the conceptual phase is completed through consideration of management goals, site characteristics and the human and financial resources available to the biodiversity monitoring programme. The analysis will show the optimal scope of the programme.
Source: Compiled by the report authors

3.1 Why: The purpose of monitoring

When answering the question of ‘why’, the manager should specify the purpose of the results for site management. By doing so, different uses can be targeted, for example whether the results will be used locally, regionally, nationally or internationally. A point allocation system can help to prioritise the most important purposes for the biodiversity monitoring programme (Annex Table 1).

Helping to determine management effectiveness is one of the main points of a biodiversity monitoring programme (Hockings et al., 2008). First, a determination is made on what type of monitoring should be conducted, for example, as a baseline study, as a research project, for regional documentation or for management purposes (see Box 1). This in turn supports the development of appropriate management activities. Targeted monitoring informs managers and decision-makers on whether the desired outcomes have been achieved, guiding adaptive management. Different audiences should receive descriptions of site management in diverse contexts. Monitoring results can therefore be used for outreach, educational and instructional purposes.

3.2 What: Indicators in a biodiversity monitoring programme

A biodiversity monitoring programme typically provides information about biological indicators. An indicator is the entity that a monitoring programme works with: the object that is recorded, measured and documented in a time series (Figure 6). An indicator should be sensitive to change, characteristic for the site, and as easy as possible to sample or determine. In some cases, it may be effective and useful to monitor biological indicators along with meteorological, hydrological, physical or other abiotic indicators if they are easier to track. Ecological variables such as habitat size or quality may also be useful to estimate species populations. If the indicator is not available or hard to track, a substitute of abiotic or ecological variables can be used, so-called proxies. The main challenge of using a proxy is to ensure that it accurately represents the state of the conservation target (Table 1). Pressures such as land use change can also be monitored as proxy indicators for the biological community because certain species depend on the quality of their habitat for survival (Harris et al., 2021). In addition, there is the possibility to use aggregated or sum indicators such as the degree of human influence in an ecosystem, or ecosystem services (Grabherr et al., 1998).

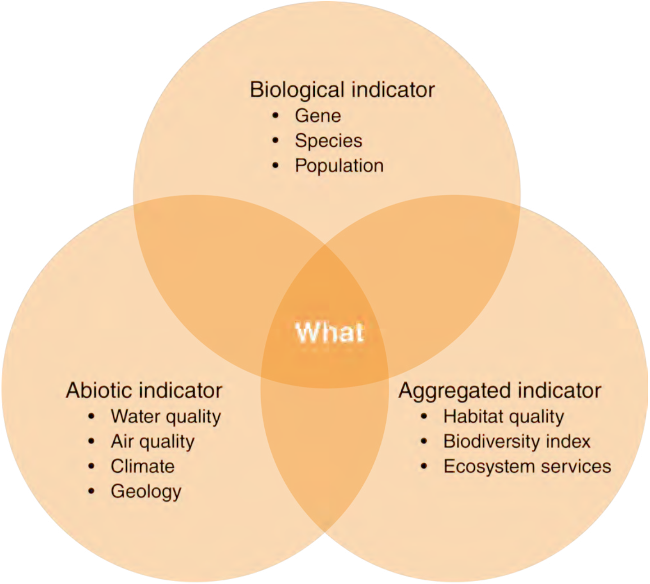


Figure 6 Indicator selection will be site-specific and based on biodiversity monitoring system objectives. The conservation target may be a biological indicator, an abiotic indicator or an aggregated indicator combining environmental information with ecological properties. *Source: Compiled by the report authors*

Table 1 Examples of proxy indicators for biodiversity monitoring
Some biotic indicators are difficult to monitor due to the cryptic nature of their life cycle, dependencies on abiotic factors or logistical reasons. These biological features can be tracked through monitoring closely associated proxy indicators.

Conservation target	Challenge of monitoring conservation target	Proxy indicator
Rosalia alpina, Alpine longhorn beetle: endangered species	Larvae live in old partially dead *Fagus sylvatica* (beech trees), the limiting ecosystem factor.	Dead or dying beech wood in large-scale surveys to deduce beetle conservation status
Calcareous fen containing *Cladium mariscus*, swamp sawgrass: priority habitat	The favourable conservation status of the habitat depends on the range of fluctuation of the water level.	Fluctuations of the water level can be measured with a data logger
Habitat that is difficult to access or reach	Survey of habitat is laborious or hazardous.	Remote sensing data for habitat-based metrics

Source: Compiled by the report authors

Because life is so diverse, monitoring must focus on the minimum number of indicators or else the programme will face resource limitations (Box 5). This reduction is a key process. A scorecard approach assumes that the priority for monitoring is determined by two attributes (Figure 7). First, the status of a key species or habitat is addressed through observation of an appropriate indicator (1st ranking). The second criterion relates to the difficulty in managing the species or habitat on-site (2nd ranking). The more management activities and resources that are needed to gain a favourable conservation status of key species or habitats, the more important it is to monitor change in the indicator conservation status. The next step is to check whether the indicator can be observed with reasonable effort. Effective management may involve taking note of what is happening in the surrounding environment because major changes may be occurring that do not affect the current indicator group. The monitoring programme should be designed to include additional indicators at a later time, if necessary. The decision on what to monitor will be strongly influenced by a third attribute, the resources required to conduct the monitoring programme (see chapter 3.6). This illustrates why it is important for staff to examine all details of the monitoring concept worksheet and revisit all sections after a first comprehensive discussion.

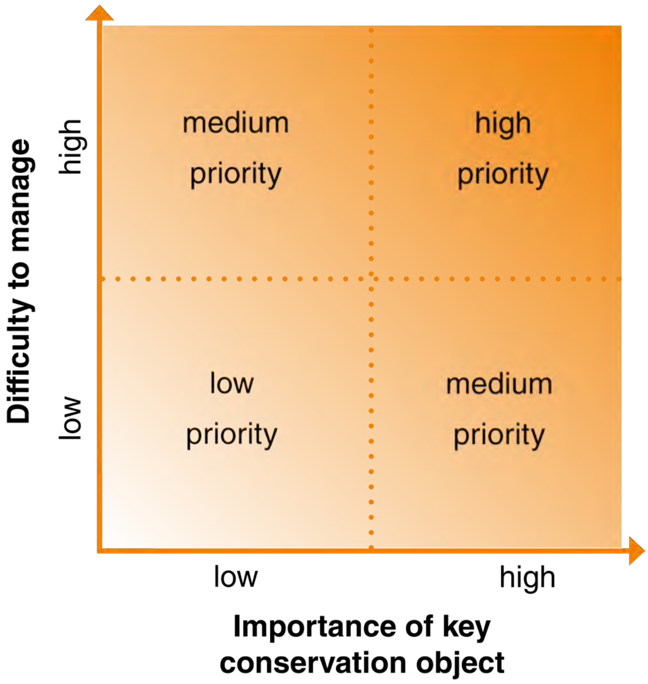


Figure 7 Selection of key indicators is ideally based on two attributes. The first component is the importance of the species or habitat to meet site management objectives. The second component is how challenging the species or habitat is to manage. In reality, selection of indicators may be limited by the resources available to the monitoring programme. *Source: Compiled by the report authors*

Box 5

Indicator selection: Biosphere Reserve Integrated Monitoring in the Nock Mountains of Austria

The UNESCO Man and the Biosphere (MAB) programme describes the concept of a biosphere reserve. All biosphere reserves should support three main functions: conservation; development; and logistical support (UNESCO, 2020).

The Salzburger Lungau & Kärntner Nockberge Biosphere Reserve was established in Austria in 2012 following a long participatory planning process. As a condition for its establishment, stakeholders requested that an integrated monitoring scheme already be in place to evaluate management activities, the so-called Biosphere Reserve Integrated Monitoring (BRIM) approach. For establishing BRIM$^{\text{Nockberge}}$, four pillars of monitoring were addressed: social, economic, ecological and management effectiveness. Within each pillar, indicators were selected based on their relevance, their availability, their sensitivity to management action, and consistency (Jungmeier et al., 2013). Using these criteria, a narrow set of 12 indicators was chosen out of more than 100 proposed indicators. The 12 indicators are evaluated annually through field monitoring, questionnaires or externally. Evaluation can be simply summarised through marking an arrow on the evaluation form indicating the direction of change of the indicator.

Ecological indicators represent the condition of the mountain environment, as measured by an umbrella species representing the animal community, and two additional ecological indicators. Economic indicators involve statistical analysis of local and visitor taxes, as well as description of local agricultural activities. Socio-cultural indicators are based on active stakeholder participation and the migration balance of regional inhabitants. Management indicators are based on the number of visitors to sanctioned events, number of press reports, and the number of research projects that occur in the biosphere reserve.

By using the short list of 12 indicators, evaluated annually, biosphere reserve managers can track the effectiveness of management activities. The BRIM$^{\text{Nockberge}}$ approach was driven by stakeholder input, fulfilling the key aspects of the UNESCO MAB programme and serving as a model of a successful biosphere reserve integrated management approach.

Source: Michael Jungmeier, Carinthia University of Applied Sciences. Picture: View from the Nock Mountains. © Michael Jungmeier

3.3 Where: Scale of spatial features

As part of developing an effective biodiversity monitoring programme, the area of interest, sampling approaches and statistical analysis should be considered (Figure 8). Depending on the indicator, the area of interest can vary from the plot level (mm^2 – m^2) up to the site level (several hectares) to the habitat scale and beyond (Figure 9). To demonstrate the impact of area-based management practices, it may be necessary to monitor beyond the area of interest, allowing comparisons. Different monitoring approaches and statistical tests will result in choosing the appropriate target organism. For example, monitoring the behaviours of mobile or migratory bird species will require a different spatial approach than monitoring the genetic diversity of fish species in lentic waters.

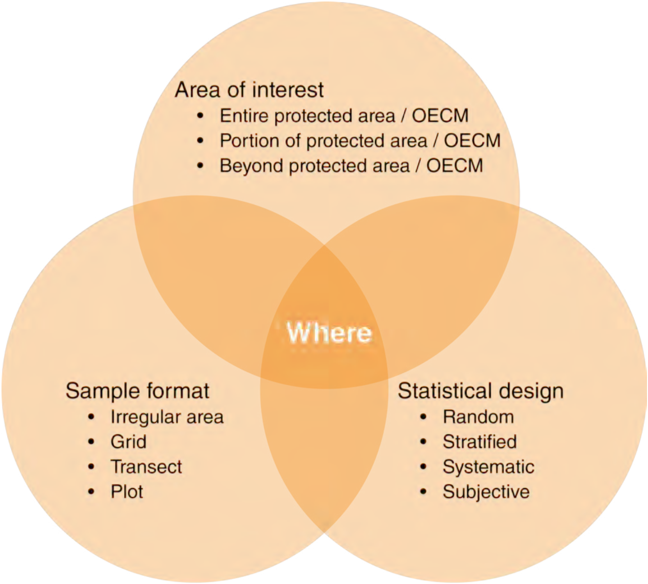


Figure 8 Spatial considerations of monitoring include area of interest, sampling format and statistical design. The area of interest may be the entire protected area or other effective area-based conservation measure (OECM), a portion of it, or it may extend beyond the site boundaries. The biological characteristics of the indicator determine the selection of the best sampling scheme, and the statistical design may depend on the objectives of the management plan. *Source: Compiled by the report authors*

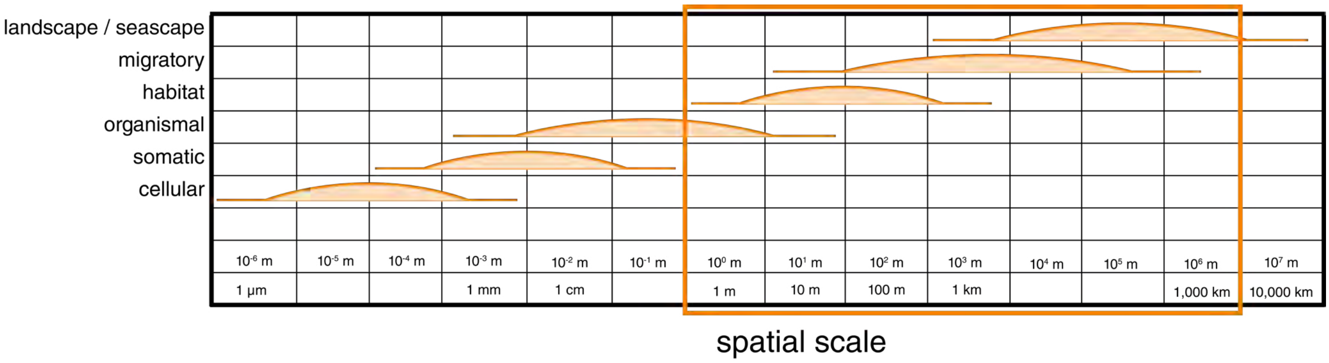


Figure 9 The spatial scale of a biodiversity monitoring programme can range from a genetic to landscape level. This chart illustrates the spatial range of indicators that can be monitored in a monitoring programme. The box indicates the typical range of most monitoring programmes. *Source: Compiled by the report authors*

Decisions about the sampling design must account for area-based features such as the spatial distribution of the indicator. Species and habitats are unevenly distributed across the landscape. Elevation, exposure, water regime, water depth and nutrient availability are some factors that restrict the distribution of species or habitats. Geomorphological features or coarse vegetation types – as revealed by remote sensing or satellite imagery (see chapter 7.3.3) – can often be correlated with key species or habitats in the area of interest where indicators are most likely present. It is important to perform some sampling outside the expected areas to confirm whether selected features match the expected distribution of the target. If necessary, voucher specimens can be collected outside a plot to minimise any disruption of the monitoring sites. Permissions must be secured prior to removal of biological resources from field sites.

The better the understanding of the ecological relationship between the indicator and its environment, the more accurate the prediction of its spatial distribution will be. Knowledge of the distribution and behavioural patterns of the indicator will help determine the minimum mapping unit or spatial scale that can be reliably analysed. This accuracy will help to reduce sample numbers. The selection and distribution of plot, transect or point designs can be random, stratified based on previous findings, or systematic (Elzinga, Salzer & Willoughby, 2019; Magurran, 2004) (see chapter 4.1). Using a polygon-based approach is of special importance for the survey of vegetation or land cover. Likewise, it is possible to set up a systematic area-based survey using a grid-based approach. In this case, the indicators are surveyed in plots along the grid. When comparing features across sites, the sampling units should be standardised and spatially independent for statistical purposes. When possible, plot design should be consistent across sites, particularly when they are part of the same national monitoring network.

3.4 When: Scale of temporal features

Because monitoring is an investigation over time, the temporal design of a monitoring programme is very important and must be defined in the context of the larger biodiversity monitoring system. Monitoring can take place over very different timescales. To answer the question on when to monitor, three key principles should be considered: timing of programme initiation; programme duration; and the interval between monitoring events (Figure 10).

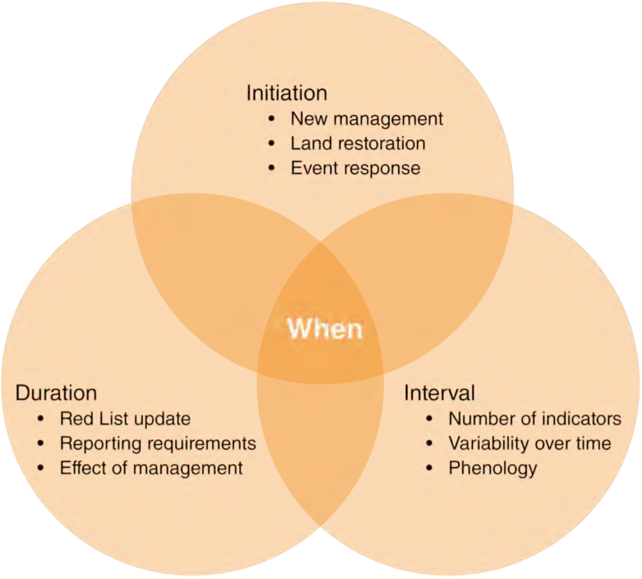


Figure 10 Temporal aspects of a biodiversity monitoring programme include timing of initiation, programme duration and sampling interval. *Source: Compiled by the report authors*

Initiation timing of a monitoring programme must be determined in the conceptual phase. Monitoring can begin as a response to an ecosystem disturbance such as a catastrophic storm, coral bleaching event or flood (Obura et al., 2019). Starting a monitoring programme may occur before restoration efforts or new management strategies begin. This timing will document the baseline condition of the indicator, allowing before-and-after comparisons. Potential considerations of site accessibility may further guide initiation timing, for example if seasonality, potential non-target effects or cultural considerations might affect access to key sites.

The duration of a time series must be long enough to identify trends or changes in the status of the indicator as a response to management actions. If a monitoring programme is designed for a short-term timescale, it can produce valid results after only a few monitoring cycles (e.g. 3 to 5 cycles). In this case a predetermined end date can be set. Monitoring can also occur over medium-term (e.g. 5 to 25 years), long-term and indefinite time spans, depending on the management question and the variability of the indicator.

Trends of an indicator can only be accurately observed following many monitoring cycles. For example, one way for a species to be classified as ‘Threatened’ on the IUCN Red List is for its population to be in decline for at least 10 years or three generations, whichever is longer (IUCN Standards and Petitions Committee, 2022). For animal population studies, the minimum duration of a monitoring programme depends on the species but in general must continue for a minimum of 16 years to confirm trends (White, 2019). In a practical sense, the timeframe of a monitoring programme will more likely be based on the available resources, rather than the biology of the indicator. Innovative programme funding – for example through foundation funding or tax measures – may support indefinite long-term monitoring of key species (Lindenmayer et al., 2012a). As required by the CBD, National Biodiversity Strategies and Action Plans may provide a strong justification to administrators for long-term, sufficient funding to maintain biodiversity monitoring programmes in protected areas and OECMs.

The third factor concerning timing of monitoring is the interval of the monitoring activity. The interval will depend on the phenological activity of the indicator and its variability over time (Figure 11). Certain indicators have short lifespans or are only briefly present in the ecosystem, whilst other indicators have a long-term presence. If possible, the beginning of a monitoring programme should feature frequent monitoring intervals, with reduced frequency at a later stage once trends and variability are known. More frequent intervals early in the programme allow managers to react quickly to any methodological or technical errors. Not all indicators will be appropriately surveyed at the same interval. Therefore, a modular approach should be applied in the case of monitoring multiple indicators. Biodiversity monitoring may focus on trends of species occurrence, distribution and dispersal, as well as on their drivers such as climate change or fragmentation of habitats. These features are generally visible over long periods of time.

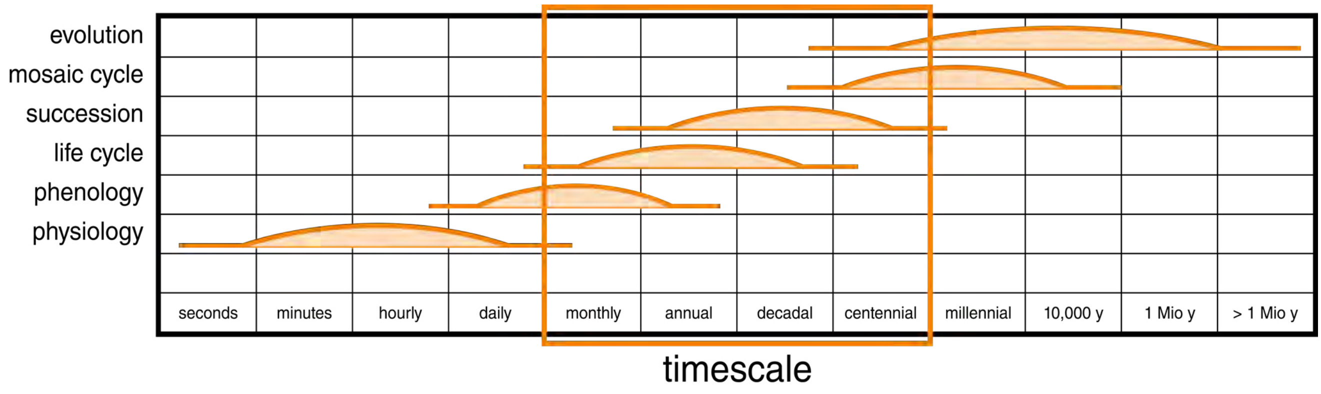


Figure 11 Timescale of different biological processes Depending on the species or habitat, a biodiversity monitoring programme should occur at the relevant timescale of the indicator. Some species may have rapid life cycles that require closely spaced monitoring intervals, whilst other species may be present in the environment for decades or centuries. The box indicates the typical temporal frame of most indicators. *Source: Compiled by the report authors*

Long-term, consistent and well-documented biodiversity monitoring programmes are the 'gold standard' because the value of monitoring accumulates over time. Long-term monitoring may continue for decades. This scope goes beyond a professional career and even the lifespan of institutions; therefore, turnover in personnel, institutional, legal or financial situations is guaranteed. To ensure continuity, these limitations require consideration prior to implementation of the biodiversity monitoring programme. Complete records of monitoring protocols and objectives are necessary to maintain continuity despite these changes over time.

3.5 Who: Identifying actors and stakeholders

This step identifies the core team responsible for implementing the monitoring procedures, supporting staff, active contributors of ideas and resources, and stakeholders who should be informed about the processes and results (Figure 12). The core team will be directly involved in making on-site decisions. It may include the managers of the protected area or OECM, personnel who lead and conduct the field work, directly involved Indigenous community representatives, and local expert consultants.

1 Core monitoring team, e.g.

- Staff experts
- External experts
- Indigenous representatives

2 Supporting staff, e.g.

- External experts
- Citizen scientists
- External service providers

3 Stakeholders to be involved, e.g.

- Farmers
- Associations
- Union groups

4 Stakeholders to be informed, e.g.

- Landowners
- Visitors
- Policymakers

Figure 12 Example stakeholder worksheet listing key participants in a biodiversity monitoring programme
Managers and staff should work together to identify potential stakeholders for an overview of who may be involved in the monitoring programme and the scope of their participation.
Source: Compiled by the report authors

The actors involved in the monitoring activity will affect the scope and quality of data collection. Institutional help and external collaborators can be identified at this early stage. Permanent staff positions should be secured for monitoring. Supporting staff may include scientists, statisticians, GIS experts, IT experts, database managers, field crew leaders and other specialists. Early and ongoing co-design of the monitoring programme between involved scientists, governmental agencies, non-governmental organisations, and Indigenous peoples and local communities is essential. Indigenous peoples and local communities should be actively engaged in all stages of the design of a monitoring programme, from conceptualisation and field work to logistical support (Dyck, LeClair & Bockstael, 2022). Involving these key stakeholders at all steps of programme development will incorporate valuable traditional ecological knowledge, providing essential scientific and social support for the programme. A primary role of managers is to then translate traditional ecological knowledge and scientific findings into recommendations for policymakers (Thompson, Lantz & Ban, 2020). More generally, it is important to include people and interests who are sceptical about the management programme because conflicts or even vandalism can be prevented through involving and informing the full spectrum of potential stakeholders (Hodgkinson & Young, 2016). A blank stakeholder worksheet is provided to help managers determine the level of involvement of different stakeholder groups (Annex Figure 3).

The responsibilities of monitoring should be assigned to professionals and experts. Depending on programme objectives, some aspects of monitoring can be accomplished by volunteers including students, nature enthusiasts and citizen scientists. The participation of volunteers in monitoring requires a series of support measures for effective training; however, involving non-scientists has many benefits ranging from scientific output to education to programme visibility (Box 6).

Box 6

Integrating citizen science to estimate the Slovenian brown bear population: It counts to be involved

Brown bear (*Ursus arctos*) populations were nearly exterminated in western Europe following centuries of intolerance, but large populations remained in parts of eastern and central Europe. Populations from south-eastern Europe are a source for reintroduction efforts elsewhere on the continent. In the Dinaric Mountains of Slovenia, cull quotas increased dramatically beginning in the early 2000s, supported by high official population size estimates and an increased number of recorded human–bear conflicts. Population estimates lacked a scientific basis and varied widely, igniting a debate on how many bears actually lived in the region, rather than focusing on effective management to facilitate co-existence.

To provide a robust, scientific estimate of the brown bear population size, a mark–recapture study utilised non-invasive genetic sampling (Skrbinšek et al., 2019). Bear scat was sampled and genotyped to identify individuals. Each genotyped specimen was considered a 'capture' of an individual, providing a basis to model population abundance. This design required high-intensity sampling on a large spatial scale. Considering limited funding, a sampling strategy was conceived using a citizen-science network of volunteer stakeholders, mainly hunters. Recruitment of volunteers was possible due to the flagship status of the brown bear and was supported by the very good organisation of Slovenian hunters. The project was advertised through different media, including a Slovenian hunting magazine which allowed contact with the local hunting community. The main guiding principles were for the scientists to maintain a professional appearance so that people would take the project seriously, and that participation would be as simple as possible for all volunteers. Organised workshops provided well-designed sampling materials and training on how to collect bear scat for genetic analysis. The scientists took care of material distribution, handling of samples, and kept in contact with representatives of all hunting clubs. In total, more than 1,000 volunteers collected 1,057 samples over a three-month period covering an area of approximately 6,000 km^2. At the project's end, all results were published in the hunting magazine with sincere acknowledgement of the volunteer contributions.

Findings indicated a Slovenian brown bear population of 380–460 bears providing the first robust, scientifically based population estimate. The estimate stopped the endless debates about the number of bears and opened the more important discussion about managing human–bear conflicts. It has had a profound and continuing impact on brown bear management in Slovenia.

A well-designed study, combined with a large citizen scientist volunteer force, can accomplish impressive results. Motivation is the key factor, and the rewards for participation must exceed the effort. After all, volunteers don't work for free, they are just not paid money.

Source: Tomaž Skrbinšek, DivjaLabs, University of Ljubljana. Picture: Brown bear family. © Miha Krofel. Flickr

3.6 Required resources: Identifying the resource pool

A biodiversity monitoring programme will be successfully implemented only with the support of an adequate resource base (Figure 13). First, a realistic estimation of financial costs should be made, considering the difference in costs between the establishment phase of the programme and continuation in subsequent monitoring cycles. Generally, the establishment phase will require the greatest financial resources (Lindenmayer et al., 2012b). Furthermore, an estimated 25–30 per cent of the programme budget should be provided for data management, assessment and reporting (Caughlan & Oakley, 2001). A simple worksheet is provided to help to determine the amount of financial resources required for sufficient data collection (Annex Table 2). The second component is the demand for human resources. If there is a mismatch in the availability of resources, an adaptation of the monitoring objectives, indicators or methods will be required. Identifying synergies among funding sources or pooling resources from multiple programmes could increase the resources that are available for implementation of the monitoring programme. In some cases, the manager might be able to access extra resources for a critical procedure, or find innovative ways to acquire resources. These resources could come in the form of in-kind support from local communities, schools or research institutions.

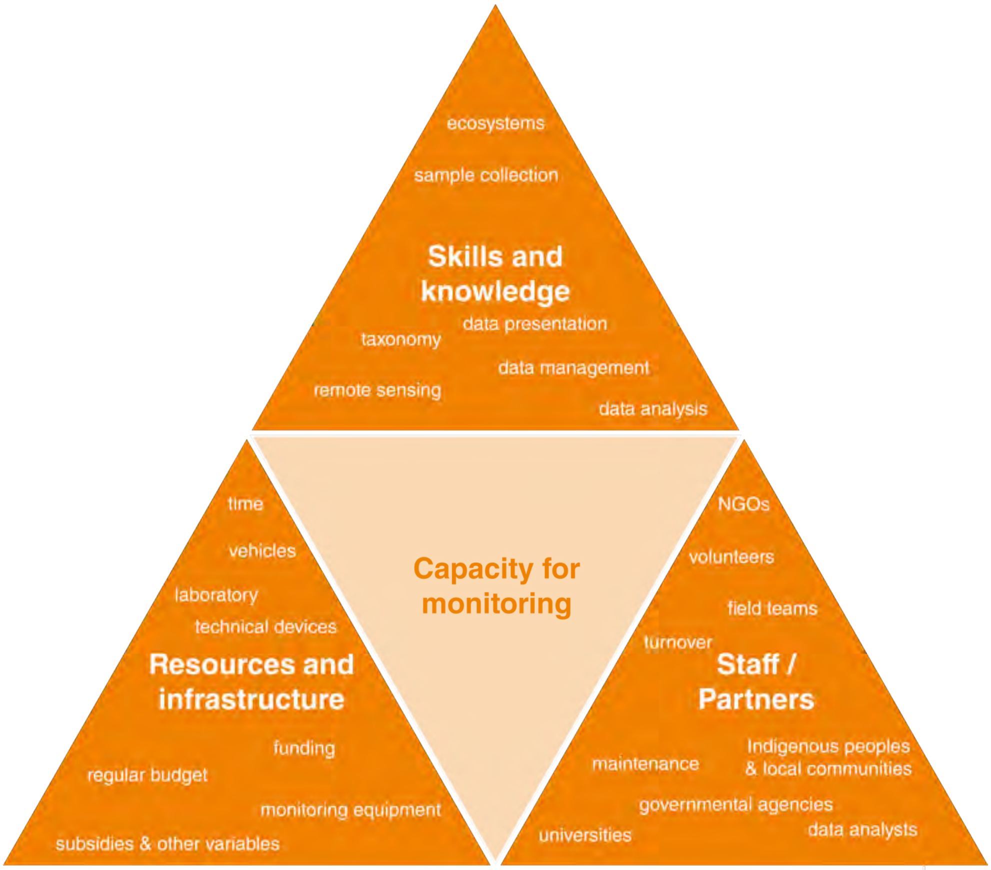


Figure 13 A biodiversity monitoring programme depends on the available staff, resources and knowledge. Two categories of resources must be considered. Financial resources and the available management infrastructure are required for an operational management base. Specialised human resources including technical skills, logistical support and field work are also necessary to carry out an efficient monitoring programme. *Source: Compiled by the report authors*

3.7 Output: Defined scope of the biodiversity monitoring programme

Examining the six questions of ‘why’, ‘what’, ‘where’, ‘when’, ‘who’ and ‘required resources’ will complete the conceptual phase. The necessary research questions for establishing the biodiversity monitoring programme should now be identified, but they will not be worked out in detail. The balance of the monitoring concept worksheet will be completed in the following phases by outlining details on how the monitoring activities will be performed in practice, and through identifying potential synergies of the programme with other elements of the protected area or other effective area-based conservation measure management plan. The implementation phase, described next in chapter 4, will help the monitoring team to decide on the specific methodologies that will be used in field monitoring.

CHAPTER 4.

Implementation phase: Setting up the infrastructure

4 Implementation phase

The implementation phase addresses how monitoring will be conducted (Figure 14). Ethical and cultural topics must be considered from the beginning, and potential legal constraints need to be resolved (Checklist 1). At the start of the implementation phase, the sampling design and methods of monitoring will be determined, followed by the acquisition and configuration of tools. Training of field technicians should include all steps planned for the actual monitoring, from setting up monitoring tools, collecting, storing and analysing data, and finally, presenting the findings. Presentation is a key step for communicating with decision-makers and local stakeholders. It shows how the monitoring programme contributes to conservation of biodiversity so that it is broadly supported both socially and through policy decisions such as resource allocation. Protocols should be documented in a detailed preliminary manual.

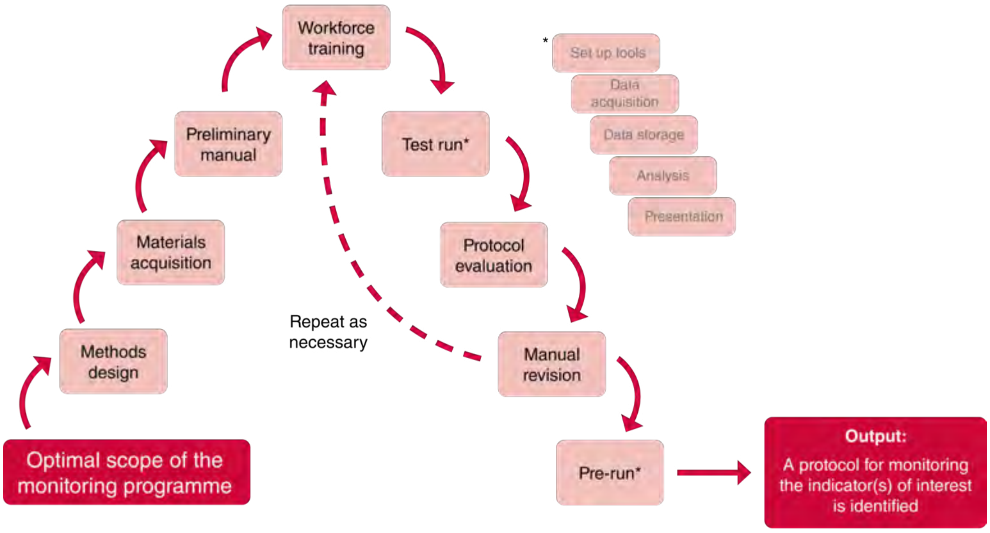


Figure 14 Ontology of the implementation phase
The findings of the conceptual phase are the starting point for implementing the biodiversity monitoring programme. Next come considerations of plot and methods design, followed by acquisition of required materials. A preliminary manual detailing the methodology is developed and is provided to the workforce for training. Following training, at least one test run should be conducted, involving setting up the tools in an accessible area, acquiring, storing and analysing the data, and concluding with a brief presentation of results. The test run provides a basis for evaluating the methodology and revising the preliminary manual. Following any changes, the workforce should be retrained and a new test run should be conducted. Once the process works as described in the manual, a protocol for monitoring the selected indicators is finalised for implementation as a pre-run in the field. *Source: Compiled by the report authors*

Before workflows, tools and methods are implemented on a large scale, they must be tested. Test runs should be performed to ensure proper implementation of all steps in the preliminary manual (see chapter 4.4). Test runs are best performed at a test site where data collection and installation of tools can be easily achieved (Box 7). In addition to relevant natural features, appropriate infrastructure such as electricity, wireless communication systems or a laboratory may be necessary to support the analytical steps. A test site can further be used as a learning and training centre, and for awareness-raising and public relations. It can also be used jointly by different institutions, for example park management, scientific institutions, companies and schools.

Box 7

Test and experimental sites: BioDivTecs Hub Carinthia, Austria

The Lakeside Science and Technology Park (Klagenfurt, Austria) is home to a university, numerous technology companies and research institutions, and an educational laboratory for schools. The Lendspitz-Maiernigg Natura 2000 area sits directly adjacent to Lakeside Park and is used for research and education. All nature protection regulations must be observed in the protected area. An international test site for monitoring technologies is currently being developed at this location.

Increasingly, biodiversity monitoring systems are sophisticated technical systems consisting of different components. This requires testing the methods and individual devices. A test site is an outdoor research area with high demands imposed on it. First of all, the relevant species and ecosystems must be well known. Good accessibility, sufficient technical and logistical infrastructure, and comprehensive reference data are also necessary prerequisites for effective test runs for these technologies. The consent of owners or official permits may also be necessary.

Under the name BioDivTecs Hub Carinthia, various research, educational and nature conservation organisations and companies are currently developing test and experiment sites, providing an opportunity to test and certify the technologies. There are several sites, called FieldLabs, designed for different requirements. In addition, the sites are embedded in a network of international reference programmes including GLORIA and LTERnet.

The test site is designed for use by both the developers and users of biodiversity monitoring systems, as well as educational institutions, ecologists and public bodies. The technological readiness levels of individual tools are determined through hands-on work at this easily accessible site. These tests act as pre-runs of technological workflows, breaking one of the barriers of real-world biodiversity monitoring. The results provide examples of how technologies can be applied in other protected areas.

Source: Jennifer Insupp, Ilja Svetnik, Carinthia University of Applied Sciences, Austria.
Picture: View of the Lakeside Science and Technology Park. © Ulf Scherling

4.1 Deciding on sample design and methods

Sampling designs and methods differ considerably depending on the site research objectives, indicators and habitats (Elzinga, Salzer & Willoughby, 2019; Feinsinger, 2001; Magurran, 2004). Using polygons allows an area-based survey of habitats across the whole protected area or under predefined conditions (e.g. an elevational gradient) or zones (e.g. biosphere reserve core zone). Depending on the desired resolution, this approach can be very costly or not suitable for the selected indicators. Therefore, the most efficient tools to accomplish monitoring objectives should be identified at this stage, and the capacity for their proper implementation must be verified. Assessment methodology should be carefully considered. This includes the number of plots per site, spatial layout, size and shape (Figure 15). Involving a statistician during the study design process will be necessary for meaningful analysis (Adams-Huet & Ahn, 2009). A combination of different plots – a so-called nested plot design – may be implemented during test runs in order to identify the most efficient approach for plot establishment. Each plot design has its benefits and drawbacks, and selection of plot design should be carefully considered (Table 2). When different approaches yield similar results, the most cost-effective methodology should be prioritised.

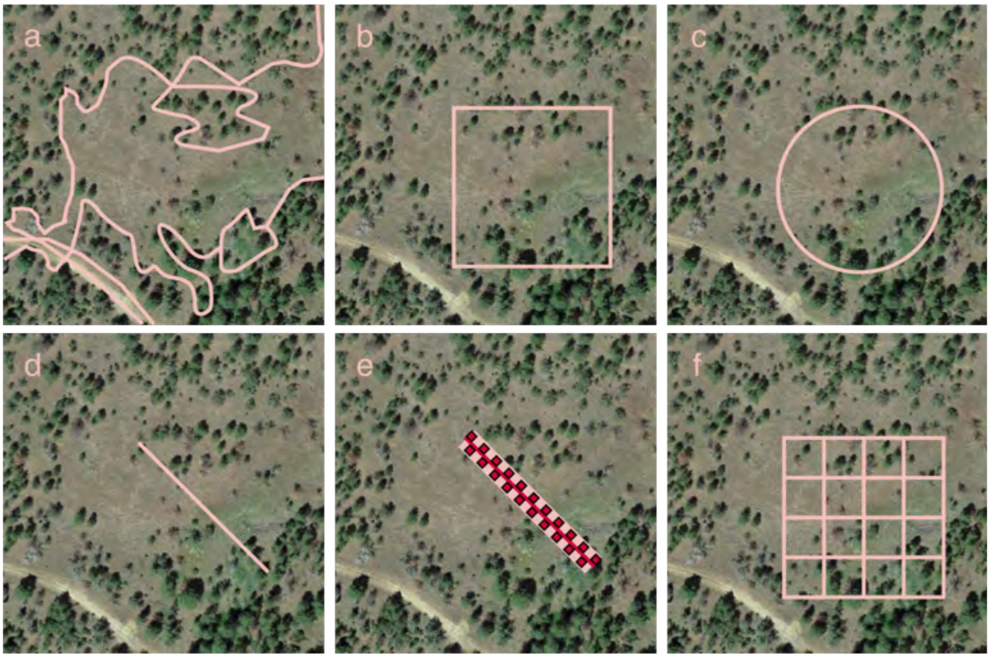


Figure 15 Example plot designs for biodiversity monitoring
a) Surface mapping using polygons; b) quadrat; c) circle; d) line transect; e) belt transect; f) grid. See Table 2 for more information on plot designs. *Source: Compiled by the report authors*

With the exception of the areal survey (polygon), the selection of the trial areas, transects or points, their number, and especially their location, is of crucial importance. Some common ways to select a survey area include:

- **Random:** In the case of random sampling, a very high number of samples is usually necessary to obtain a reliable result.
- **Systematic:** Sampling is carried out according to a regularly placed predetermined layout system (e.g. every third plot of a grid).
- **Stratified:** On the basis of a previous detailed survey, areas with similar characteristics are clustered and used as a basis for a representative selection of areas (e.g. 10 per cent of plots within forested areas).
- **Expert-based:** Often the area selection is made by experts who select the plots based on their experience (e.g. expected breeding sites, known intervention areas).

In practice, plot selection is often influenced by very practical criteria (accessibility, infrastructure, etc.), which can lead to a considerable distortion of the results. For example, acoustic monitoring is an excellent method to determine bird community composition, but managers must be sure that they can acquire enough devices and ensure adequate training for personnel to install them, collect and analyse the data.

Table 2 Plot designs used in field-level biodiversity monitoring programmes. Some purposes, benefits and limitations of different plot designs are described along with an example of each.

Design	Purpose	Example of use	Benefits	Limitations
Surface mapping using polygon	Complete coverage of habitat units or catchment area	Remote sensing to improve habitat mapping (Radoux et al., 2019)	Surveys the full area of interest; valuable and necessary background information for all types of monitoring; analysis of areal change over time possible	Combination of remote sensing and terrestrial mapping required; not all polygons may be accessible; delimitation depends on data resolution; polygons change over time (phenology, land uses, etc.)
Quadrat and rectangle	Area-based technique for abundance and distribution	GLORIA plot design (Pauli et al., 2015)	Simple inexpensive design; can be structured into subplots; redundant demarcation possible; mainly for immobile indicators (plants, vegetation); single lost corner markers can be restored	Selection and location of plots decisive for results; optimal plot size and number to be identified; strong disturbance and edge effects; individual plots may be dispersed and difficult to (re-)find; not easy to locate in dense vegetation; subset of whole area
Circle	Area-based technique for abundance, distribution with minimum edge	Forest inventory (Packalen et al., 2023)	Simple inexpensive design; can be structured into segments; mainly for immobile indicators (plants, deadwood)	Selection and location of plots decisive for results; optimal plot size and number to be identified; strong disturbance and edge-effects; centre point required for reconstruction; edges of large plots are hard to indicate in the field; subset of whole area
Line transect	Habitat gradient or species distribution, documentation of ecotone	Spatial mapping of rare trees (Bäuerle & Nothdurft, 2011)	Line-based simple design; time efficient; needs a starting and an endpoint; analysis and interpretation of distribution patterns or gradients quite simple	Number and location of transects decisive for results; difficult to set up in dense vegetation and over large distances; areal distribution difficult to conclude; subset of whole area
Belt transect	Habitat gradient or species distribution, documentation of ecotone	Prairie restoration (Grant et al., 2004)	Simple area-based design; time-efficient; field work uncomplicated; analysis and interpretation of distribution patterns or gradients quite simple	Number and location of transects decisive for results; allows for more sophisticated analysis than line transect; areal distribution difficult to conclude; subset of whole area

Source: Compiled by the report authors

Well-designed methodologies should permit consistent data acquisition over a long-term timescale. Methodologies may be useful to measure species population parameters including abundance, distribution or genetic diversity (Elzinga, Salzer & Willoughby, 2019). Identifying how these parameters change over time is very often the objective of the biodiversity monitoring programme and will help guide adaptive management strategies. A good biodiversity monitoring programme will allow for modular expansion of monitoring designs to adapt to changing resources or needs. Most biodiversity data fall into four categories: species surveys, community surveys, habitat types and animal–habitat relationships (Jones, 1986; Elzinga, Salzer & Willoughby, 2019). State-of-the-art approaches to implement efficient and effective biodiversity monitoring programmes are shown in Table 3.

Table 3 State-of-the-art approaches to biodiversity monitoring

Suitability for protected area management	
Very well suited	1
Well suited	2
Less suitable	3
Unsuitable	4
Not relevant	-

	Objects of observation	**Passive acoustic devices and sensors**	**Optical devices (camera trap, etc.)**	**Satellite remote sensing**	**Close / mid-range remote sensing**	**Telemetry and tracking tools**	**Olfactory devices**	**Genetic methods**	**Mapping (area-based, polygons, plot)**	**Mapping (grid-based)**	**Mapping (transects)**	**Trapping (nets, enclosures, etc.)**	**Indirect observation (tracks, nests, etc.)**	**Attractants (pheromones, light, colour, etc.)**
Landscapes, land cover, vegetation	Forests and shrublands	-	3	1	1	-	4	4	1	2	3	-	-	-
	Glaciers, mountains, rocky habitats	-	3	1	1	-	4	4	1	2	3	-	-	-
	Wetlands, rivers, water bodies	-	3	1	1	-	4	3	1	2	3	-	-	-
	Grasslands, savannas, deserts	-	3	2	1	-	4	4	1	2	3	-	-	-
	Urban areas, artificial habitats	-	3	2	1	-	4	4	1	2	3	-	-	-
Species and populations	Funghi and lichen	-	3	4	3	-	4	1	4	1	1	-	-	-
	Microbes	-	-	4	4	-	4	1	4	1	2	-	-	-
	Plants and algae	-	2	3	2	-	4	1	4	1	1	-	-	-
	Mammals	2	1	4	2	1	3	1	4	2	2	3	1	1
	Bats	1	3	4	4	2	4	1	4	2	3	2	2	3
	Birds	1	2	4	3	1	4	1	4	2	2	2	2	3
	Fish	3	2	4	2	3	4	1	4	2	4	2	4	3
	Reptiles	3	2	4	4	3	4	1	4	2	3	2	3	3
	Amphibians	2	2	4	4	3	4	1	4	2	3	2	4	3
	Insects	2	3	4	4	3	3	1	4	2	2	2	4	1
	Other invertebrates	3	3	4	4	3	3	1	4	2	2	2	4	2

Source: Compiled by the report authors

4.2 Acquisition and customisation of tools and materials

Once the field design is determined, the tools and materials may be acquired. When possible, standardised protocols from similar programmes should be used. Managers should factor in possible delivery time delays due to administrative processes or supply chain problems. When selecting tools or materials, managers should verify whether adequate staff are available to use and maintain the devices. For digital tools, access to a reliable power source must be considered, for example whether the batteries will last for the duration of time between site visitation, or whether a solar array or alternative power source may be appropriate. Some digital tools require an internet connection for full functionality. Field data storage issues should be considered in advance. Data processing requirements, including volume or compatibility with cloud-based technologies, should also be considered. Data transfer from devices should be tested prior to field work. Selected tools must be resistant to climatic conditions to prevent data loss. Calibration of data collection devices should be performed once materials are in hand. Often, additional hardware or other items are necessary to physically set up the tools in the field. For equipment that will be installed in the field, extra devices should be secured in case some devices become lost or damaged. Managers and field technicians should record their experiences customising the monitoring tools in detail in a preliminary field manual.

4.3 Elaboration of a field manual

All decisions made in the implementation phase should be recorded in a preliminary field manual. The preliminary manual is a 'living document' and should include a detailed section on the analysis, archiving and presentation of data. It can be revised and adapted as needed over the course of several test run cycles. The manual should be written in a modular way, allowing specialists to focus on the relevant components of the monitoring programme. Pre-existing field manuals can serve as templates to develop key sections. Possible topics may include field logistics, data quality control, and work expectations, among others (Checklist 2). Worker safety is particularly important, as the protected area or OECM administration may be liable for negligent actions or insufficient training. Field technicians should receive adequate training for using field equipment and handling emergencies (Checklist 3). For all field work, risk analysis should be conducted, and technicians should not work alone, especially in potentially hazardous conditions. Special consideration towards possible encounters with dangerous animals or hazardous situations should be given.

Data quality is of the highest importance. Data sheets should be carefully designed. Minimum standards for metadata must be presented and explained in the preliminary manual. This includes information on who collects or revises records, the exact locations, dates and times of records, which literature and methods are used to determine species, and other site-specific or programme-specific information. These 'hidden data' are essential for the interpretation of results. All data and metadata must be relevant and precise. Data that are found to be unusable in statistical analysis do not need to be collected in future cycles.

4.4 Conducting test runs

Two types of field trials should be completed in advance of the main field work. These are test runs and pre-runs of the monitoring workflows. Test runs take place in easily accessible locations and occur after completion of each draft of the preliminary field manual. Pre-runs take place under actual field conditions and occur after finalisation of the field manual.

Test runs will verify the proposed workflows of the monitoring programme. The value of test runs cannot be overstated because they identify the most efficient methodologies, optimising investments of time and resources. Test runs may identify features of unexpected value. They will demonstrate the most effective combination of methodologies to measure the indicators. If test runs cannot be performed, simulated data should be generated and analysed to determine whether the planned sampling and analyses are sufficient to draw conclusions.

Test runs should be set up at an easily accessible site. Tools should be calibrated and set up just like they would be in an actual field survey. Data should be collected, stored, analysed and presented. It is important to perform data analysis directly after each test run to identify any problems in the statistical design or methodology. Above all, field supervisors, technicians and other participants should discuss whether the preliminary manual is applied uniformly by everyone, or whether individual steps are unclear or incompletely developed. This feedback will direct the revision of the preliminary manual. If any changes are made, additional test runs should be conducted following the revision. Every step should be repeated. Metadata from one test run to the next should be linked for analysis. Reference data are required to calibrate the methodology. This is because comparative analysis is only possible with clear spatial and temporal consistency. Preliminary data analysis may provide the basis to reduce plot numbers or indicators to an acceptable minimum.

At least one complete assessment of collected data should result from the test run cycles. If the criteria are fulfilled in the test run, it shows that selected proxies and indicators are adequate for monitoring. Once implementation functions as recorded in the preliminary manual, the methods of the biodiversity monitoring programme are documented in a finalised field manual.

The next step is to conduct pre-runs in the field. The pre-run is the first monitoring run in the field and the last chance to revise the manual prior to starting the ongoing monitoring cycles. Different field teams should conduct the monitoring protocols on the same plot as a test of methods and workflows. Pre-run data can identify significant correlations between the measured indicators, helping to optimise the most effective methodologies. Any changes to the protocol must be noted in detail for future monitoring cycles.

4.5 Ongoing monitoring cycles

Field implementation is the roll-out of the finalised field manual as developed through test runs. In the field implementation phase, the workflow is applied in actual monitoring sites. Data collection may now begin on a regular schedule. It is important to follow the field manual as closely as possible to secure the comparability of data with findings from all monitoring cycles. High quality control should be prioritised in the data acquisition process.

Using a more frequent monitoring interval at the beginning of the programme will identify potential or unexpected trends of the indicator that may inform early revision of the field manual. Ideally, a greater number of indicators and similar methodologies could be surveyed in the first monitoring period to identify the optimal combinations of resources. Redundant information can be identified through a detailed analysis of the results and allow more efficient resource use in the long term. It should also be considered whether it is necessary to collect all indicators on all plots, or whether a subset of plots is sufficient to answer a specific question. Unforeseen events may change the required approach. Anticipating these possibilities requires enough flexibility in the monitoring cycle to permit adaptive management whilst reducing the risk of data loss to an acceptable minimum. All changes in methodology must be documented so that changes in data collection can be accounted for when analysing data over multiple monitoring cycles.

4.5.1 Field work and data acquisition

Field work is a crucial factor in any biodiversity monitoring programme. Many challenges arise in field data collection, including correctly recording information and ensuring safety of field personnel.

Taxonomy is a common challenge for the field staff. For this reason, training by an experienced taxonomist may help to maintain consistent species identification in programme activities. In many protected areas and OECMs, Indigenous and local knowledge of species is key for proper identification of valuable indicators. This emphasises the value of including Indigenous peoples and local communities in data collection planning or involving Indigenous guides in the field. Preservation of voucher specimens, for example herbarium pressings or insect collections, will help to verify the data in the case of future taxonomic disputes. If the species pool is well known and baseline data already exist, photographs may be sufficient for verification and are preferable over physical removal of plants or animals. Special permits may be required to remove specimens from the environment. Depositing genetic barcodes from environmental DNA analysis (see chapter 7.3.6) is another potential way to verify field-based findings.

Human labour is increasingly supported by advanced technologies and equipment (Dalton et al., 2022). Safe field work and efficient data acquisition must be well planned (Checklist 4). For effective field work, a systematic approach should be uniformly applied to establish for instance all field plots, such as maintaining the same directional orientation in all plots, marking the same corner, or taking plot photographs from the same angle. The use of tablets or smartphones can help standardise data collection by providing a first quality check of the data directly in the field (Joly et al., 2018). If digital tools will be used, the skill set of the user must be kept in mind. One way to ensure consistent data collection is to use digital platforms such as QField that can be loaded onto smartphones or tablets (Nowak et al., 2020). A well-prepared digital data sheet will prompt field technicians to collect all required data. It will minimise errors through offering drop-down lists, plot photography, and by using graphical interfaces rather than text (Box 8). This approach will facilitate merging datasets at a later time. Using graphical interfaces will break language or literacy barriers, allowing trained field technicians to collect data despite linguistic background. If digital options are not realistic, hard copies of the relevant data and data sheets should be provided to the field data manager as soon as possible. The data manager can identify inconsistencies while still at the field site, providing an opportunity to correct the monitoring technique or data.

The primary technical goal of data acquisition is the production of high-quality datasets for long-term time series. Each monitoring cycle is an asset whose value increases with every additional cycle of data collection. To ensure data quality, staff training should be given at the beginning of each monitoring cycle. Ranger training programmes can be provided by a conservation organisation, whilst a number of IUCN PAPACO Massive Open Online Course offerings (https://mooc-conservation.org/) may also provide training services to a protected area or OECM monitoring programme. As with the pre-run step, repeated assessment of a small set of plots on the same day and comparison of results by different staff will help clarify individual variation. Techniques ranging from simple – such as repeated site visitation adding to historical records – to complex (e.g. data analysis for extrapolation, interpolation, scenario modelling, trend detection, etc.) should be used to maximise the data. Similar data may be available from other monitoring activities or sites. Suitable data should be integrated into the analysis and interpretation of the monitoring results. It is almost always advisable to bring along descriptive information gathered from the previous monitoring cycle, for example photographs or GPS coordinates of the site. It is very important to mark the field in a way that ensures the spatial precision of sampling points for future surveys. Providing lists of species known to the area is advisable and should be included as a resource during training of field personnel (Halloy, Ibáñez & Yager, 2011). Field trials from a long-term monitoring programme revealed that the main source of error was random rather than systematic, suggesting that adequate field training is sufficient for consistent results (Futschik et al., 2020). Therefore, providing previous findings to field technicians is not recommended and could actually bias the findings.

Box 8

Working with SMART and CyberTracker: An example at Lake Tana, Ethiopia

The Spatial Monitoring and Reporting Tool (SMART) is an open-source software programme to help protected area and OECM managers handle and interpret conservation data. SMART is a desktop app that can be used in conjunction with mobile apps such as CyberTracker or SMART Mobile to enable remote data collection on a tablet or other mobile device. CyberTracker utilises an icon-based user interface to simplify data collection. Field technicians receive project-specific training to ensure that data are collected in a reliable way.

At Lake Tana Biosphere Reserve, Ethiopia, SMART is being implemented with CyberTracker in an effort to track the control of the water hyacinth (*Eichhornia crassipes*), an invasive aquatic plant species that out-competes all other species growing in the vicinity and poses a threat to aquatic biodiversity. Several control techniques are available, including chemical control, physical removal, biological control and multiple techniques in combination. To date, physical control techniques have been implemented at Lake Tana. Local farmers play an important role in removing the water hyacinth from the water. The quality of the work is observed by development agents who are required to create awareness about the adverse effects of the weed and report the daily volume of plants removed from the lake. The development agents are a natural choice to collect data using the CyberTracker app because their job is to oversee the weed control work. Collecting infestation data with CyberTracker takes no extra time in the field.

At Lake Tana, the first step of the SMART / CyberTracker workflow was to develop a desktop computer model for data collection using the SMART app. The model was then exported to CyberTracker as a checklist of possible conditions at a survey point. For water hyacinth infestation, different categories are allowed, such as presence / absence, levels of plant density, or per cent cover over a standardised area.

Scientific researchers provide periodic training to the development agents on how to use CyberTracker. Following training, test runs are conducted to correct potential problems in the workflow. All steps are recorded in a field manual for future reference. After collection by trained local participants, data are transferred from the mobile device to the computer, and georeferenced data are exported in the office to SMART. Depending on the configuration of the mobile device, upload can occur via email, Bluetooth or directly to the cloud. Data from the Lake Tana SMART / CyberTracker workflow can be used to generate maps showing changes in the state of the water hyacinth infestation over time. This information can be evaluated to recommend possible changes to the adaptive management programme.

Source: Daniel Mengistu and Tirusew Ayisheshim Ebistu, Bahir Dar University, Ethiopia, and Melanie Erlacher, Carinthia University of Applied Sciences, Austria. Picture: Detection of the spread of water hyacinth (Eichhornia crassipes) through the use of remote sensing technologies. © Geospatial Data and Technology Center, Bahir Dar University

4.5.2 Storage, backup and archiving

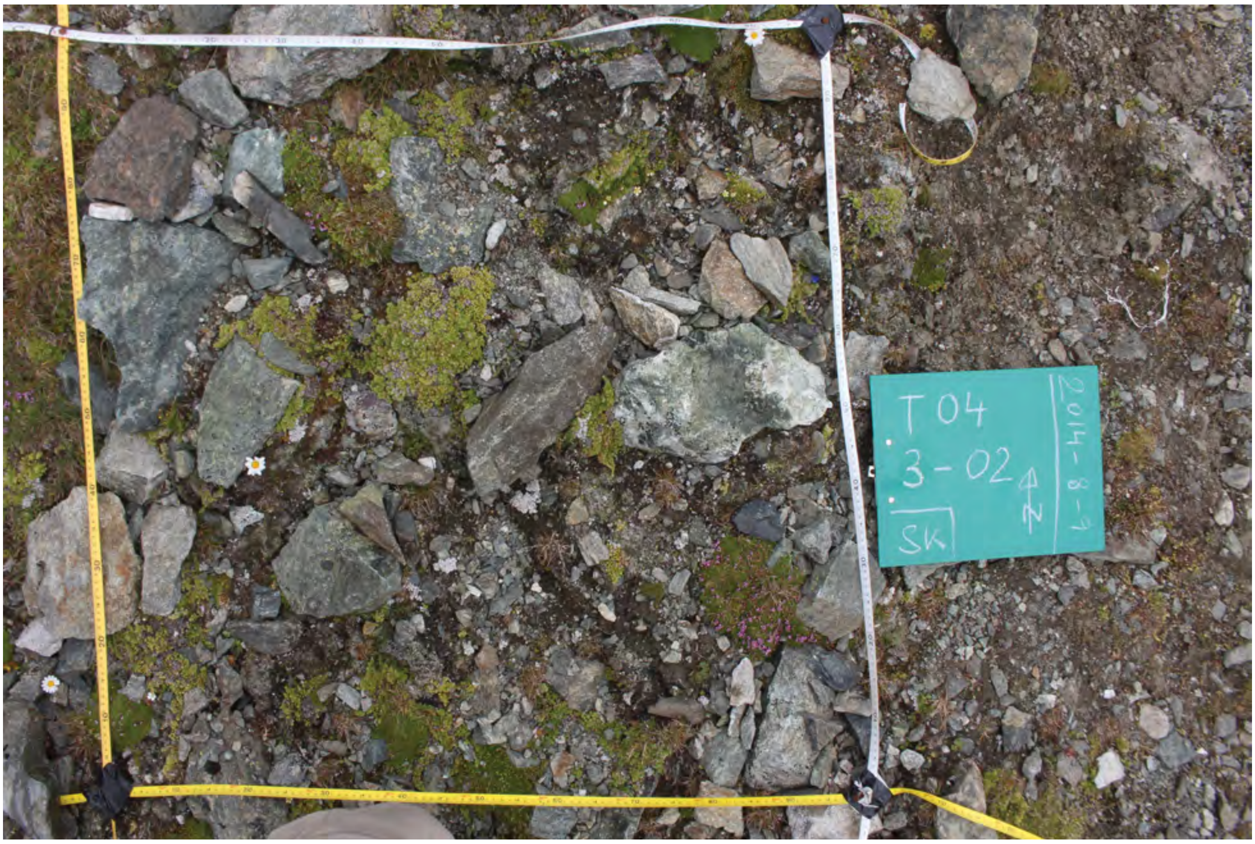
Today's digital biodiversity monitoring devices are producing data at an unprecedented rate. These so-called 'big data' are now a component of modern biodiversity monitoring systems, allowing advanced statistical analysis that can transform evidenced-based decision-making (Strohbach et al., 2016). There are many benefits of remote data collection, but managers of protected areas and OECMs must decide how to address the many challenges of storing and using big data. It is therefore crucial for managers to implement a holistic data model for each biodiversity monitoring system. Individual programmes should develop datasets that conform to the data model. Big data management is divided into five steps: data collection, uploading, processing, analysing, and visualising the findings (Mazumdar et al., 2019).

For both traditional data and big data, the first step is collection. Once collected, data should undergo a quick, immediate analysis to detect gaps or inconsistencies that cannot be remedied at a later stage. The easiest way to do this, if resources allow, is by using smartphones or tablets to collect field data. Data can be synchronised onto different devices to avoid data loss. In the next step, managers need to identify how the data will be entered into the database. Data should be delivered in their simplest raw form into a permanent data repository so that they can be read years into the future. Some example formats include entering data in columns, as a document or spreadsheet, or as a time series. Database management systems are available for common formats (Mazumdar et al., 2019). Metadata that are attached to the raw data will enable the server to process the information and store it across cloud networks. Early consideration of which metadata will be included will improve data management.

Storage of data is usually independent of data analysis. To enable future analysis, it is important that raw data and metadata are stored not only in readable formats with unique identifiers of each dataset, but also that backup archiving mechanisms are in place. Metadata allow data from different programmes to be compared to one another, increasing their long-term value (Huettmann, 2009) (Box 9). Using protocols for data archiving and backup is very important. In some cases, automatic cloud-based data transfer will enable instant, transparent and open data access worldwide. Approaches using artificial intelligence are assisting the archiving process through automatically categorising new data (Colavizza et al., 2022). If resources allow, a physical printed copy of the data could be stored as an additional defence against loss. Considering long-term data accessibility, data rights and data security is important and should be built into the project from the early design stages. Technical concepts and data storage strategies are provided (Checklist 5).

Box 9

Unified approach to scientific monitoring in the mountains: Example of the GLORIA network



Biodiversity monitoring networks help managers understand how biodiversity behaves in certain biomes. The Global Observation Research Initiative in Alpine Environments, GLORIA, is an exemplary long-term scientific network. It is designed to record changes in plant species distributions due to climate changes in high mountain environments. The GLORIA network provides standardised data on species richness and abundance through long-term surveillance, describing the abiotic environment, useful biodiversity indicators, large-scale risks and potential conservation strategies. Mountain biomes are ideal for these objectives because they occur in all ecozones from the tropics to the polar regions, and plants in mountain zones are restricted by cold temperatures (Pauli et al., 2015).

Many GLORIA monitoring sites are located in protected areas. Parameters affecting biodiversity are investigated systematically at each site according to three activity levels as defined in the freely available GLORIA field manual (Pauli et al., 2015). Protected area managers can implement the standardised GLORIA methodologies and upload monitoring data to the central database whilst retaining data property rights. This allows local site data to be compared globally with data from the GLORIA network, increasing the power of the dataset to make inferences on drivers of local biodiversity change or threats facing the region.

GLORIA is an example of a monitoring programme that is successful due to its uniform approach to the monitoring design at all sites. Specific criteria must be met in order to establish new sites. Field methodologies and survey intervals are established in a clear manual of protocols. Also, datasets must follow a certain structure and fulfil a given quality standard.

Project metadata are customisable. Before data collection begins, it is important to define the required metadata, as is the case within the GLORIA network. Generally certain elements should always be included: title, dataset reference date, topic of the dataset, language and an abstract, contact information in case of questions, and a time stamp (Huettmann, 2009). Metadata management tools (e.g. Metadata++, ExifTool) allow users to record relevant metadata, verify that files contain all necessary metadata, and decrease the risk of omitting important elements. The generous release of these invaluable datasets will allow a variety of ground-breaking, large-scale analyses to be conducted, further leveraging the immense potential of locally collected biodiversity data.

Source: Klaus Steinbauer, Carinthia University of Applied Sciences, Austria. Picture: Monitoring plot according to the standardised GLORIA methodology.
© Klaus Steinbauer

4.5.3 Data policy

Having a culture of open data access across protected area networks is an ideal situation. But, if not required by national or institutional policies, biodiversity data might not be shared. Reasons can be a sense of data ownership, national security concerns, poor coordination across institutions, and perceived disadvantages from international obligations (Liang & Gamarra, 2020). Paid technicians and researchers may face poor job security, a dangerous and demanding work environment, and may be expected to dedicate their own resources for data collection (de Lima et al., 2022). For citizen scientist volunteers, motivation to participate may be for social reasons, for learning about and connecting with the natural world, and to gain a sense of personal achievement (Ganzevoort et al., 2017). Clear communication with data collectors about the intended use of their data is key to maintaining motivation for current and future projects.

Biodiversity data produce improved knowledge on the species examined in monitoring programmes and scientific research. The data policy of the protected area or OECM should be clearly stated in the overall management plan. Generally, information and raw data are considered facts and may not have legal protection under copyright law (Egloff et al., 2016). If collected through public funding, biodiversity data may even belong to the public. Free universal access to data gives a sense of transparency to the data collection process, leading to wider acceptance of findings. For these reasons, biodiversity data and research results should be published in open access sources. Within this context, well-justified restriction of certain data should be accepted. Special circumstances include masking the location of endangered species, maintaining the privacy of a co-operator, or protecting Indigenous communities. To safeguard the rights and interests of Indigenous peoples and local communities, and to guarantee transparency in the data collection process, a number of data sharing principles must be followed (Box 10).

Data policies should outline who owns the data, whether it will be freely available in an online data repository, and how the data will be used. One established framework is to designate data using Creative Commons licenses (Culina et al., 2018). Different Creative Commons licenses provide a range of privileges and permissions of data access. Publishers may have programmes offering waivers to pay reduced publication fees for open access content. Managers should communicate directly with publishers to learn whether they qualify for such programmes.

Box 10

CARE and FAIR data sharing principles: Protecting the data sources

To explicitly consider Indigenous peoples' rights and interests, CARE Principles for Indigenous Data Governance focus on the people and purpose underlying the data (Carroll et al., 2020). CARE principles include **collective benefit** allowing Indigenous peoples to benefit from the data, **authority** of Indigenous peoples to control how they are represented in the data, **responsibility** of data managers to show how data will support Indigenous peoples, and **ethics** emphasising Indigenous peoples' rights and well-being.

Online deposition of metadata allows discoverability of project data, helping to compare results across programmes. Metadata describe the permanent record of observation. They are a requirement for modern standard data management processes meeting the FAIR data sharing principles (Wilkinson et al., 2016). When data are submitted to digital repositories, they should be assigned a **findable** persistent identifier and described with high-quality metadata. They should be open and freely **accessible**. To be **interoperable**, metadata should be described in a common and accepted language, with appropriate reference to additional metadata. To be **reusable**, metadata should meet discipline-related standards and have a clear data usage license describing any limits to reusing the data, such as defined in Creative Commons licenses (Kissling et al., 2018).

Source: Compiled by the report authors

4.5.4 Data analysis and evaluation

Data analysis techniques should be suitable for the hypotheses and research goals. Analysis of monitoring data should be scheduled with a statistician (Adams-Huet & Ahn, 2009). The procedures should be standardised using well-documented or scripted semi-automatic processes. Interpretation of findings can be improved with the help of a specialist for the target object, if available. Interpretation is the process of understanding data, trends and statistical tests (Cooperrider, 1986). It is the critical link between data collection and adaptive management. Interpretation should address the following questions: What do the data mean?

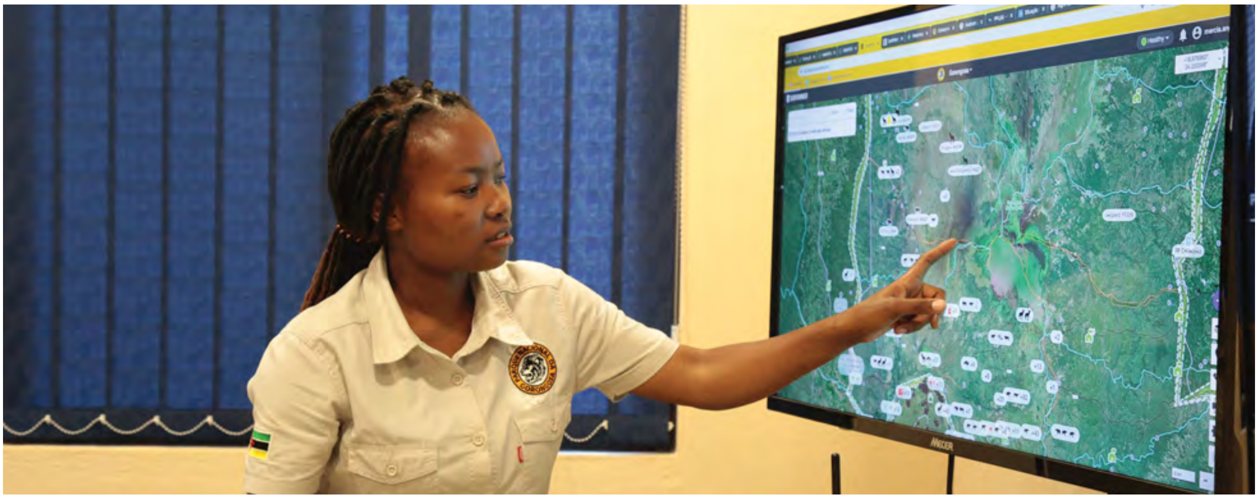
What is the cause of the trend? Are the data of good quality? Are the data sufficient to make decisions? What are the expected impacts of the proposed management? Answers to these questions will ideally be based on the scientific results but might require a 'best guess' opinion in order to continue with the decision-making process, particularly if the manager is faced with knowledge gaps. Notably, conclusions from data analysis might make sense only after multiple monitoring cycles have been completed.

4.5.5 Aggregation and integration into the management cycle

The conclusions of the biodiversity monitoring programme should support management decisions and reporting obligations. The 'classic' means of communication is through programme reports and scientific publications (Checklist 6). These formats of communication are typically very technical. However, management decisions rely on both technical and managerial experiences. As digital technologies improve, visualisation of trends is facilitated through online dashboards (Box 11). A site dashboard is designed to allow easy and regular observation of information by decision-makers. Visualisation is the next step to give value to the biodiversity data. Using dashboards is a useful form of data visualisation, giving particular value to the biodiversity data and making the complex processes and trends accessible in a simple form. Data can be visualised graphically to improve analysis. Appropriate visualisation of the data further contributes to the presentation of findings to various stakeholders. Presentations are a format that may generate stakeholder engagement. Presentations should be given early and often to stakeholders. Data should be presented in an open and transparent context so that the audience can freely reflect upon the findings.

Box 11

Dashboard view: The example of EarthRanger



EarthRanger is a data visualisation and analysis platform that gives conservationists the real-time information they need to keep wildlife, habitats and communities safe. The platform collects, integrates and displays all historical and available data. These data are combined with reports from the field to provide one unified view of collared wildlife, rangers and any other assets whether on land or sea. The applications of EarthRanger are diverse and are customisable to the primary needs of the area or organisation. Among them, the platform is used to track and study wildlife, coordinate ranger units and proactively mitigate human–wildlife conflict. Through active partnerships, features like instantaneous alerts and patrol management, and integrations with cutting-edge satellite services, EarthRanger enhances how organisations monitor vast areas in real-time.

The system is user-friendly, easily accessible via computer, tablet and smartphone, and ideal for use in the field without radios or satellite trackers. The platform is compatible with greater than 100 leading hardware devices, data services and platforms like SMART and Skylight, saving time and resources, and increasing impact.

EarthRanger is part of the Allen Institute for Artificial Intelligence (AI2), a non-profit institute created by the late Microsoft co-founder Paul G. Allen, with the mission of conducting high-impact artificial intelligence research and engineering in service of the common good.

Source: Jordan Steward, EarthRanger. Picture: A wildlife biologist uses EarthRanger to visualise the real-time movements of wildlife across a protected area. © Gorongosa National Park

Free and easy access to monitoring data ensures the legitimacy of the monitoring programme. A reasonable exception would be to exclude sensitive data from public access (Lunghi et al., 2019). The importance of open communication is critical, regardless of whether observations and trends are positive or negative. Standard algorithms should be used to avoid errors, to ensure comparable results, to help visualise the results, and to reach appropriate stakeholders. In this way, trends of the selected indicators can be visualised for scientists, administrators and the public. Sharing the findings within the monitoring network or with research institutions allows the possibility for wider comparisons across ecosystems and species. This is a crucial step to distinguish anomalies from actual trends. It may also justify the possible need for increased resources to achieve management objectives.

Monitoring vegetation using GLORIA methodology, Annapurna, Nepal. © *Robbie Hart*

CHAPTER 5.

Re-evaluation phase: Decision on adapting or terminating

5 Re-evaluation phase

The biodiversity monitoring system should be designed in a way to let managers and administrators reflect on the successes and shortcomings of individual programmes. It is recommended to review a biodiversity monitoring programme at a predetermined interval. Individual components should be reviewed at more frequent intervals in order to determine the best use of available resources. Completion of a monitoring cycle may lead to additional questions, and experiences should be shared across borders or within a protected area network. Technological advances, new funding schemes or other changes may allow a more efficient approach to conduct future monitoring, as identified through reflection.

Even simple changes in data collection methodology can lead to incompatibility between datasets and loss of statistical power. During re-evaluation, if the managers consider changing the field manual, possible effects on data analysis and presentation should be thoroughly assessed. If it is necessary to change the approach, a dataset comparing the old and new methods should be collected to assess the impact of the changes on data analysis and presentation.

Outcome: Monitoring approaches and goals should be re-evaluated after several monitoring cycles or following major changes to reporting obligations. Successes or shortcomings of the biodiversity monitoring system and its components can be communicated to administrative agencies and other stakeholders. A decision on continuing, modifying or terminating the biodiversity monitoring programme should be made. In the case of major revision, managers and stakeholders may need to go back to the conceptual phase to determine the scope of the monitoring programme based on available resources and site factors.

Ephemeral pond, William L. Finley National Wildlife Refuge, Oregon, USA. © *Daniel Dalton*

CHAPTER 6.

General considerations for effective monitoring

6 General considerations

With the framework for establishing effective biodiversity monitoring programmes in mind, this chapter describes an overview of basic considerations that will promote effective biodiversity monitoring. Knowledge of site-specific conditions and management objectives are required for effective planning of monitoring procedures.

6.1 Obligations: International conventions and policies

The main purpose of protected areas and OECMs is to conserve the unique biodiversity that is contained on site. Many international policies require or imply biodiversity monitoring and reporting efforts (Mitchell, 2003) (Box 12). Managers should have a clear understanding of which institutions, treaties, instruments and the corresponding mechanisms apply to their site reporting requirements. These may include the CBD, various reports for UNESCO, World Conservation Monitoring Centre, linkages to the IUCN Red List and IUCN Species Survival Commission, Living Planet Index, Natura 2000 network, and more (Table 4).

Box 12

Monitoring in Natural World Heritage sites: Japanese island ecosystems in focus

Natural World Heritage Sites are areas of high biodiversity that are listed by the World Heritage Convention, an international treaty that aims to permanently protect the most unique ecosystems on the planet. Sites are nominated based on their Outstanding Universal Value. This is defined in a way that emphasises a site's importance for the international community because these sites are globally unique and cannot be replaced (Bertzky et al., 2013). Natural World Heritage Sites are expected to stimulate local economies through international valorisation and branding. Through ecotourism, visitors are encouraged to take an interest in natural ecosystems, promoting conservation action.

Once an area is registered as a Natural World Heritage Site, site-based conservation and sustainable use of biodiversity must be well planned. Real and potential threats to Natural World Heritage Sites include over-tourism, invasive alien species and the impact of climate change (Osipova et al., 2014; Osipova et al., 2017; Osipova et al., 2020). The intensification and increased risk of natural disasters due to climate change threaten not only the ecological attributes that support heritage values, but also the livelihoods of visitors and residents. To mitigate these threats, implementing monitoring systems and adaptive management activities are essential tools (Osipova et al., 2020).

Local residents play a major role. Japan's Natural World Heritage Sites include a series of islands containing rare and endemic species of Outstanding Universal Value (Toyama et al., 2023). These island ecosystems are in danger of losing endemic species due to climate change, invasive species introductions and other human impacts (Working Group for Comprehensive Assessment of Biodiversity and Ecosystem Services, 2021). Discovering changes in biodiversity and endemism can be achieved through monitoring, helping managers understand how pressures contribute to ecological changes. This is essential knowledge for establishing a management system to mitigate threats. A scientific committee should be established in each Natural World Heritage Site to allow monitoring to support the corresponding National Biodiversity Strategy and Action Plan. In Japan, a policy is being considered that will improve sustainable development through the promotion of ecotourism. Using Nature-based Solutions, it is expected that the co-benefits of ecosystems will extend to local communities, balancing economic sustainability with conservation and utilisation (Study Group on the Next National Biodiversity Strategies and Action Plans, 2021).

Source: Yayoi Takeuchi, Senior Researcher, National Institute for Environmental Studies, Japan. Picture: Asarum fudsinoi. © Yayoi Takeuchi

Table 4 List of main international biodiversity treaties and conventions

Effective date	Name of convention / programme	Type and interval of reporting / monitoring
1971	Man and the Biosphere Programme (MAB)	Every 10 years (5-year interim reports): site-specific evaluation report to MAB Programme
1975	Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES)	Annually: national reports to the Secretariat on imports, exports, re-exports and introductions of specimens
1975	Ramsar Convention on Wetlands	Every 3 years: national reports to Conference of the Parties
1975	World Heritage Convention (WHC)	Every 6 years: report on site integrity to World Heritage Centre
1979	EU Birds Directive	Every 6 years: report on population size and trends of bird species
1983	Convention on Conservation of Migratory Species (CMS)	Every 3 years: national progress reports on implementation
1992	EU Habitats Directive	Every 6 years: conservation status and trends of species and habitats
1993	Convention on Biological Diversity (CBD)	Every 4 years: national reports to CBD
1996	Convention on the Protection, Management and Development of Marine and Coastal Environment of the Western Indian Ocean (Nairobi Convention)	Every 2 years to the Conference of the Parties for review
1998	Convention on the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention)	Every 2 years: assessments of the status of the OSPAR network of Marine Protected Areas
2016	UNESCO Global Geoparks	Every 4 years: site-specific revalidation report to UNESCO Global Geoparks

Source: Compiled by the report authors

A global standard on implementation of Nature-based Solutions is available (IUCN, 2020). Implementing Nature-based Solutions should align biodiversity conservation with sustainable development. Effective solutions will help realise ecosystem-based management decisions that address societal challenges whilst improving the state of biodiversity and human well-being. The global standard links eight criteria guiding the background principles of Nature-based Solutions with the assumptions required for effective management interventions (Table 5).

Table 5 Criteria and assumptions for integrating Nature-based Solutions into management activities

Criteria for implementing effective Nature-based Solutions	Assumptions
1. Solutions target societal challenges.	The most urgent challenges are prioritised;
	Managers adequately understand the targeted challenges;
	Outcomes of human well-being are benchmarked and periodically assessed.
2. Spatial scale helps design implementation measures.	Economic, societal and ecosystem factors interact with each other;
	Activities should be synergetic across sectors;
	Risk assessment extends beyond the intervention site.
3. Solutions improve biodiversity and ecosystem integrity.	Evidence-based response to the state of the ecosystem and its main drivers;
	Minimum benchmarks established to help determine the effect of the measure;
	Monitoring and evaluation plan examines unintended effects of the measure;
	Strategies identified to improve ecosystem integrity and connectivity.
4. Solutions are economically viable.	Benefits and costs of a measure are documented, including who pays and who benefits;
	Cost-effectiveness study determines level of support for implementation;
	Value of implementation is greater than possible alternatives;
	Material, financial and human resources available for proper implementation.
5. Solutions assume inclusive, transparent and empowering governance.	All stakeholders can use a readily available feedback and resolution mechanism;
	Participation founded on gender equality, respects the rights of Indigenous peoples, and does not depend on age or social status of participants;
	All affected stakeholders should be involved in the processes of the measure;
	Joint decision-making should be possible across jurisdictional boundaries.
6. Solutions balance achieving their primary goal(s) and providing other benefits.	Costs and benefits of different intervention scenarios are considered;
	Rights, usage and access to land or resources are recognised and valued;
	Safeguard systems are in place to avoid negative consequences of a measure.
7. Solutions are managed adaptively.	Monitoring and evaluation of the measure against the baseline condition is regularly performed;
	Monitoring and evaluation plan is used through the full course of the intervention measure;
	Learning opportunities from the intervention measure will contribute to adaptive management.
8. Solutions are sustainable and can be mainstreamed.	Design, implementation and findings from the measure should be shared for wider transformative changes;
	Measures must be aligned with other current regulations and policies, and incompatibility across sectors is documented to provide learning opportunities;
	Measures contribute to targets from national and sub-national policies.

Source: IUCN, 2020, adapted by the report authors

The CBD is a landmark agreement intended to promote the conservation of biodiversity, the sustainable use of biodiversity, and the fair and equitable sharing of the benefits derived from genetic resources (CBD, 1992). Since ratification in 1993, multiple annexes to the CBD have been implemented, including the Cartagena Protocol on Biosafety in 2003 and the Nagoya Protocol Access to Genetic Resources in 2014. Currently, in the UN Decade on Ecosystem Restoration 2021–2030, conservationists and policymakers are addressing the biodiversity crisis through the Kunming-Montreal Global Biodiversity Framework (GBF) (Nicholson et al., 2021). Target 2 of the GBF calls for effective restoration of 30 per cent of the area of degraded terrestrial and aquatic ecosystems.

Target 3 is a headline indicator of the GBF and contains the '30 × 30' goal. To meet this goal, 30 per cent of the Earth's surface should be placed under effective conservation by the year 2030. Integration of conserved sites in the larger landscape should occur with full recognition and respect for the territorial rights of Indigenous peoples and local communities. Coverage calculations and importance of sites involves calculations and mapping based on submitted reports by national governments (UNEP-WCMC, 2023b). The effectiveness component of Target 3 is still being defined but is focused primarily on creating positive outcomes for the conservation of biodiversity (CBD, 2023). We define a consistent monitoring strategy in this guideline that is intended to be a key tool to satisfy effectiveness requirements.

6.2 Art of omission: Daring to simplify

Monitoring programmes can suffer from collecting data on too many variables. Each dataset increases the complexity of data analysis. Because data collection and analysis require human effort, uninformative or poor-quality data represent a waste of time and resources. In a worst-case scenario, poor data may increase the risk of errors by introducing inconsistency in the dataset (Box 13). Mixing a variety of data formats further challenges comparisons across sites or over time. The narrowest set of indicators representing the status of the site should be selected (Butler et al., 2012). Indicators can include key habitats, species or proxy parameters that are tightly linked to the component of interest (Lindenmayer et al., 2015). Abiotic factors such as air quality, water quality or temperature may be monitored as proxies of biological elements in cases where the factor is well correlated with the biological feature of interest. Simplification of a monitoring programme may be informed through test analyses of simulated data to help identify the most informative indicators (Figure 16).

Figure 16 The effort required for monitoring system implementation and data management increases with large numbers of selected parameters. For efficiency and the greatest likelihood of obtaining time-series data, indicators and data collection techniques should be kept to the minimum required level. *Source: Compiled by the report authors*

Box 13

'Best of' mistakes in monitoring: Succession in a fallow field in Austria

The change in the plant community on abandoned agricultural fallow land was analysed within the framework of a 30-year monitoring programme in a conservation area near Liebenfels, Austria. Surveys were conducted using a very simple study design. Plant species and cover were recorded on 29 study plots (5 × 5 metres). Through data analysis, the scientific team found numerous errors.

Here is an excerpt of the monitoring mistakes. Some plots and transects could not be found from one survey to the next despite their locations being redundantly marked. Individual plot records, photos, files and documents could not be found. Available photos and documents were not labelled or could not be assigned in time and space and therefore could not be utilised. Individual data files could no longer be read because file formats became outdated. Species composition changed 'suddenly' with a change of scientific staff or new taxonomic designations. Phenological recordings at slightly different times of the year changed the result. Lack of metadata complicated the interpretation of the findings.

These examples lead to the following conclusions: 1. Each individual set of data is vulnerable; 2. Each indicator multiplies complexity and costs disproportionately; 3. Each irregularity reduces the quality of results disproportionately.

When the monitoring plan is more complex than necessary, the chances increase that some important data will be lost. Considering that mistakes will always be made in long-term programmes, it is better to design simply and realistically at the beginning. Monitoring is the art of omission.

Source: Michael Jungmeier & Melanie Erlacher, Carinthia University of Applied Sciences, Austria. Picture: View of the monitoring area. © Elisabeth Wiegele

6.3 Biodiversity monitoring systems: Designing modular, multi-scale and multi-purpose monitoring systems

Integrating different regional, national or transboundary management programmes is essential to create synergies and promote management effectiveness beyond the boundaries of protected areas and OECMs (Karadeniz & Yenilmez Arpa, 2022a). When designing a new biodiversity monitoring programme, data should be acquired from various sources to improve the concept and design, as well as to identify the appropriate required materials. In some cases, data will come from external partners. National programmes may already have valuable information available, such as assessments of key species that are relevant for protected area management. Effective modular components of a monitoring programme may be adapted for different regions or transferred to similar ecosystems (Dallas, 2021) (Box 14).

Box 14

From individual sites to a protected area system: The Brazilian Programa Monitora

Since the beginning of the 21st century, the number of protected areas and their coverage have more than doubled in Brazil, today numbering about 2,000 units covering more than 1.5 million km^2 (OECD, 2015). Programa Monitora was formalised in 2014 after several years of conceptualisation. The main goal is the evaluation of conservation effectiveness of the 334 protected areas managed by Instituto Chico Mendes de Conservação da Biodiversidade, Brazil. The programme also produces qualified information for management decisions at local and regional scales. Today, Programa Monitora contains three subprogrammes focusing on 10 types of ecosystems. Currently, 23 targets are being monitored, some of them corresponding to previous long-term monitoring initiatives (e.g. marine turtles), and others representing novel indicators (e.g. dragonflies in streams). Some targets are related to resource use, like artisanal fisheries and Brazil nut harvesting, and all protocols deliver information about ecosystem health.

The programme was designed after considering successes and drawbacks of previous worldwide examples, thus adopting a set of integrated principles. Common targets and protocols allow comparison across regions. Targets are selected based on local environmental and social factors. The scale of sampling is optimised according to the national, regional or local scope of the subprogramme.

Protocols are simple enough to allow data collection by people without formal biological training, but effective because they are based on sound science. Protocols are modular to allow specific combinations for each site.

A participatory process utilising community-based volunteers is used in order to generate programme acceptance. All participants receive appropriate training. The national protected area network utilises a unified data management strategy, with a policy to provide open and immediate data access, showing transparency. Finally, qualified scientific debate around the findings allows widespread development of learning and knowledge.

The resulting programme is widely recognised by protected area managers, local communities, funding agencies and the scientific community. Programa Monitora strengthens links between institutions and people of different backgrounds, generating local results, national reports and scientific papers.

Programa Monitora — Português (Brasil)

(https://rb.gy/0naso8)

Source: Katia Torres Ribeiro, Instituto Chico Mendes de Conservação da Biodiversidade, Brazil. Picture: Butterflies are part of the Terrestrial Component of Programa Monitora. It is a group that arouses interest for many people, and through simple protocols it is possible to collect information about the health of forests. © Instituto Chico Mendes de Conservação da Biodiversidade

An indicator can be used to evaluate multiple monitoring obligations, or on the other hand multiple indicators can be used together for detailed area-based reporting. Ideally, components can be used in a modular way, meaning that certain indicators of past and existing programmes can be monitored in future programmes, or across multiple scales. A biodiversity monitoring system should include a monitoring programme on habitats (e.g. ecosystems and land cover), in addition to monitoring key species. Findings should be disseminated in various formats, from scientific reports to stakeholder outreach (Figure 17). This background allows integration of further monitoring programmes and interpretation of results based on actual management activities.

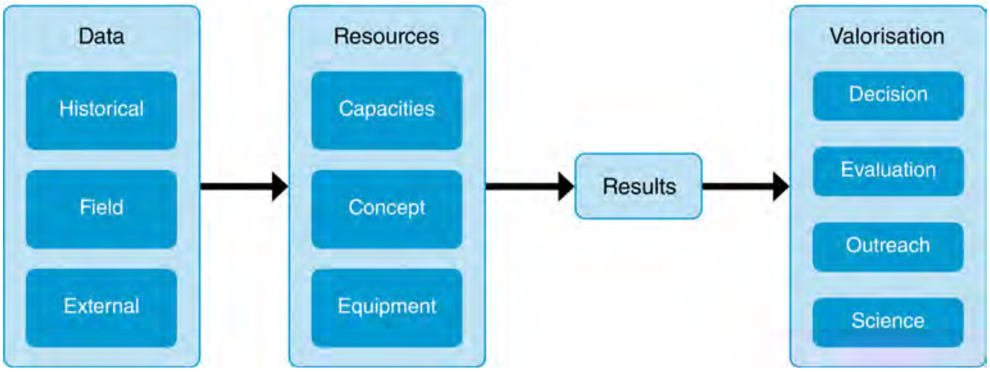


Figure 17 Data are brought together to determine a modular framework of new biodiversity monitoring programmes. Data allow identification of improved concepts, realistic capacities, and required equipment for monitoring, leading to informed decision-making, project or programme evaluation, and outreach to stakeholders. *Source: Compiled by the report authors*

6.4 Combining forms of knowledge

A high amount of the world's biodiversity is conserved in areas that were managed sustainably for generations by Indigenous peoples and local communities using traditional ecological knowledge (IUCN, 2022a). Protected areas and OECMs lie at the intersection of scientific and traditional ecological knowledge because sites are often managed by organisations that were not historically part of the area (Danielsen et al., 2009). Co-creating knowledge through linking traditional ecological knowledge and scientific approaches demonstrates how partnerships can improve conservation outcomes (Box 15). To ensure that a protected area or OECM management strategy will produce the best outcomes for biodiversity and traditional land uses, traditional ecological knowledge and scientific knowledge need to be viewed as equal contributors towards understanding nature (Thompson, Lantz & Ban, 2020). For the highest chance of success, managers must work towards developing strong relationships and trust with Indigenous community members. Utilising the input of Indigenous communities in all phases of the biodiversity monitoring programme is essential for equal power-sharing and developing trust. Engaging Indigenous peoples and local communities in genuine participatory processes will eliminate one-way flow of information (Borrini, Kothari & Oviedo, 2004). Assigning leadership roles to Indigenous group members will help to equalise the influence of scientific and Indigenous forms of knowledge (Thompson, Lantz & Ban, 2020). Empowering Indigenous or community members in decision-making processes will break down biases and allow community members to be confident that they control how their knowledge will be used and represented. Developing a mutual understanding of the cultural backgrounds of involved stakeholders will further contribute to increasing different forms of knowledge. In some cases, working with a cultural liaison advisor can help with this process. Potential technological barriers can be broken down through the use of digital tools such as the Spatial Monitoring and Reporting Tool (SMART) allowing a user to collect raw data based on icons.

Box 15

Forest restoration using traditional ecological knowledge in a transboundary biosphere reserve, Peru and Ecuador

The iconic tropical dry forests of the Bosques de Paz Transboundary Biosphere Reserve of north-western Peru and southern Ecuador are recognised as an important world biodiversity hotspot (Olson & Dinerstein, 1998). The biosphere reserve covers more than 1.5 million ha and contains multiple protected area designations within its boundaries, including Cerros de Amotape National Park of Peru that comprises much of the core zone of the biosphere reserve (UNESCO, 2021). The area has been greatly affected by human pressures in recent decades, such as livestock husbandry and extraction of natural resources. Today, conservation of the wilderness and restricted use areas of the dry forest Bosque Seco Denso de Montaña is a primary objective of the national park.

Restoration of special use and buffer zones of Cerros de Amotape National Park provides an opportunity for local contribution to management objectives. The park management plan calls for restoration of more than 60,000 ha of national park land to recover its environmental quality to a historically natural condition, or about 38 per cent of the national park (SERNANP, 2015). This goal meets the main objective of Target 2 of the Kunming-Montreal Global Biodiversity Framework, where: "by 2030 at least 30 per cent of areas of degraded terrestrial, inland water, and marine and coastal ecosystems are under effective restoration, in order to enhance biodiversity and ecosystem functions and services, ecological integrity and connectivity" (CBD, 2022).

Researchers interviewed stakeholders from communities located in and around Bosques de Paz Transboundary Biosphere Reserve on their perspectives for using native plant species for provisioning of ecosystem services (Fremout et al., 2021). They compiled more than 4,000 responses of local expert and non-expert community members on traits including the potential use, stress tolerance and perceived threat status of nearly 150 species. Available scientific knowledge was then compared to the traditional ecological knowledge of the stakeholders.

Favourable comparisons were realised between traditional ecological knowledge and scientific knowledge for 97 per cent of the species for which scientific knowledge was available. About half of the species lacked scientific knowledge altogether. The findings showed that the close relationship of local communities to native plant species had allowed development of traditional ecological knowledge that could not be replaced by scientific knowledge (Fremout et al., 2021).

Traditional ecological knowledge provides a strong basis upon which the most useful species can be prioritised for restoration purposes. Utilising local knowledge resources further invites communities to contribute meaningfully to restoration projects, representing community members and leading to greater support and improved chances for successful long-term management.

Source: Compiled by the report authors. Picture: Local community members explaining the uses of the choloque tree, Department of Piura, Peru. © Tobias Fremout

6.5 Continuity risks: Avoiding disruptions and gaps in data

Robust statistical design must be considered in advance of data collection (Zuur et al., 2009). The value of a long-term monitoring programme is diminished if the data are collected at the wrong time or season or at insufficient intervals. If data are collected at an inadequate frequency, the interpretation of the time series may be fundamentally flawed (Figure 18). Contingency plans accounting for potential loss of resources or financial support should be developed in advance of any disruption. After collection, data should undergo a rapid preliminary analysis to identify any problems with the conceptual approach of the monitoring strategy or with its implementation. Consultation with a statistician can identify statistical tests that may be used with irregular datasets. Finally, a timeframe for data analysis should be designated.

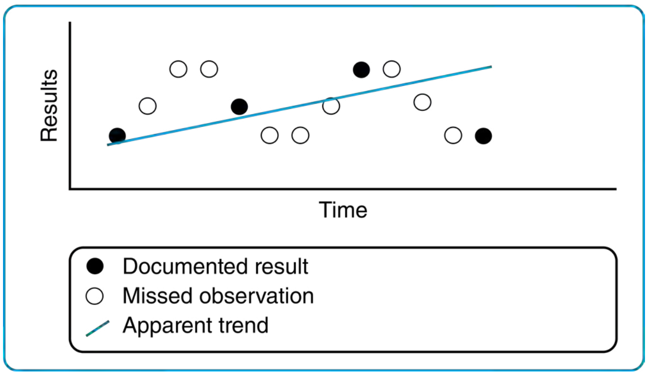


Figure 18 Monitoring at an improper frequency may display faulty trends. *Source: Compiled by the report authors*

It is essential to keep in mind the long-term nature of biodiversity monitoring and to ensure continuity across institutional, technical or organisational changes. This is a significant challenge given the relatively long course of biological processes compared to rapid changes in monitoring resources and technologies. For instance, major changes in scientific theory, technology and human societies have occurred within the lifespan of a tree (Figure 19). Building on the experiences gained from previous programmes will improve the outcome of following efforts.

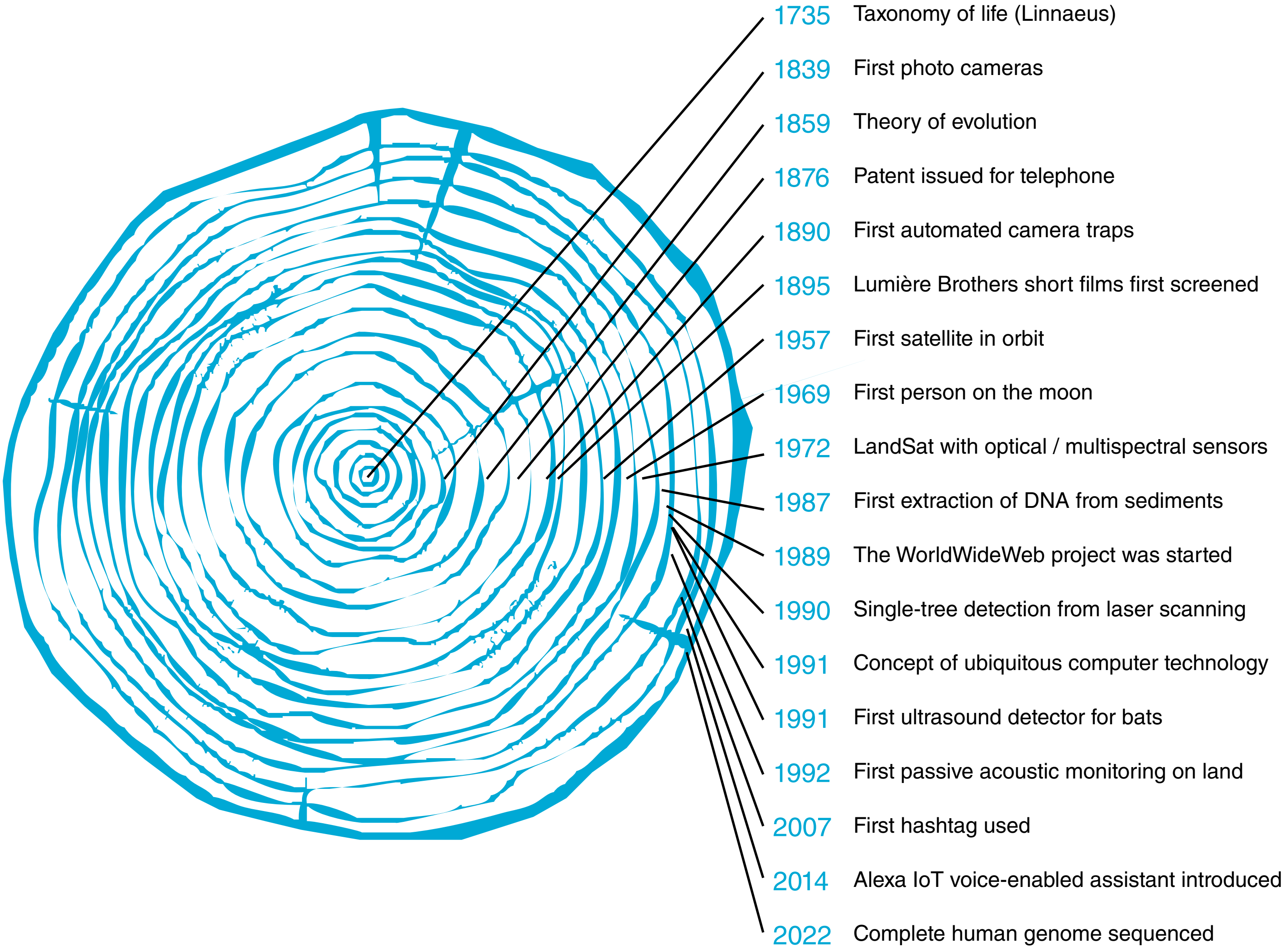


Figure 19 Timeline of key achievements advancing monitoring capacities
Scientific discovery occurs slowly from the perspective of a human lifespan. The tree rings represent the idea that important discoveries occur rapidly on the scale of ecosystems. Over the past three centuries, our understanding of life has fundamentally changed. The way we monitor the life around us is undergoing a similar revolution today. *Source: Compiled by the report authors*

6.6 Detecting trends and correlations: The value of time series

Monitoring involves a regular and long-term process of data collection. This information provides a measure of whether management goals are being met. Biodiversity monitoring should provide objective measurements of the state of key ecological features. The value of monitoring increases the longer the protocols are in place because precise estimation of indicator status – and in some cases even the existence and direction of change – can be determined only with sufficient observations over time (Figure 20). Accurate and timely observations provide an important basis for decision-making, whilst faulty conclusions based on too few data points can harm the integrity of the management programme. For conservation or restoration purposes, objectives or impacts may be evaluated over time through monitoring (Box 16). Multiple sites implementing the same approaches will help to identify and compare long-term trends. Threats can be identified in long-term datasets through correlating changes in the state of a sensitive indicator. In this way, the state of the indicator can be monitored as a basis for adaptive management decisions (Westgate, Likens & Lindenmayer, 2013).

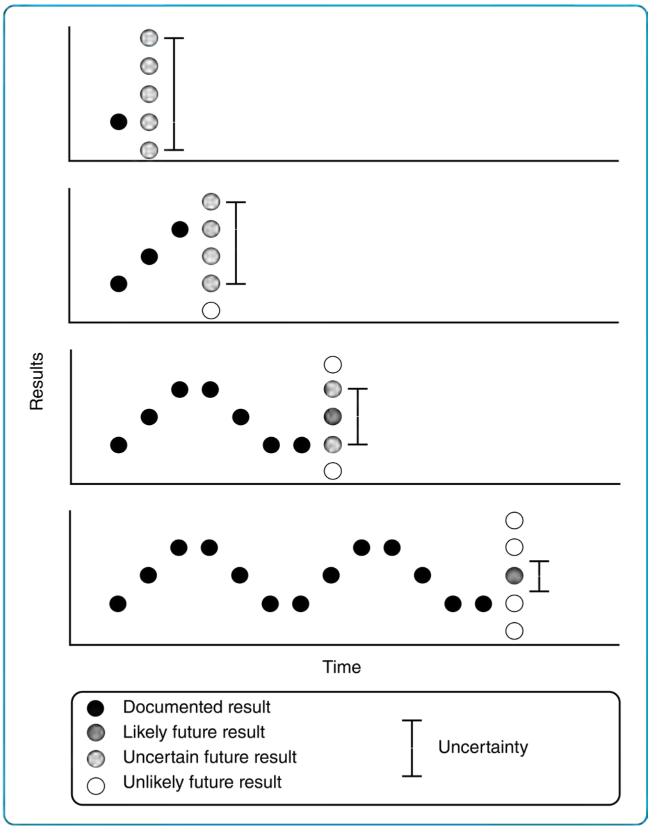


Figure 20 Long-term monitoring provides increasingly accurate knowledge.
In this example, the long-term cycles of the indicator become clear over time, leading to less uncertainty in future predictions.
Source: Compiled by the report authors

Box 16

Monitoring and evaluation of environmental measures: Water usage in the south-east of the United States

The concept illustrated in Figure 18 and Figure 20 shows that regularly collected data will show trends on the subject. In the context of protected area management, available data from multiple monitoring cycles should therefore allow managers to predict future observations given no changes to an intervention. Conservation and management decisions are often limited due to one-time observations or at best limited pre- and post-intervention measurements (Adams, Barnes & Pressey, 2019).

To show the value of time series in an environmental context, we draw upon studies that used data in a randomised control trial to decrease household water use (Ferraro & Price, 2013). To test how much an experimental design with paired controls and limited pre- and post-intervention measurements can match the intervention's 'true' impact, the authors of the water use study ran a number of experiments. They found that where only one pre-intervention period was considered, serious challenges occurred in matching real-world findings to experimental estimates (Ferraro & Miranda, 2014). A follow-up study with multiple pre-treatment observations resulted in far better predictions (Ferraro & Miranda, 2017).

These studies show that when pre-intervention observations are unavailable, evaluating the intervention is challenging even with the best statistical approaches. Surveillance monitoring to detect trends over time will still be possible post-intervention but will be poorly correlated with the intervention itself. When pre-intervention observations are available, multiple post-intervention measurements will improve interpretation.

The take-away message is that investing in multiple pre- and post-treatment observations will improve the understanding of the changes in environmental outcomes and attributing those changes to the management interventions.

Source: Vanessa Adams, University of Tasmania

6.7 Maintaining ecological balance: Establishing baselines and thresholds

The ability of an ecosystem to return to a stable state following a disturbance is called resilience. The ecosystem can transition to a different stable state if a disturbance is strong enough to pass an ecological threshold, or tipping point. Depending on the disturbance, the threshold might be irreversible. In other cases, returning to the desired state would require extreme actions with unknown consequences.

Considering thresholds in a management plan can contribute to achieving a favourable conservation status of a species in a protected area or OECM. For evidence-based site management, critical thresholds play an essential role. A known minimum amount of habitat is required for certain animal species where below the threshold area, populations cannot thrive. If threshold responses can be identified and measured, adaptive management will become more efficient and easier to execute. It is crucial to understand the circumstances in which thresholds are likely to be crossed and the mechanisms behind threshold behaviour (Groffman et al., 2006).

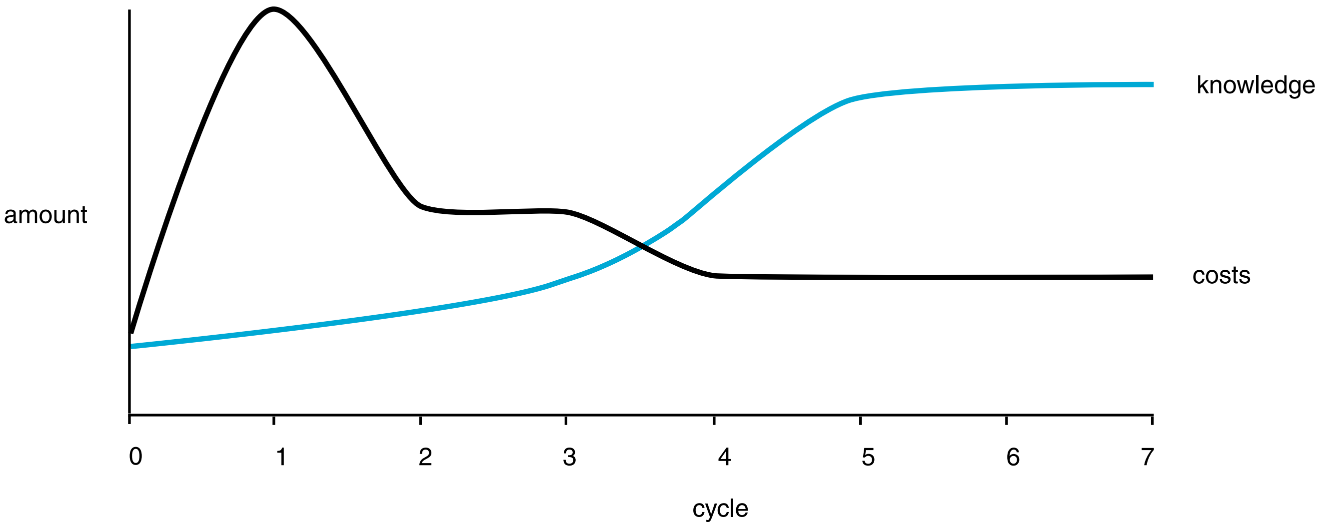
Threshold values can be derived from a baseline survey or from historical findings. They can sometimes be developed by stakeholders as a management target (e.g. re-establishment of 50 km^2 of natural habitat). Sometimes, and unfortunately far too rarely, these thresholds are anchored in the management plan of a park. In any case, these thresholds must be taken into account in the orientation and calibration of the monitoring programme. If certain thresholds are exceeded or not reached, it is time for adaptive management actions to change.

6.8 Setting up monitoring systems: Costs and outcomes

“Monitoring is to record change” (Bayfield, 1997). Many sectors in modern societies are steered, evaluated and driven by monitoring indicators such as employment rates, stock market indices, demographic features, and so on. For decision-making, the identification of trends is much more important than obtaining simple snapshots of the indicator over time.

It is essential to understand the long-term costs and benefits of monitoring. The costs are highest at the beginning of a monitoring programme, whilst the benefits become apparent only after several monitoring cycles. The value of the data therefore increases over time (Figure 21). Funding and project continuity should be considered in a long-term context. Such an approach will maintain continuity of monitoring despite changes to personnel or funding programmes. Institutionalised support from national protected area networks and agencies is important because it can guarantee long-term programme funding.

Figure 21 The initial stages of a monitoring programme come with high up-front costs. The required effort during initial cycles of a biodiversity monitoring programme must be evaluated against the value of knowledge that accumulates after several monitoring cycles. *Source: Compiled by the report authors*



6.9 Protected Area Management Effectiveness evaluation tools

In the Kunming-Montreal Global Biodiversity Framework, protected areas and OECMs are becoming more accountable for outcome-based management. A robust National Biodiversity Strategy and Action Plan (NBSAP) will provide a framework for managers to ensure that the objectives of the management plan work towards the national strategy. NBSAPs are required under Article 6 of the CBD (CBD, 1992). Site-specific planning methods are also used extensively in protected area management, such as the Conservation Measures Partnership's Open Standards for the Practice of Conservation and its software platform Miradi (CMP, 2020). These planning methods are designed to provide standardised approaches for implementing conservation projects and evaluating their outcomes, with a key focus on improving adaptive management.

Management effectiveness in protected areas and OECMs requires good decision-making, planning and implementation (Borrini, Kothari & Oviedo, 2004). PAME evaluations are necessary to understand the impact of management activities at the site level, as determined by sufficient and appropriate monitoring (Hockings et al., 2006). PAME evaluations usually use standardised forms that are completed by managers of protected areas and OECMs, with help from staff, stakeholders and policymakers. Since the 1990s, some of the most widely used PAME methodologies include the Management Effectiveness Tracking Tool (METT), the Rapid Assessment and Prioritisation of Protected Area Management (RAPPAM) and the Integrated Management Effectiveness Tool (IMET) (Bialowolski et al., 2022). To show the outcome of management interventions, protected area managers can provide periodic reports through using PAME evaluation tools (Box 17). If possible, managers should report on what the status of the protected area would be in the absence of the management activity, in other words use counterfactual thinking. Findings may support continuing the management actions, or may alternatively prompt a long-term strategic change in management. PAME evaluations should be recorded in the Global Database on Protected Area Management Effectiveness (http://tinyurl.com/yc2cr7bd).

Box 17

Integrated Management Effectiveness Tool (IMET): Implementation in central Africa

To help improve the management of protected areas and achieve conservation objectives, IMET provides an integrated framework to support planning, monitoring and evaluation processes.

IMET assesses protected area management effectiveness through analysing results of management activities. Actions that solve problems, minimise pressures or transform threats into opportunities can be continued or even applied to other protected areas. The ultimate goal of IMET is to integrate planning and evaluation to determine which management changes are necessary to meet the desired conditions derived from the long-term site objectives. If a protected area does not use good planning or a long-term strategy, IMET can be used as a dashboard to indicate which changes should be adopted and integrated in short-term and long-term planning.

In central Africa, the first IMET evaluations were implemented as a test in 2014 on a small number of pilot sites. In 2016, after a consolidation of the tool, a large campaign was organised by the Central African Forest Observatory (OFAC) with the support of the BIOPAMA programme. Institutional agreements were arranged between the Central African Forest Commission (COMIFAC) and the national agencies in charge of protected areas. As of 2018, many partners had integrated IMET into their work plans to respond to their diverse needs. Such needs include revision of management plans, development of monographs, implementation of monitoring evaluation systems, evaluation of management effectiveness, mobilisation of financial resources, and more.

To facilitate its application in different countries, the use of IMET is supported in central Africa by a team of national coaches. These experts are trained in administering IMET evaluations and analysing the results. Coaches are mobilised by OFAC or national agencies as needed for field implementation of the tool. Today, the network of IMET coaches in central Africa numbers 42 experts across 8 COMIFAC countries.

Today more than 140 IMET exercises have been carried out in 77 central African protected areas. The findings have already permitted OFAC to produce national and regional reports on the management effectiveness of protected areas in central Africa.

IMET is accessible via the OFAC website at the following link (in French):
https://www.observatoire-comifac.net/monitoring_system/imet

Source: Florence Palla, Donald Jomha Djossi and Quentin Jungers, Project RIOFAC in support of OFAC/COMIFAC, Central Africa. Picture: African elephant with tracking collar in a protected area. © Vanessa Berger

Flowering *Sempervivum montanum* in the Nock Mountains, Austria. © *Daniel Dalton*

CHAPTER 7.

A review of methods and technologies to implement efficient and effective biodiversity monitoring programmes

7 A review of methods and technologies to implement efficient and effective biodiversity monitoring programmes

Collection of biodiversity data requires significant human effort. Many traditional data collection approaches are becoming insufficient to match today's requirements for protected areas and OECMs. However, over the past few decades advanced technologies have been developed that support effective biodiversity monitoring campaigns (Table 6). These modern approaches may enhance public interest in support of conservation actions (Verma, van der Wal & Fischer, 2016), and these technologies continue to improve (Lahoz-Monfort & Magrath, 2021).

In conservation applications, digital sensors, for instance, can convey threats to wildlife in near-real-time, may promote staff and visitor safety, and can enhance visitor experiences (Hodgkinson & Young, 2016). Users may initially be wary of new technologies, thereby limiting their adoption. But once they become familiar, the technologies may become the new standard, breaking previous barriers (Weiser, 1999). Because of high up-front costs and special user requirements, automated sensors are not always a perfect solution. Therefore, a combination of automated and traditional methodologies will be important to meet future monitoring objectives (Stephenson, 2020).

Table 6 Overview of different techniques for biodiversity monitoring with examples, benefits and limitations

Technique	Example	Benefits	Limitations
Acoustic devices and sensors	Acoustic recorder	Less restricted by activity of targeted organism; suitable for long-term data collection; non-intrusive method; portable; verification by multiple experts possible	Sound / call must be unique for species identification; many battery powered; large volumes of data are produced; limited detection range; background noise lowers data quality; vandalism
Optical devices	Camera trap	Data can be uploaded onto cloud-based network; less restricted by activity of targeted organism; suitable for long-term data collection; non-intrusive method; portable; verification by multiple experts possible	Species ID not possible for all species on picture (e.g. insects); limited field view; triggering issues; many battery powered; large amounts of data are produced; vandalism; privacy issues
Remote sensing	Drone-based monitoring	Great value for visualisation of landscape; high resolution comparison of habitats; temporally flexible; cost-effective; accessibility of rough terrain	Ground-truthing necessary for precise data; short flight time; professional technician needed; large volumes of data are produced; regulatory compliance; privacy concerns; collision and disturbance risk
Telemetry and tracking tools	GPS collar	Long-term method to survey species movement; real-time data enable early warning system of threat; data-driven conservation strategy	Capturing animals may alter behaviour; device retrieval; limited battery life; lack of generalisability; data accuracy and availability limited in rural areas
Olfactory devices	Pheromone detection	Non-invasive; find sources of pheromones or act as a source / attractant for targeted organisms	State-of-the-art sensors still in experimental stage; electronic noses in use especially in chemical analysis and safety-related issues mostly not calibrated for nature conservation; limited sensor range; hard to locate source of pheromones
Genetic methods	Environmental DNA sampling	DNA can be obtained from environmental samples (water, soil, air) as well as other organic matter such as feathers, dung, hair etc.; non-invasive; specific species detection; overview of species of taxa; analysis of large-scale surveys	Some expertise in sterile sampling to be acquired; specialised equipment and laboratory work required; data analysis and management might be challenging; spatial and temporal variability; sample can degradate or get contaminated; lack of reference data

Source: Compiled by the report authors

7.1 Early bird or late adopter: Drivers and barriers of technology deployment

Adoption of a new innovation is influenced by many factors, including the type of innovation, how and for whom it is designed, user acceptance and cultural contexts in which the innovation is used (Mascia & Mills, 2018; Rogers, 1995). In conservation, a new practice will only be adopted if it is expected to help managers and field staff achieve their goals (Pannell et al., 2006).

In protected area and OECM management, the use of digital tools is poised to revolutionise biodiversity monitoring (Joppa, 2015). Often, different target organisms require unique sets of tools and methodologies to effectively monitor their status, and many expert-based classic approaches are suitable to monitor species. But there are many positive aspects to using new approaches for biodiversity monitoring. Foremost, by using remote data collection the presence of an expert is no longer required for field work. High-tech devices can provide a simplified workflow whilst allowing rapid collection of greater amounts of data than traditional observer-based approaches (Arts, van der Wal & Adams, 2015). Objective and standardised automated data collection may allow improved data comparability across protected area network sites. Such devices reduce the human impact of monitoring by minimising the required number of site visits, allowing documentation of timid or elusive wildlife species without the presence of field workers. Knowledge exchange and enforcement activities can be improved through the use of online dashboards powered by Internet of Things technologies. Internet of Things describes a network of sensors that are connected to the internet and can communicate with each other and send the data to a defined location. Digital workflows lead to more cost-effective monitoring programmes in the long term because many technologies allow for a reduction in the number of personnel field days, freeing up resources for other purposes. Large biodiversity monitoring networks may also have the purchasing power to acquire devices at bulk prices, whilst institutions can provide incentives for implementing technologies through research funding, educational programmes and promotional opportunities. Partnering with research programmes may allow protected areas or OECMs to be early adopters of new technologies.

Despite the benefits, many barriers to digitalisation exist. It is challenging to determine the true value of a new technology because its effectiveness is often reported in the best light (Arts, van der Wal & Adams, 2015). Costs of digital technologies remain an obstacle for many management programmes, particularly in the developing world (Stephenson, 2020). High-tech innovations may fail to capture the cultural elements of a site or may exclude untrained groups (Cole & McCallion, 2018). Practitioners may be sceptical or distrustful of new approaches, instead favouring techniques that are more familiar to them. Data analytical infrastructure and reliability of the technology may be poor, particularly in remote areas. The large volumes of collected data introduce potential problems of data management. Continual improvement of technologies is a natural process; however, potential future changes in the workflow may create uncertainty for managers around adopting new tools (Ferrari et al., 2022).

The labour savings and quality improvement of using automated devices may easily make up the cost difference within a few cycles of use. Identifying how a digital workflow has operated in other sites can help managers adapt a tool to their own needs. Yet, high-tech solutions may not be realistic in many areas of the world or may not fully replace long-standing methodologies for certain indicators.

7.2 Toolkit: Overview of the indicators

Biodiversity monitoring has historically relied on trained field personnel to collect data, often in paper formats. Today, the need for monitoring outpaces the availability of trained staff. Restrictions on staff time may limit the scope of data acquisition, and storage of raw data in the form of paper records is difficult to archive. Field work is often implemented in habitats that are occupied by wildlife, thus posing a threat to the safety of observers and animals alike, or may change the very behaviours that are the focus of the monitoring effort (Verma, van der Wal & Fischer, 2016). Combining multiple methods simultaneously using specialised equipment may be an effective solution but is logistically challenging (Prosekov et al., 2020). However, traditional approaches will continue to make important contributions to biodiversity monitoring. This is because conventional data collection methods are often robust and fail-safe, cheap and easily implemented compared to high-tech methods.

Many traditional approaches to biodiversity monitoring are labour-intensive activities that target a specific group of organisms. In this chapter, a brief review is provided of the commonly applied monitoring methods for specific monitoring targets.
- plant communities;
- flying vertebrates;
- ground-dwelling vertebrates;
- arthropods;
- soil fauna;
- freshwater organisms;
- marine organisms.

7.2.1 Plant communities

Vegetation monitoring combines the identification of individual plant species with a measure of abundance or species diversity across a spatial area and over time. Timing of a monitoring cycle is key because surveying at different phenological stages can change the interpretation of findings (Pauli et al., 2015). Plants are mostly immobile; therefore, permanent plots with fixed positions offer the possibility to detect fine-scale vegetation changes over time (de Bello et al., 2020). The selection of an appropriate survey method is dependent on the management questions and the required precision and accuracy (Schulz, Bechtold & Zarnoch, 2009).

Simple presence / absence vegetation surveys can detect trends in a plant community. Abundance measurements may provide more precise estimations of change. Many suitable methods are used to estimate abundance (Braun-Blanquet, 1964), including visual plant cover estimation, point-frequency counts and subplot-frequency counts (Bråkenhielm & Qinghong, 1995). Using abundance classes has the advantage of allowing rapid quantification, especially for larger areas (Ricotta & Feoli, 2013). Detection of change in abundance over time is not very accurate compared to other measurements (Irvine & Rodhouse, 2010).

Selecting the size of sample plots in vegetation monitoring depends on the vegetation type and the target indicator. Knowledge of the indicator and its habitats will help managers determine the minimum mapping unit within the area of interest. Monitoring plots in open areas and low-lying vegetation, such as tundra, use plot sizes of about 1 m^2, whilst dense forest plots usually require larger plot sizes of several hundreds or thousands of square metres, as in the case of tropical forest monitoring (e.g. Picard et al., 2010). The shape of a monitoring plot additionally varies from quadrats (e.g. in grassland vegetation) to circles, which are often used in forest monitoring (Paul, Kimberley & Beets, 2019). Square- or rectangle-shaped plots are preferable when cover of many plant species should be estimated, as the straight boundaries can be easily marked by corner posts or measuring tapes (Elzinga, Salzer & Willoughby, 2019). Circular plots are useful when the number or attributes of large plants such as shrubs and trees should be assessed because only the centre point needs to be marked and the distance to the individual has to be measured. Linear transects are a useful option in areas where there is a sharp gradient of species (Pauli et al., 2015).

7.2.2 Flying vertebrates

Birds and bats can be identified through visual recognition, vocal identification and through indirect evidence. For visual recognition, birds and bats may be captured using mist nets that are placed in flight paths or tree canopies. Captured birds can be fitted with small leg bands that are marked with a unique identifying code. If a banded bird is recaptured, scientists can determine movement based on where or when the animal was previously handled. Harp traps are modified mist nets used to capture bats (Hoffmann et al., 2010). Captured bats can be fitted with semi-permanent light-tags (Buchler, 1976) or small radio transmitters (Timofieieva et al., 2019) to track movement behaviours. Permits are generally required to capture birds and bats, both for the animals' and the handlers' safety.

Less invasive techniques can be used to determine bird and bat activity. These techniques require a basic level of field training to be confident in the findings. Transect walks and visual point counts at roosting or nesting sites are standard approaches (Schieck, 1997; Stahlschmidt & Brühl, 2012). Vocal identification occurs through expert recognition of calls in the field, in combination with territory or spot mapping. Field playback of bird species calls is also used for monitoring because animals often respond to calls (Gregory, Gibbons & Donald, 2004). Modern state-of-the art sound recording devices are now used across the globe. So-called passive acoustic monitoring uses removable memory cards, and devices can also be linked to a cloud-based data repository. Computer algorithms can automatically determine species by their calls. Experts can then verify the species identities in the office. Metadata gathered during recording events provide information on the audio device, time of day and the seasonality of species.

Another form of non-invasive monitoring of birds and bats is the collection of physical samples such as spoor prints, faecal pellets, hair or feathers. The biological samples may allow food web analysis. Genetic techniques are now available to support analysis of physical collections.

7.2.3 Ground-dwelling vertebrates

Medium and large animals can be tracked visually or through telemetric approaches (Fuller & Fuller, 2012). Movement behaviours of large animals can be mapped through the use of small aircraft or drones (Prosekov et al., 2020), through tagging of individual animals (Verma, van der Wal & Fischer, 2016) or through following spoor marks (Pirie, Thomas & Fellowes, 2016). Signs such as dung or fur can provide DNA for indirect evidence of animals, including food web associations (Skrbinšek et al., 2019). One common method for long-term large animal observation is to capture the animals in box traps or pens, fit them with radio collars or GPS tags and then release them for tracking. This approach requires professional expertise to minimise animal stress.

Small animals can be captured through live trapping. Trapping is used for species identification, analysis of diet and to determine the level of parasitism, among other applications. The technique can also be applied for collection of DNA (Hoffmann et al., 2010). This approach is particularly effective when traps are placed on a transect line that is situated along a drift fence. A major drawback of live trapping is the stress that can be placed on the animals. Field technicians must frequently check the traps so that captured animals do not starve or become dehydrated.

The use of camera traps is a passive way to document species (Rovero & Kays, 2021). Visual evidence of the animal is obtained through wildlife cameras. Camera trapping is now a well-established monitoring technique for warm-blooded animals. Time-lapse techniques and innovations in motion detection are poised to allow camera traps to document cold-blooded and small animals (Rovero et al., 2013). Acoustic sensors can also be deployed to survey for the presence of animals in the landscape. Computer algorithms may automatically identify species documented from camera traps and acoustic sensors, but expert verification is still required. Metadata from digital collections are automatically stored, giving information on the phenology and diurnal activity of species.

7.2.4 Arthropods

Field monitoring of insects and other arthropods requires multiple techniques to describe the diversity of even one taxonomic group in the environment (Magurran, 2004). Common approaches include using attractants such as light, colour, plant volatiles or pheromones that lure insects into collection containers. Non-attractant methods include sticky traps, flight interception traps and immunomarking–recapture techniques (Grootaert et al., 2010; Hagler, 2019). Artificial nesting aids can be effective for inventorying species of bees, wasps and spiders. Active collection techniques include using aspirators or vacuums, sweep nets, hand collection or visual observation. Passive techniques include using coloured pan traps, pitfall traps, emergence traps and Malaise traps. An advantage of physically collecting insects is that specimens can be sent to expert taxonomists for identification. Physical samples are also necessary for genetic identification. A main disadvantage is the lethal nature of many collection techniques. In some cases, photographs from the field may aid in the identification of insects. Images must clearly show the distinguishing features of the organism, and therefore a basic level of taxonomic knowledge is required for useful photographs. Many programmes using machine learning for photographic verification of arthropods are now in operation.

7.2.5 Soil fauna

Soil fauna can be collected with Berlese funnels and through direct searches of the environment. The diversity of soil fauna is influenced by environmental factors, for example the amount and age of coarse woody debris on the forest floor (Siitonen, 2001). Pitfall traps are commonly used to collect soil-dwelling arthropods. Baits can be added to pitfall traps to increase attractivity of the trap to a target species, and screens can be added to prevent by-catch of non-target animals. Pitfall traps are also used for collecting arthropods in caves, rock crevices and other hard-to-reach habitats (Nitzu et al., 2010). Taxonomists can identify physical specimens, whilst genetic analysis of soil samples can provide evidence of soil community composition (Oliverio et al., 2018). Genetic analysis can be outsourced to specialised third-party laboratories.

7.2.6 Freshwater organisms

Aquatic species are observed primarily through collection. Netting is the primary technique for sampling standing waters such as lakes, ponds and reservoirs. Different net types target certain types of animals. Deploying the appropriate mesh size will help capture target organisms and decrease by-catch (Stark et al., 2001). After removal from water, invertebrates and microfauna are sorted by sieves and preserved in ethanol. Collected specimens can be sorted morphologically using a hand lens in the field, or with stereomicroscopes in the laboratory. Grab samplers and traps baited with meat or dairy are effective ways to sample fish. Many techniques allow catch-and-release of larger organisms.

In freshwater ecosystems that cannot be fully accessed on foot, collection methods include electrofishing and sink nets. Algae can be sampled by planktonic nets. Biofilms may be sampled directly by skimming objects from the water surface. After collection, species are usually directly identified in the field or in the laboratory based on their morphology. In addition, species may be detected and identified with genetic methods. DNA can be obtained directly from target organisms, from bulk samples of invertebrates, or from DNA in the environment. Techniques for collecting environmental DNA (eDNA) have greatly improved in recent years.

When sampling multiple water bodies for comparison, measurement of water temperature, water current, pH, conductivity and oxygen saturation should ideally accompany the biological collections. These abiotic parameters can be measured using specific devices. In addition, water pollutants can be measured, including nutrient levels, heavy metals, pesticides and pharmaceuticals. Based on the collected organisms, water quality may be correlated with anthropogenic pressures (Dallas, 2021; Poikane et al., 2016).

7.2.7 Marine organisms

Monitoring marine ecosystems is more demanding and expensive in comparison to freshwater methods due to the unique challenges of the marine landscape (Cato et al., 2006). As with terrestrial ecosystems, no single set of monitoring approaches is sufficient to describe the full range of organisms present in a marine ecosystem. To guide data collection on the most important indicators, panels of experts at the Global Ocean Observing System have developed Essential Ocean Variables (EOVs). These EOVs are a set of physical, biochemical and biological measurements that are used as a guide to collect data on the most important indicators of marine ecosystems (Canonico et al., 2019). Methods used for monitoring the biological EOVs include satellite remote sensing, plankton net tows and trawl net surveys, metagenomics, acoustic telemetry, and visual or video underwater surveys (Muller-Karger et al., 2018). The use of passive acoustic monitoring on marine animals is applied to survey abundance and migration of large marine animals (Malinka et al., 2018).

7.3 Technology-based approaches for biodiversity monitoring

In recent years, development of advanced sensor-based devices has dramatically improved capacities for biodiversity monitoring. Examples include acoustic sensors for passive acoustic monitoring; optical and passive infrared sensors for camera trapping; Earth observation sensors for remote sensing; and GPS sensors for wildlife telemetry (Lahoz-Monfort & Magrath, 2021). The following sensor-based technologies are discussed:

- acoustic devices and sensors;
- optical devices;
- remote sensing;
- telemetry and tracking tools;
- olfactory devices;
- genetic techniques.

7.3.1 Acoustic devices and sensors

Recent improvements in passive acoustic monitoring now allow identification of birds, bats, amphibians, insects and even chainsaws or gunshots in the environment (Darras et al., 2019; Sethi et al., 2020; Sugai et al., 2019). Modern acoustic devices are small, portable and are designed to blend into the environment. Acoustic devices do not restrict the activity of the target organism. They can detect sounds within the range of human hearing, as well as sounds that cannot be heard by people (e.g. ultrasonic frequencies for detection of bats, geophones for detection of marine animals). Devices can be programmed to function continuously, can be activated through incoming sound, or can be programmed to be active at specific times (Lahoz-Monfort & Magrath, 2021). In aquatic ecosystems, acoustic telemetry is advancing as a primary technique to track the behaviour of animals. This technique uses small tags that are attached to an animal, and a stationary receiver that collects data on the animal's movement (Matley et al., 2022).

Optimal distribution of audio sensors in terrestrial landscapes depends on the targeted animal community, landscape barriers, weather conditions and the equipment used for detection. The signal-to-noise ratio is the main factor determining the range at which a microphone can detect a sound. High signal-to-noise ratios allow greater detection of the target animal (Darras et al., 2020). In general, traps spaced less than 10 m from one another will effectively capture most sounds in an area-wide arrangement, with louder sounds detectable at greater distances (Hill et al., 2018; Sethi et al., 2020).

Networks of audio devices typically generate several hundred trap-days of data per deployment period. This large volume of data requires sophisticated procedures for data analysis. With improvements in computer technologies, passive acoustic monitoring is now assisted through automated species identification. Many open-source programmes and proprietary software are available for acoustic data analysis (Priyadarshani, Marsland & Castro, 2018). Artificial intelligence algorithms help to identify calls based on characteristics of the sound profile, visualised as a spectrogram. Some programmes can group all readings of a similar pattern together. So-called cluster analysis eliminates non-target sounds, reducing the size of the dataset and helping an expert to verify the findings.

7.3.2 Optical devices

Biodiversity assessment using camera traps has undergone sophisticated changes since the technique's beginnings in the 1890s (Box 18) (Kucera & Barrett, 2011). Modern camera trapping uses passive infrared sensors that are installed onto digital cameras. When an animal passes in front of a sensor, the camera is triggered to take a photograph or a short video. Data files are downloaded from internal memory cards or can be uploaded directly onto a cloud-based network (Wearn & Glover-Kapfer, 2017). Many brands of trail camera are commercially available. Trail cameras may have customisable features allowing users to change settings including the sensitivity of the sensor and image resolution. However, there is a clear trade-off of quality between lower-cost and more expensive devices (Newey et al., 2015).

Camera trap arrays are normally placed in a grid pattern but can be placed opportunistically, depending on the goals of the monitoring programme. If possible, camera stations should be located at least 2,000 m away from one another. Cameras should be placed within 500 m of the predetermined grid coordinate. This spacing ensures independent data collection (Abrams et al., 2018). For mammals, cameras should be installed to have a focal distance between 1.2–4 m. A total of 1,000 or more camera trap-days is sufficient for most studies (Rovero et al., 2013). Therefore, a camera trap array of 50 cameras needs to be in place for only about three weeks to document the biological community. The phenology of the target animal will affect decisions on when to begin the trapping period (Dalton et al., 2022).

There are several limitations to camera trapping. Camera traps detect moving animals. Depending on their route past the sensor, not all animals will be captured in the images. This is called 'imperfect detection' and must be considered during the sampling design stage. An open access journal article by Burton et al. (2015) provides further references on field design, including targeting uniquely patterned animals, unmarked animals, occupancy modelling, multi-species surveys, and incomplete coverage of the area of interest. Additionally, because passive infrared sensors work based on body heat of the target animals, standard camera trapping is not very effective at documenting amphibians, reptiles or invertebrates. Insects can be documented using time-lapse photography (Collett & Fisher, 2017). Other types of motion sensors have been used for remote detection of small or cold-blooded animals (Hobbs & Brehme, 2017). As with acoustic recording devices, monitoring using camera traps generates large volumes of data that require sophisticated computer analysis for interpretation (Norouzzadeh et al., 2018).

In marine systems, camera and video technologies are used for continuous, long-term monitoring of aquatic organisms. Video cameras and drop mount cameras can be mounted on remotely operated vehicles and autonomous underwater vehicles. These vehicles are equipped with additional sensors to gather information about the benthic environment. In shallow waters, divers can also collect photos of species and the aquatic environment (Danovaro et al., 2016).

Box 18

High-tech approaches: Camera trapping for biodiversity monitoring

Camera trapping is the use of motion-sensitive cameras to record images or videos of animals passing in front of them. Today this technology represents the preferred method for several types of wildlife studies (Steenweg et al., 2016), with growing scope and applications in conservation science and practice (Rovero & Kays, 2021). Medium-to-large (i.e. above 500 g), ground-dwelling mammals remain the optimal target.

Camera traps have many advantages, including the ability of trail cameras to work remotely, their cost-efficiency, and ability to collect large amounts of data. The TEAM project illustrates these advantages. TEAM is a network of 17 sites of tropical forest protected areas that have collected standardised camera trapping data using a strict sampling design since the mid-to-late 2000s (Rovero & Ahumada, 2017). The design consists of arrays of 60 sampling sites that are surveyed annually for a minimum of 30 days. Results have provided temporal trends of wildlife populations at an unprecedented resolution (e.g. Beaudrot et al., 2016). TEAM has also been instrumental in developing the Wildlife Picture Index (O'Brien et al., 2010). This index uses data from camera traps to detect changes in the presence of different species and the number of species in a community. This metric is officially recognised as an indicator by the Convention on Biological Diversity for Sustainable Development Goal 15 and other targets along with the Living Planet Index and the Red List Index (https://shorturl.at/cdB35). In the current digital era, the most prominent developments have been in tools and software to store, manage, annotate and analyse the data. Multiple solutions are available to process the images (Young, Rode-Margono & Amin, 2018), including stand-alone desktop tools (CPW Photo Warehouse), cloud-based solutions (eMammal, Wildlife Insights, Conservation AI) and crowdsourcing to identify animals (Zooniverse). Artificial intelligence tools are being developed to automatically identify species in images (He et al., 2016; Norouzzadeh et al., 2018), as well as including dashboards to visualise findings. These approaches are now being integrated into data management platforms such as Wildlife Insights. These advances help improve biodiversity monitoring, as practitioners and protected area managers now have the means to master the entire process from data collection to reporting the findings.

Camera trapping continues to have a bright future in biodiversity monitoring, although some limitations still exist including patchwork regulations by public management agencies or private landowners, and challenges related to providing open access to photographic libraries.

Source: Francesco Rovero, University of Florence, Italy.
Picture: Camera traps allow managers to get up close to wild animals in their natural habitats. © Instituto Chico Mendes de Conservação da Biodiversidade

7.3.3 Remote sensing: Applying geo-information, geo-statistics and geo-modelling tools

Earth observation refers to gathering information about the Earth's surface using remote sensing tools, without being in physical contact with the ground or water. This approach is ideal for habitat mapping of terrestrial and marine areas. Aerial vehicles can be equipped with customised packages of sensors to monitor animals and plants. Drone-based monitoring, coupled with artificial intelligence approaches, represents a new avenue of animal tracking and is particularly promising in terms of geospatial analysis (Prosekov et al., 2020). Satellites, drones and aeroplanes can capture remote sensing data using wavelength sensors or ranging sensors. Wavelength sensors determine reflectivity of the surface and include visual RGB, near infrared, thermal vision, multispectral and hyperspectral sensors. Ranging sensors such as LiDAR or ultrasonic sensors emit pulses of energy that bounce off an object's surface and return to the device. Ranging sensors provide a 3-D digital reconstruction of the object. Low-flying drones or aeroplanes can be equipped with high-resolution onboard sensors. These arrays can provide greater accuracy and detail than satellite imagery (Martínez-López et al., 2021).

Because wavelength sensors can capture spectra that are not visible to the human eye, they offer a different way to visualise the landscape based on canopy patterns. Modern data mining programmes can process spectral information to identify landscape trends (Bailey et al., 2017). This is called geostatistical analysis. Geo-modelling techniques can provide information on abiotic variables, can outline habitat borders and topographic gradients, and can identify plant phenology (Martínez-López et al., 2021).

Earth observation-based approaches may permit using the same dataset to compare habitats in different protected areas and OECMs. They may also help interpret changes in the environment based on changing climates and land use (Carilla et al., 2013). Data going back in time are often useful to gain an understanding of the environment before a major disturbance. Historical series of satellite data may allow a retrospective analysis of landscape changes over time (Szantoi et al., 2016). Pre-satellite aerial photographs can provide similar information and are available for many areas of the world (Seimon et al., 2017). Satellite- and UAV-based sensors are being designed to harmonise data collection allowing comparison of Essential Biodiversity Variables between sites and networks (Skidmore et al., 2021). Earth observation technologies are currently undergoing a rapid evolution. The technologies are well positioned to create new opportunities for biodiversity monitoring.

Remote sensing is often outsourced to professional technicians because of the required expertise, the large range of applications and the high expense. The appropriate sensors for the monitoring programme must be identified in advance of data collection. Ground-truthing of remote sensing data is required for modelling or validating Earth observation data (Danovaro et al., 2016). If validated, use of satellite or laser scanning data provides an efficient alternative to field monitoring, particularly in remote or inaccessible areas (Box 19).

Box 19

High-tech approaches: Airborne laser scanning for forest biodiversity assessment in an Austrian national park

LiDAR is a laser scanning approach that uses pulsed laser light to determine the 3-D structure of a landscape. Forests in steep, mountainous terrain face unique pressures that shape their biodiversity. One pressure is the impact of avalanches on forest structure. In Gesäuse National Park, Austria, a forested area that experienced an extreme avalanche was assessed using LiDAR scanning data from 2010 and 2020 (Berger, Kirchmeir & Hirschmugl, 2021). First, a digital terrain model was generated from the 2010 dataset, allowing a baseline measurement of topography. Next, digital surface models of the vegetation were extracted from both datasets. The difference in vegetation height was used to model forest stand regeneration. Based on this result, different areas were assigned to represent growth, knocked down and destroyed trees. The site was ground-truthed to confirm the apparent cause of vegetation change. Trees that had fallen were facing downhill, following the direction of the avalanche track.

Overall, areas of tree growth were concentrated in pockets that are protected from avalanches by topography. Large stands of trees offer protection against avalanches, limiting the impact on forest structure, whilst small stands of trees are vulnerable to being completely destroyed. Frequently affected areas tend to be grassland habitats with only young trees. The dynamics of the avalanche track create a natural mosaic landscape that increases the diversity of the forest vegetation.

Source: Vanessa Berger, Carinthia University of Applied Sciences, Austria. Picture: Trees knocked down by an avalanche in Gesäuse National Park. © Vanessa Berger

7.3.4 Telemetry and tracking tools

In recent years, miniaturisation of devices has expanded the applications of wildlife tracking using telemetry. Using commercially available microprocessors such as Arduino units, lightweight GPS modules can now be custom-built for small- to medium-sized animals (Cain & Cross, 2018). Experimental transceivers may even effectively track insects of conservation value including beetles, crickets, bees, dragonflies (Kissling, Pattemore & Hagen, 2014) and butterflies (Wang et al., 2015). This is an area where sensor-based technology is poised to improve. Telemetry tools have many benefits for tracking movement of species, particularly in remote areas. Before using telemetry tools in the field, a number of factors must be considered. First, managers should be certain about which type of tracking device is most appropriate for their purposes. Capturing wild animals will cause stress that could change their behaviour. The logistics of pursuing the marked animals should be considered, including recapture for data collection and device retrieval. Further, the range of motion of animals is dependent on the individual. A review of radio telemetric approaches for tracking carnivores is given in Fuller and Fuller (2012).

7.3.5 Olfactory devices

Plants and animals produce unique signatures of volatile organic carbons that differ between healthy or stressed individuals. Volatiles can be determined in the laboratory through a number of traditional techniques. These approaches are impractical for most biodiversity monitoring programmes. State-of-the-art olfactory sensors, or electronic noses, are under development for field use. So-called GC-IMS sensors can collect plant volatiles in the field for up to four hours without external power (Wägele et al., 2022), but are relatively large and therefore limited in where they can be installed. Other hand-held devices are still in an experimental state for conservation but are poised to allow rapid field assessment of plant health without highly technical expertise. One promising device is the C-320 e-nose that is already used for many diverse applications including food quality assessment, agriculture and forestry, and biomedical applications, among others (Karakaya, Ulucan & Turkan, 2020). Machine learning is used to recognise signature patterns of the volatiles. In the coming years, improved pattern recognition, in combination with miniaturisation of the hardware, will support the wider use of e-noses directly in the field (Cui et al., 2018).

7.3.6 Application of genetic methods in biodiversity monitoring

Genetic approaches are promising techniques for biodiversity assessment in protected areas and OECMs (Pascher, Švara & Jungmeier, 2022). These techniques can detect single or multiple species based on the sequences of DNA in a sample. DNA can be obtained directly from individuals, bulk samples containing multiple organisms, or environmental samples including water, soil and air (Carvalho et al., 2019).

Nowadays, several guidelines are available, presenting the best approaches for species detection and identification based on genetic approaches (e.g. Bruce et al., 2021; Minamoto et al., 2021; Pawlowski et al., 2020). Community assessment can be performed using metabarcoding approaches (Lim et al., 2022; Taberlet et al., 2012b). Metabarcoding is extremely fast and applicable to species detection and assessment of environmental quality (Aylagas et al., 2016; Ruppert, Kline & Rahman, 2019). The processing of environmental samples and metabarcoding will usually be outsourced to expert laboratories because the technique requires specialised expertise and equipment (Figure 22).

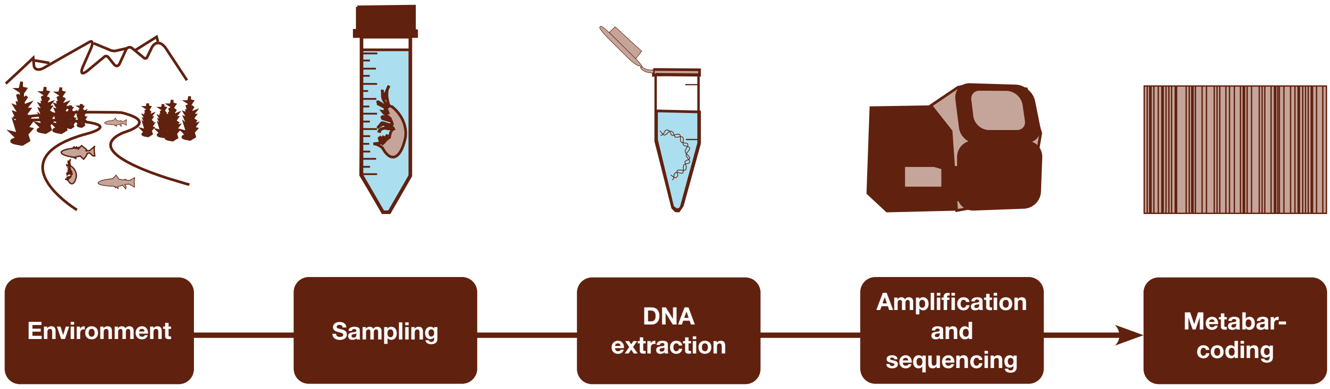


Figure 22 Biodiversity assessment using genetic methods follows a uniform workflow. Samples are collected in the field and returned to the laboratory. Then, DNA is extracted from the samples, amplified and sequenced to detect target organisms. The result is a list of DNA sequences that were present in the samples. Using bioinformatic analysis, species can be determined based on sequence assignment to the reference databases. *Source: Compiled by the report authors*

Collecting DNA directly from the environment can significantly improve monitoring efficiency and success by detecting species that are difficult to detect using traditional approaches (Taberlet et al., 2012a). One major advantage of eDNA collection is that sampling depends relatively little on the developmental stages of the sampled groups (Takeuchi et al., 2019). For reliable determination of species presence, a good temporal and spatial sampling plan needs to be developed (Erickson, Merkes & Mize, 2019) which makes consultation with experts necessary. With appropriate training, sample collection can be performed by non-experts (Biggs et al., 2015). Sampling of eDNA can be standardised, for instance the same volume of the medium can be collected and standardised equipment (e.g. filters) can be used. The exact collection methods will depend on the environment in which sampling will occur, but the analytical steps are largely identical between terrestrial, freshwater and marine ecosystems.

Certain limitations of eDNA sampling need to be considered to avoid incorrect species detection. Assessment of species abundance is still challenging and cannot be directly estimated from sequence number because the amount of DNA from each sample may vary considerably due to sample and analytical biases (Bista et al., 2018). In certain environments, samples of eDNA may be transported over long distances (Deiner & Altermatt, 2014). Windy weather conditions may also transport genetic materials (Lim et al., 2022). DNA may be preserved in soils and sediments for several days to years, potentially adding uncertainty to the findings (Foucher et al., 2020). Due to possible sample contamination and DNA degradation, using sterile DNA-free equipment and correct storage and transportation are essential. Correct sequence detection largely depends on the completeness of barcode reference databases. Well-established databases include Barcode of Life, DNA DataBank of Japan, the European Nucleotide Archive, and NCBI GenBank (Lawniczak et al., 2022). Many additional national databases are coming online, including the Norwegian Barcode of Life, German Barcode of Life and Austrian Barcode of Life (Weigand et al., 2019).

7.4 Analysis: Applying advanced computer technologies for big data

The development of digital technologies in conservation has resulted in a fast-growing volume of data. These data have great potential to revolutionise scientific understanding of the world's biodiversity. In the context of modern computing, data can be used in machine learning approaches, analysed through data mining, shared to generate more knowledge, and safely archived for future use.

7.4.1 Online data platforms, automated recognition and data logging

Online platforms are becoming more important than ever before for the management of big data in conservation. Real-time tracking tools have come into widespread conservation use with the rise of digitalisation. Tools such as Global Forest Watch can help recognise changes in vegetation and landscape structures. In citizen science networks, automated recognition software is now mainstream, enabling apps such as iNaturalist to have the capacity to document species on an enormous scale. Species identification apps are based on a combination of artificial intelligence algorithms and crowdsourced for expert verification (Silvertown et al., 2015). Some examples include Flora Incognita, iNaturalist, iSpot and many more (Table 7). Data entry programmes like QField and CyberTracker are valuable for collecting and organising large-scale monitoring data in the field. The number of available apps will continue to expand in the future, and the value of high-tech conservation solutions will increasingly depend on capacities to handle the large volumes of data (Lahoz-Monfort & Magrath, 2021).

Table 7 A selection of apps and data logging tools for modern biodiversity assessment

Topic	Name	Website
Biodiversity image archiving	eMammal	https://emammal.si.edu/
	Wildlife Insights	https://www.wildlifeinsights.org/
Citizen Science platform	BirdTrack	https://shorturl.at/bctz6
	eBird	https://ebird.org/home
	iNaturalist	https://www.inaturalist.org/
	Merlin	https://merlin.allaboutbirds.org/
	Zooniverse	https://www.zooniverse.org/
Genetic sequence repository	Barcode of Life	https://www.boldsystems.org/
	Basic Local Alignment Search Tool	https://blast.ncbi.nlm.nih.gov/Blast.cgi
	European Nucleotide Archive	https://www.ebi.ac.uk/ena/
	DNA DataBank of Japan	https://www.ddbj.nig.ac.jp/index-e.html
	NCBI GenBank	https://www.ncbi.nlm.nih.gov/genbank/
Mobile data collection	CyberTracker	https://cybertracker.org/
	Open Data Kit	https://getodk.org/
	QField	https://qfield.org/
Satellite imagery	Copernicus Sentinel (ESA)	https://shorturl.at/hltEQ
	Global Forest Watch	https://www.globalforestwatch.org/
	Landsat (NASA)	https://landsat.gsfc.nasa.gov/
	MODIS (NASA)	https://modis.gsfc.nasa.gov/
Species identification	Flora Incognita	https://floraincognita.com/
	iNaturalist	https://www.inaturalist.org/
	iSpot	https://www.ispotnature.org/
	Pl@ntNet	https://identify.plantnet.org/
	Plant.id	https://plant.id/
	PlantSnap	https://www.plantsnap.com/

Source: Compiled by the report authors

7.4.2 Machine learning

A decades-old branch of computer science, machine learning can be applied to many data science problems. Many different types of learning can occur, with separate algorithms behind each type (Christin, Hervet & Lecomte, 2019). A task is assigned to the computer, for example recognising an animal in a photograph. The algorithm learns through 'supervised learning'. In all cases, large datasets produce better algorithms because more experience is gained (Alzubi, Nayyar & Kumar, 2018). In practice, machine learning uses part of a dataset as training data, and the remainder of the dataset for model testing. The performance of the algorithm is evaluated by an expert, and the computer algorithm uses the feedback to later help complete a similar task.

Deep learning is a particular type of machine learning that uses either 'supervised learning' or 'unsupervised learning'. Currently, most algorithms use one of many types of supervised learning. Unsupervised learning does not require training data and can function even if data points are missing (Christin, Hervet & Lecomte, 2019), eliminating the requirement for labelled data. Unsupervised learning is therefore used to find underlying patterns or groupings in a dataset without explicit guidance. Deep learning can be used for identification and classification of digital signals, behavioural studies, population monitoring, ecological modelling and conservation management. Whilst the setup of a deep learning framework is complex, its ability to analyse very large datasets is unmatched. Partnering with computer scientists will allow application of machine learning and will also establish synergies benefiting protected areas, OECMs and collaborating institutions alike (Carey et al., 2019).

7.4.3 Data mining

Whilst machine learning is 'learning-driven', data mining is 'discovery-driven' (Tuysuzoglu, Birant & Pala, 2018). Data mining is an approach for biodiversity assessment that brings together information on species or habitats from multiple sources. Data mining has strong application when the knowledge of a system is low but large volumes of data exist. It is therefore exploratory in its application. The main use for most data mining methods is to discover patterns within a dataset, even when the parameters are unknown (Box 20). Methods are suitable for analysis of large datasets, or for datasets with many predictor variables. Discovered correlations should be confirmed through advanced statistics (Hochachka et al., 2007). For biodiversity monitoring, historical data can be combined with more recent information to help determine how species diversity has changed over time and space. Cause-and-effect relationships do not have to be known in advance for data mining to identify interactions. Differences in spatial resolution of different programmes usually make data mining appropriate for large-scale comparisons rather than for local features.

Managing and interpreting large sets of data are significant challenges. A drawback of data mining is that managers cannot be assured of equal data quality between studies because of methodological differences. Another challenge is the development of good algorithms to describe the feature being assessed (O'Sullivan et al., 2010). Because data mining is driven by algorithms, no two programmes will produce identical results (Hochachka et al., 2007). Therefore, a combination of independent classifiers, each detecting different patterns in the data, may indicate the best way to predict the next results (Tuysuzoglu, Birant & Pala, 2018).

Box 20

High-tech approaches: Terrestrial laser scanning for forest biodiversity assessment

Terrestrial laser scanning is a fully automated technique that can generate point clouds of more than 1 million data points in 3-D space, capturing the physical structure of a forest. In Ireland, afforestation of the landscape is occurring due to increased cultivation of plantation forests. Plantation forests constitute a potentially significant change in the biological community of Irish forests, but the exact effects are unknown. A data mining system was applied to terrestrial laser scanning point cloud data to address whether biodiversity measurements could be predicted based on forest structure. Findings would help the country comply with international regulations for biodiversity.

First, arthropod and bird species diversity counts were conducted in plantations and native forests. Terrestrial laser scanning point clouds were then generated at all sites. Point clouds identified the number and position of trees, their height and stem diameter at 10 cm height intervals. To determine relationships between species richness and the woodland parameters, five statistical procedures were applied using the open-source data mining system Weka.

Through data mining, it was found that the number of beetle species could be accurately predicted across 37 forest locations based on forest stand age and the average tree stem diameter. Using this approach, future forest inventories may be conducted using only terrestrial laser scanning, an automated procedure that will require less expertise to conduct the field work (O'Sullivan et al., 2010).

Source: Compiled by the report authors. Picture: Rendition of a forest after terrestrial laser scanning. © Vanessa Berger

Laser scanning in Rohrach Nature Reserve, Vorarlberg, Austria. © *Vanessa Berger*

CHAPTER 8.

Synthesis: A new age of biodiversity monitoring

8 Synthesis: A new age of biodiversity monitoring

As national and international biodiversity reporting requirements become more rigorous, managers of protected areas and OECMs are becoming increasingly accountable for outcome-based management activities. This publication proposes a comprehensive framework and workflow for developing biodiversity monitoring programmes in protected areas and OECMs. The framework promotes robust investigation of the state of relevant indicators, supporting effective biodiversity monitoring systems and adaptive management. It is written for managers of marine, coastal, terrestrial and freshwater protected areas and OECMs.

The ambitious call to action of the Kunming-Montreal Global Biodiversity Framework and other international agreements highlights the importance of an internationally recognised biodiversity monitoring framework that can be applied in protected areas, OECMs, and national or international monitoring networks. The monitoring framework supports consistency in the decision-making processes for which good methodological and technical preparation is mandatory. Long-term and well-structured monitoring programmes should be considered the 'gold standard' because they become more valuable with every additional dataset. Long-term monitoring provides greater understanding of the natural world with each passing monitoring cycle. Many monitoring cycles are required before the benefits of the programme become apparent. It is therefore important to invest enough resources at the beginning of a programme for the purpose of gaining knowledge in later cycles. Effective and continued communication between managers, decision-makers and local stakeholders is required to sustain a monitoring programme in the long term.

A unified approach to biodiversity monitoring should be applied to ensure valid and comparable datasets. New programmes must be reliable and standardised, modular and applicable to different situations, and should adequately reflect the current state of biodiversity at the site. Monitoring should focus on the minimum number of indicators to provide reliable data, or else the programme will risk becoming overwhelmed with too many features and too few resources to monitor them. Today, these efforts may be supported by the implementation of novel technologies and approaches that provide significant transformational impact on how biodiversity monitoring can be achieved. Managers must evaluate the ever-growing list of tools that are now available, find ways to incorporate historical data with current and future data, and implement realistic procedures to document the state of biodiversity at their sites.

This publication introduces managers to this new paradigm of monitoring, providing guidance on how to most effectively utilise the available resources. A four-phase process is advised, including the preparatory phase, the conceptual phase, the implementation phase and finally the re-evaluation phase. Whilst the guideline focuses primarily on the six main questions of the conceptual phase and a seventh question about implementation, all four phases are equally relevant for managers. These phases operate as a cycle, where re-evaluation provides the basis for renewal of the framework.

The output of the first phase – where site characteristics, monitoring requirements and information gaps are identified – is to develop a statement of purpose including a priority list of monitoring targets. Next, a realistic scope for a biodiversity monitoring programme is determined through a series of six questions. Then, the actual monitoring processes are performed, first through a series of test runs and pre-runs, and then in the field. Finally, potential outcomes of the re-evaluation phase are to maintain the programme as originally described, to improve the programme through modernising the techniques or other modifications, or to dissolve the programme.

This publication further provides a review of traditional approaches compared to state-of-the-art technologies that may contribute to collection and management of biodiversity data. Requirements for biodiversity monitoring in protected areas and OECMs have undergone significant changes in recent years. Current innovations make it possible for managers to keep up with these requirements. To carry out monitoring on the scale required today and into the future, a combination of high-tech solutions and traditional techniques needs to be put into practice. Integration of suitable methods and technologies will support improved management effectiveness.

Global biodiversity is facing enormous pressure, but there is good reason for optimism. Networks of protected areas and OECMs are being supported by cohesive national and international policy decisions including the current Kunming-Montreal Global Biodiversity Framework. The biodiversity monitoring framework presented in this publication puts managers in a strong position to face today's challenges of conserving biodiversity in a standardised way. Successful implementation of the framework will make resource use more efficient, prevent data loss and lead to enhanced protected area management effectiveness.

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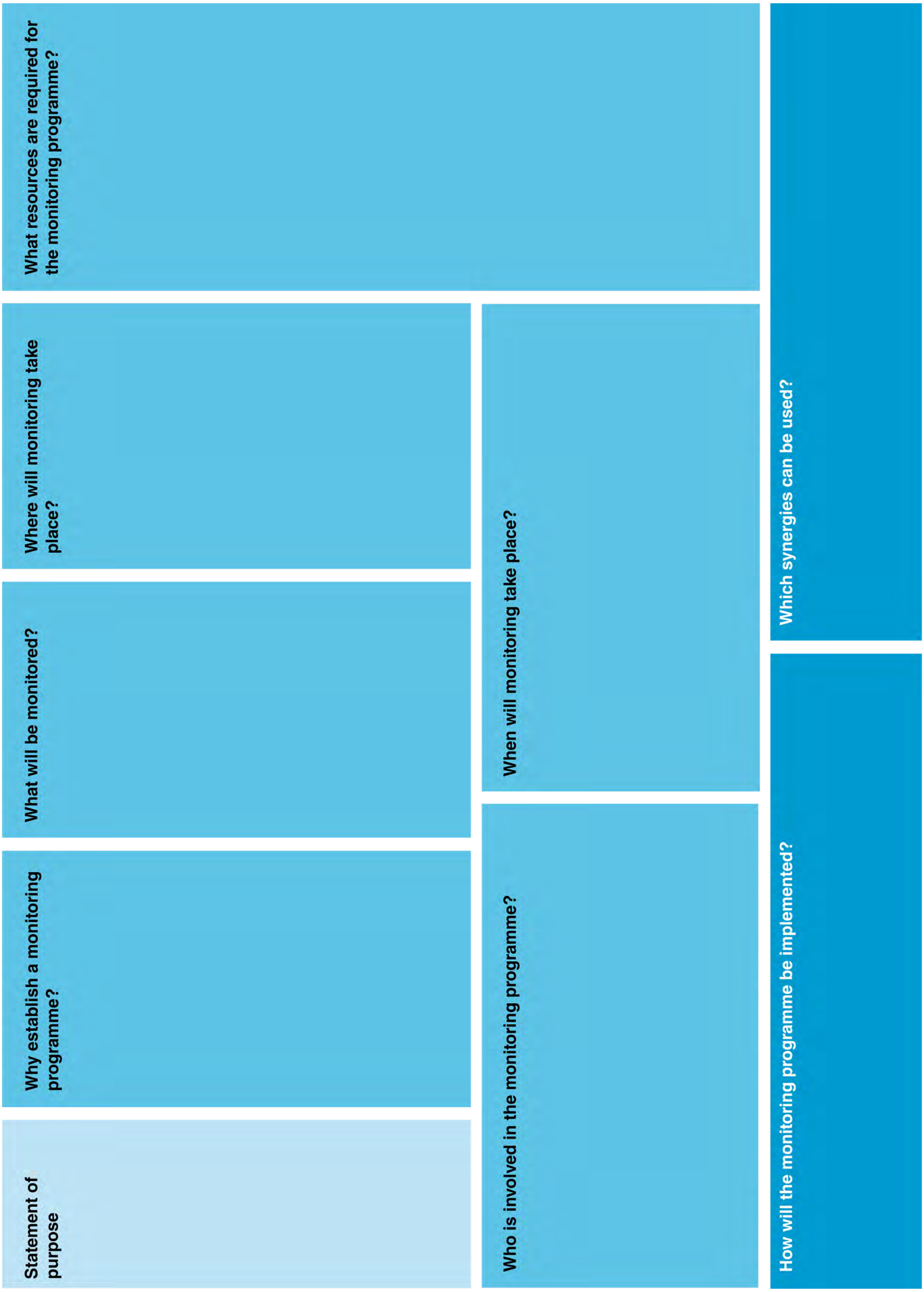
Annexes



Annex Figure 1 Blank monitoring concept worksheet
The monitoring concept worksheet should be filled out during development of a biodiversity monitoring programme to identify how it will be conducted. *Source: Compiled by the report authors*

Statement of purpose

A monitoring programme is developed to fulfil stakeholder requirements through examination of the state of key populations or habitats. Effective biodiversity monitoring will be accomplished only through sound systems knowledge, adequate and systematic planning of resources, and clear conservation goals.

Why establish a monitoring programme?

A likely answer will be to comply with national or international conventions such as meeting biodiversity targets. Monitoring can identify achievements or successes in species recovery. On the other hand, it can show where conservation efforts are lagging, thereby directing future management plans. In these ways, monitoring can support developed frameworks and allow successful elements to be used in similar sites.

- What is the study focus (e.g. population size, biodiversity assessment, species distribution)?
- What should be the outcome of monitoring (e.g. efficiency reviews of measures, reporting of conservation status)?
- What will the results be used for (e.g. documentation of species, educational purposes, scientific communication)?

What will be monitored?

A wide variety of indicators may be the focus of a monitoring programme. The state of targeted habitats or ecosystems can be monitored. Species biodiversity or species abundance can also be monitored. Depending on the goals of the programme, species genetic diversity can be estimated using appropriate tools. Protected area obligations may require reporting on a high number of indicator species or habitats, which may be unrealistic based on the allocated budget. In this case, a manager may be able to select suitable proxies representing a group of species or ecological interactions. Finally, nature-based solutions or ecosystem services may be monitored as a measure of ecosystem health.

- What is the study object (e.g. habitat type, species, biodiversity, ecosystem service)?
- Is it possible to monitor species or is it better to assess the habitat suitability?
- Are there any other proxies that could be monitored instead?

Where will monitoring take place?

This question can be answered through detailed assessment of the site. Monitoring of entire habitats will require a different approach than monitoring of single species. Highly mobile species will require a different approach than sedentary species. Through identification of the spatial resolution of the target of observation, a catalogue of suitable options will become apparent.

- What is the spatial scale of the monitoring technique?
- How is the area of interest defined (e.g. habitat type, location)?
- Does the monitoring programme use an area- or plot-based design?
- How are the plots distributed, e.g. transect line, randomly, grid, stratified sample?
- What is the minimum mapping unit or the resolution of the spatial data?

What resources are required for the monitoring programme?

There are two main components to answer the question. A realistic estimate of financial costs should be made, considering the difference of costs between the establishment phase of the programme and continuation in subsequent monitoring cycles. Generally, the establishment phase will demand the greatest financial resources. The second component is the demand for human resources.

- What is the estimated budget to set up a monitoring programme (plot establishment, monitoring devices, IT infrastructure, data, software)?
- How many teams and human resources are needed?
- Does the organisation have administrative staff, permanent field workers, or seasonal technicians available for the programme?
- Will the available funding and human resources be sufficient to effectively complete the monitoring process, and will availability in subsequent monitoring cycles be guaranteed?
- Are there human resources for analysis and reporting of long-term monitoring results or must this be outsourced?
- Can supplemental resources be mobilised if needed?

Who is involved in the monitoring programme?

Monitoring can be accomplished by a variety of stakeholders, ranging from highly trained specialists to untrained nature enthusiasts. To meet official obligations that are determined by conventions, professional staff or scientists will usually be the most suitable contributors to the monitoring programme. For continuity and training purposes, it is generally recommended to use staff that will be available for more than one monitoring cycle.

- Which stakeholder(s) (e.g. NGO, hunters, farmers) have the rights to use the findings?
- Which partners and stakeholders are involved, and what are their expected contributions?
- How many teams or people are needed?
- What level of expertise is needed from the staff (e.g. intern, ranger, field staff, junior / senior expert)?
- Should monitoring be carried out by external partners?

When will monitoring take place?

The temporal resolution of a monitoring scheme will depend on the phenological activity of the target species or habitat to best observe the selected indicators. Design in time should be determined by the available methodology and will be guided by expert consultation.

- What is the best time of year to carry out the monitoring?
- At what intervals should the process be repeated: weekly, monthly, annually, every five years?
- What is the temporal scale of the monitoring technique?
- Do the intervals of monitoring change as the programme moves on?
- Are there external circumstances that may justify additional monitoring efforts (e.g. fire or flooding)?

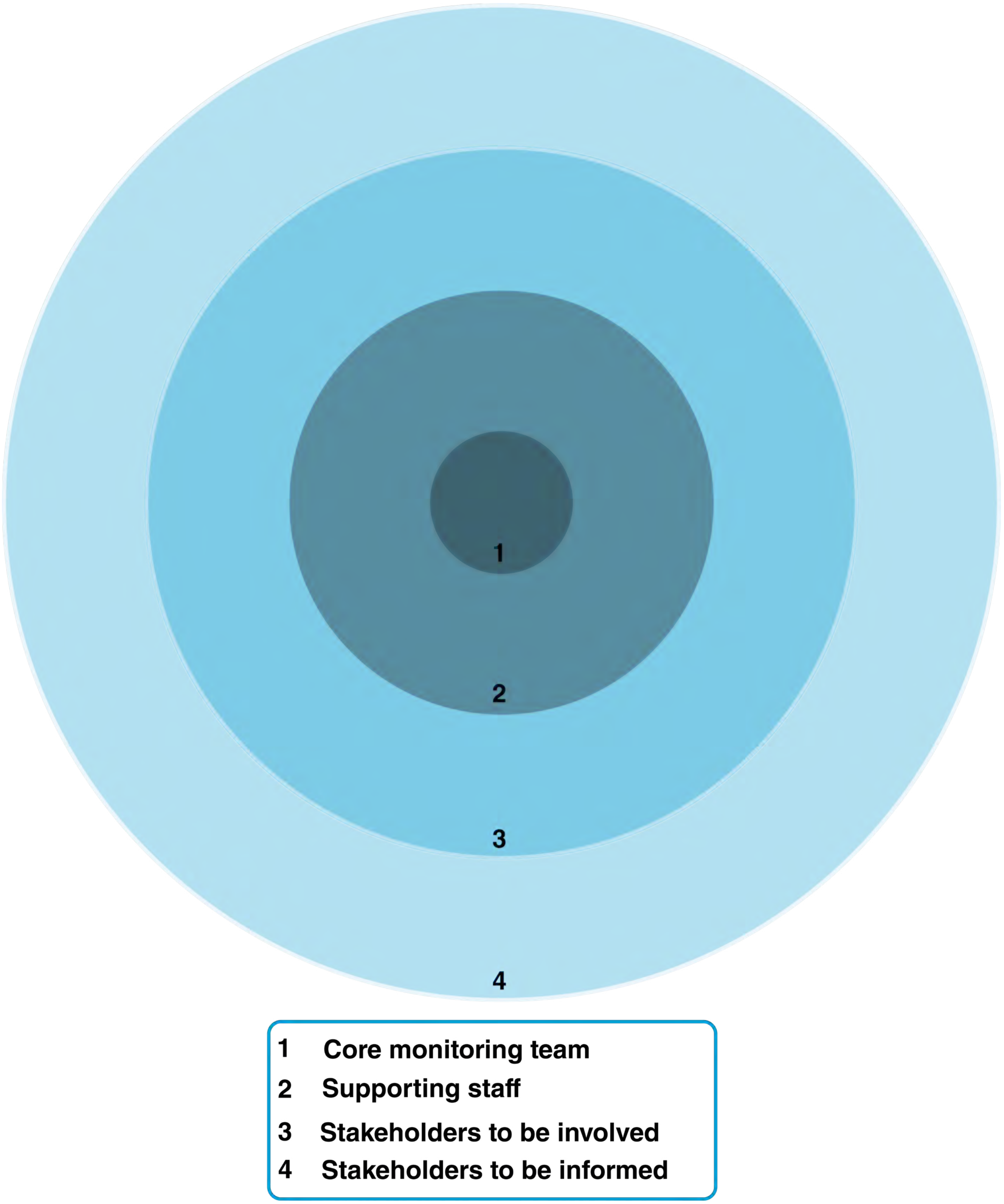
How will the monitoring programme be implemented?

- Which technologies and methodologies should be used for the monitoring programme?
- Are there social, cultural, or ethical concerns about the biodiversity monitoring system?
- Are legal constraints expected?
- Is a timetable already in place?
- At what point should the manual be finalised?

Which synergies can be used?

- Are existing baseline datasets available?
- Are there existing projects (internal / external) that may be beneficial to the planned monitoring (e.g. methodology, resources, data processing)?

Annex Figure 2 Cheat sheet for monitoring concept worksheet
Source: Compiled by the report authors



Annex Figure 3 Blank stakeholder worksheet
The stakeholder worksheet should be filled out during the conceptual phase to identify potential stakeholders. *Source: Compiled by the report authors*

Annex Table 1 Point system to rate biodiversity monitoring programme priorities
The management team of the protected area or OECM distributes a fixed number of points amongst the categories. For the best evaluation, all points must be distributed. The sum of points across rows indicates the relative purpose of the monitoring programme by different stakeholders. The sum of points across columns indicates the relative scale on which the programme is operational.

Category	Use of results	Local	Regional	National	International	Total
Purpose of monitoring programme	Planning (management)	0-5	0-5	0-5	0-5	
	Evaluation (management)	0-5	0-5	0-5	0-5	
	Governance (reporting)	0-5	0-5	0-5	0-5	
Knowledge transfer	Activation (stakeholder contribution)	0-5	0-5	0-5	0-5	
	Public relations (stakeholder outreach of information)	0-5	0-5	0-5	0-5	
	Science (research)	0-5	0-5	0-5	0-5	
	Education (awareness)	0-5	0-5	0-5	0-5	
	Total					

Source: Compiled by the report authors

Annex Table 2 Cost worksheet describing the human resources, travel and material expenses for data collection

Category	Cost category	Required resources	Sum available resources	Gaps / Comments
Human resources	staff	working days x per diem		
	volunteer	working days x per diem + incentives		
	external experts	working days x daily rate		
Travel costs	allowance	days x allowance (travel)		
	accommodation	days x accommodation cost		
	travel costs	public transportation + car rental + distance allowance		
Material costs	investment	estimate		
	consumables	estimate		
	data, purchasing, licenses	estimate		
	communication	estimate		

Source: Compiled by the report authors

Checklist 1 Ethical and cultural considerations of the implementation phase

√ **Legal requirements**
- ☐ Obtain appropriate permits from authorities and landowners
- ☐ Follow regulations when working with genetic materials (Kyoto Protocol)

√ **Behaviour**
- ☐ Respectfully acknowledge and include stakeholders
- ☐ Keep noise to a minimum
- ☐ Do not litter

√ **Data management**
- ☐ Follow FAIR data sharing principles
- ☐ Adhere to privacy rules and regulations
- ☐ Mask sensitive data whilst providing as much transparency as possible

√ **Transparency**
- ☐ Clearly mark monitoring plots with signage
- ☐ Provide sufficient information and a way to contact responsible authorities
- ☐ Make results available as soon as reasonably possible

√ **Risk mitigation**
- ☐ Generate management programme acceptance by the local population
- ☐ Follow nature conservation regulations
- ☐ Avoid unintended effects of monitoring or management

√ **Minimise your impact on nature**
- ☐ Do not extract resources from the site
- ☐ Use the least invasive techniques
- ☐ Do not harm animals or habitats
- ☐ Avoid trampling vegetation or creating new paths
- ☐ Drive or park only in designated areas

Checklist 2 Field logistics

√ **Identify field team**
- ☐ Calculate number of technicians
- ☐ Assign field crew leader
- ☐ Assign field data collection manager
- ☐ Obtain permissions and guides
- ☐ Check proper accommodation and transportation
- ☐ Schedule site visits

√ **Define methods of sample collection**
- ☐ Plot establishment
- ☐ Tool configuration
- ☐ Acquire appropriate equipment
- ☐ Data management
- ☐ Define backup system

✓ **Post-evaluation**

- ☐ Conduct training and pre-runs
- ☐ Assign specialised tasks
- ☐ Solicit feedback from field team
- ☐ Provide feedback to field team

Checklist 3 Safety and field training

✓ **Training exercises**

- ☐ Worker safety
- ☐ First aid training
- ☐ How to implement the protocols

✓ **Conduct the test run**

- ☐ Set up tools
- ☐ Collect data
- ☐ Analyse and compare data from different teams from the same plot
- ☐ Present results

Checklist 4 Safe field work and data acquisition

✓ **Logistics / equipment list**

- ☐ Check weather forecast
- ☐ Book accommodations
- ☐ Means of transport
- ☐ Food supply
- ☐ Energy supply
- ☐ First aid kit and sun cream
- ☐ Good shoes and outdoor clothing including rain protection
- ☐ Sample storage options determined
- ☐ Labelling systems / stickers prepared

✓ **Technical preparation**

- ☐ All devices are charged
- ☐ Cooling devices are ready
- ☐ Cross-check the completeness of tools including user manual
- ☐ Spare batteries / rechargeable battery pack
- ☐ Spare pens and notebooks
- ☐ Archive the data in the simplest structure
- ☐ Rainproof protection for electronic devices and paper

√ **Preparation for field work**

☐ Daily backup for electronic devices
☐ Plot visitation plan
☐ Map or GPS device to find plots
☐ Check that all equipment is ready for transport
☐ Fully loaded devices and rechargeable battery pack

√ **Data collection**

☐ Track your way
☐ Overview pictures
☐ Use optimal workflow
☐ Use systematic, uniform workflow
☐ Check data completeness before leaving the site
☐ Report issues to manager
☐ Track any changes to protocol

Checklist 5 Data management

√ **Collection of data and metadata**

☐ Unique plot identifier for all types of data in every monitoring cycle, i.e. images, GIS, spreadsheets
☐ Define metadata
☐ Use simple, standardised data sheet structure
☐ Use standardised formats – drop-down lists
☐ Determine quantitative vs. qualitative variables
☐ Label data / samples with date, time, name of collector and location of collection
☐ Note which method was used, which preserving agent was used (e.g. EtOH 96 per cent)
☐ Record site factors, i.e. habitat, weather, etc.
☐ Note special observations

√ **Data storage**

☐ Data directory and naming based on institutional standard
☐ Enter data as soon as possible
☐ Archive the data in the simplest structure
☐ Data integration into existing structures and products
☐ Metadata protocol is fulfilled
☐ Mark the most recent version of data
☐ IT security standard implemented

√ **Data backup**

☐ Daily data backup during processing period
☐ Scanning of survey data sheets
☐ Spatially separated data backup for long-term storage

✓ **Data analysis**

- ☐ Decide on which statistical approaches will be used
- ☐ Decide on who will analyse the data
- ☐ Store all interim results during analysis
- ☐ Document all steps of analysis

✓ **Communication: Reporting the data**

- ☐ Consider the format of reporting to different groups
- ☐ Keep in mind the frequency of reporting requirements
- ☐ Interpret the results to explain to stakeholders

✓ **Archiving**

- ☐ Delete sensitive data according to legal requirements
- ☐ Delete working documents at the end of project
- ☐ Check for duplicate files

Checklist 6 Communication

✓ **Reporting to decision-makers**

- ☐ Stakeholder reporting
- ☐ Scientific output
- ☐ Public outreach

✓ **Transparency**

- ☐ Open data access
- ☐ Dashboard for a good overview
- ☐ Report findings regardless of the monitoring outcome
- ☐ Share the results with all parties

Author profiles

Dr **Vanessa Adams** is an Associate Professor in Conservation and Planning in the School of Geography, Planning, and Spatial Sciences at the University of Tasmania. Her research focuses on modelling dynamic social-ecological systems to inform conservation decisions that improve ecosystems and the communities they support. This means her research is broadly aligned with three themes: ecological modelling (to understand dynamic ecosystems), socio-economic aspects of conservation (to understand the human dimensions of social-ecological systems), and conservation decision theory (to inform decision-making). She has worked in a variety of roles ranging from actuarial analyst for global consulting firm Mercer HR to research scientist at universities. She spent a year as a Fulbright scholar conducting research at University of Queensland in 2004 and completed her PhD at James Cook University in 2011.

Vanessa Berger, MSc, is a lecturer and senior researcher at Carinthia University of Applied Sciences (CUAS), Austria. Having worked in several protected areas as an ecological consultant, she is an experienced field ecologist. In addition to being a certified UAV pilot, she is a specialist in all phases of holistic data acquisition from preparation of data bases, collection of field data, post-processing of orthophotos, statistical and geospatial analysis, ecological modelling and report writing. At CUAS, she tests state-of-the-art monitoring technologies, comparing them with traditional methods and tools. She is involved in development of standardised monitoring tool platforms, training materials and video tutorials for diverse stakeholders.

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PROTECTED AREA AND OECM DEFINITIONS, MANAGEMENT CATEGORIES AND GOVERNANCE TYPES

IUCN defines a protected area as:
A clearly defined geographical space, recognised, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values.

The definition is expanded by six management categories (one with a sub-division), summarized below.

Ia Strict nature reserve: Strictly protected for biodiversity and also possibly geological / geomorphological features, where human visitation, use and impacts are controlled and limited to ensure protection of the conservation values.

Ib Wilderness area: Usually large unmodified or slightly modified areas, retaining their natural character and influence, without permanent or significant human habitation, protected and managed to preserve their natural condition.

II National park: Large natural or near-natural areas protecting large-scale ecological processes with characteristic species and ecosystems, which also have environmentally and culturally compatible spiritual, scientific, educational, recreational and visitor opportunities.

III Natural monument or feature: Areas set aside to protect a specific natural monument, which can be a landform, sea mount, marine cavern, geological feature such as a cave, or a living feature such as an ancient grove.

IV Habitat/species management area: Areas to protect particular species or habitats, where management reflects this priority. Many will need regular, active interventions to meet the needs of particular species or habitats, but this is not a requirement of the category.

V Protected landscape or seascape: Where the interaction of people and nature over time has produced a distinct character with significant ecological, biological, cultural and scenic value: and where safeguarding the integrity of this interaction is vital to protecting and sustaining the area and its associated nature conservation and other values.

VI Protected areas with sustainable use of natural resources: Areas which conserve ecosystems, together with associated cultural values and traditional natural resource management systems. Generally large, mainly in a natural condition, with a proportion under sustainable natural resource management and where low-level non-industrial natural resource use compatible with nature conservation is seen as one of the main aims.

The category should be based around the primary management objective(s), which should apply to at least three-quarters of the protected area – the 75 per cent rule.

The management categories are applied with a typology of governance types – a description of who holds authority and responsibility for the protected area. IUCN defines four governance types:

Type A. Governance by government: Federal or national ministry/agency in charge; sub-national ministry or agency in charge (e.g. at regional, provincial, municipal level); government-delegated management (e.g. to NGO).

Type B. Shared governance: Transboundary governance (formal and informal arrangements between two or more countries); collaborative governance (through various ways in which diverse actors and institutions work together); joint governance (pluralist board or other multi-party governing body).

Type C. Private governance: Conserved areas established and run by individual landowners; non-profit organizations (e.g. NGOs, universities) and for-profit organizations (e.g. corporate landowners).

Type D. Governance by Indigenous peoples and local communities: Indigenous peoples' conserved areas and territories – established and run by Indigenous peoples; community conserved areas – established and run by local communities.

The Convention on Biological Diversity defines an "other effective area-based conservation measures" (OECM) as:
A geographically defined area other than a Protected Area, which is governed and managed in ways that achieve positive and sustained long term outcomes for the in situ conservation of biodiversity, with associated ecosystem functions and services and, where applicable, cultural, spiritual, socioeconomic, and other locally relevant values.

This covers three main cases:

1. **Ancillary conservation** – areas delivering in-situ conservation as a by-product of management, even though biodiversity conservation is not an objective (e.g. some war grave sites).
2. **Secondary conservation** – active conservation of an area where biodiversity outcomes are only a secondary management objective (e.g. some conservation corridors).
3. **Primary conservation** – areas meeting the IUCN definition of a protected area, but where the governance authority (i.e. community, Indigenous peoples' group, religious group, private landowner or company) does not wish the area to be reported as a protected area.

For more information on the IUCN definition, categories and governance types, see Dudley (2008). *Guidelines for applying protected area management categories*, which can be downloaded at: https://doi.org/10.2305/IUCN.CH.2008.PAPS.2.en

For more on governance types, see Borrini-Feyerabend et al. (2013). *Governance of Protected Areas: From understanding to action*, which can be downloaded at https://portals.iucn.org/library/node/29138.

For more information on OECMs, see Jonas et al. (2023) *Site-level tool for identifying other effective area-based conservation measures (OECMs): first edition*, which can be downloaded at: https://portals.iucn.org/library/node/51296

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