From Data to Decisions: Towards a Biodiversity Monitoring Standards Framework

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Abstract

Achieving the goals of the Kunming-Montreal Global Biodiversity Framework (GBF), requires robust monitoring and reporting to track progress and guide action. However, our ability to understand trends is challenged because biodiversity data are fragmented and biased. This stems from the many different approaches used to record data, aggregate records, and analyze them to detect trends and attribute causes. While this fragmentation reflects a past lack of a unifying mandate and technological capacity, the urgency of the GBF and new capabilities in data science now make a harmonized approach both necessary and feasible. We propose the Biodiversity Monitoring Standards Framework (BMSF) as the how: a comprehensive, modular, and tiered system designed to guide the standardization of the entire monitoring workflow—from planning and ethical data collection to model-based analysis and reporting. The BMSF integrates Essential Variables, standardized protocols, and the Findable, Accessible, Interoperable, and Reusable (FAIR) and Collective Benefit, Authority to Control, Responsibility, and Ethics (CARE) data-management principles. It promotes accredited analytical workflows, operationalized through open-source tools and platforms that have standardized data protocols. This framework enables comparison and aggregation of findings across scales by ensuring consistent data capture, quality assurance, and validated analytical pathways with uncertainty reporting. It is designed to support critical decisions, such as prioritizing areas for restoration and conservation, and verifying corporate nature-related disclosures. The implementation of the BMSF is envisioned through a federated model, building on the strengths of existing organizations and observatories. If supported, the BMSF offers a pathway to actionable, globally comparable knowledge.

1. Introduction

Addressing the global biodiversity crisis requires a coordinated response underpinned by robust and comparable information to monitor change and direct targeted action (1–6). While societies have long-monitored nature, a renewed commitment is needed to provide the evidence required to meet the goals of the Kunming-Montreal Global Biodiversity Framework (GBF). Historically, monitoring has been fragmented, split among academic hypothesis testing, distinct national priorities, conservation science focused on local management objectives. Neither approach was designed to create the consistent workflows required by a single global knowledge framework. Consequently, initiatives like the GBF create an urgent need for standardization to meet the demands of robust, cross-national trend analysis (7, 8). Standardized workflows can deliver the consistent evidence needed to identify threats and attribute the causes of change, providing a reliable foundation for policy much like standards have for climate and weather monitoring.

Although the collection of biodiversity data has grown exponentially, its use is hampered by heterogeneous coverage and a lack of strategic prioritization (9–12). While foundational standards like Darwin Core (13) and information systems like GBIF and OBIS have improved data access, they only address parts of the chain required to link observations to GBF indicators. The current landscape of monitoring workflows is itself fragmented, with multiple analytical approaches for variable estimation and trend detection (14-17). This lack of end-to-end standardization severely limits the ability to synthesize findings and confidently assess progress towards international targets (8, 17).

The lack of such an integrated framework is not primarily a result of a single technological gap, but rather a reflection of historical political and institutional fragmentation. Unlike climate science, which has long been galvanized by a unified political mandate under the UNFCCC, biodiversity monitoring has been split among disparate national priorities, academic pursuits, and conservation projects, without a compelling, overarching driver for harmonization. Furthermore, until recently, the technological capacity for large-scale data integration, cloud computing, and AI-driven analytics was not mature or accessible enough to make a global framework operationally feasible. Today, these historical barriers are falling.

We argue that the entire monitoring pipeline—from survey design to reporting—needs a framework to support evolving, interoperable standards. These standards must incorporate Indigenous and local knowledge systems, ethics, and end-user needs, while also supporting adaptive improvement. Crucially, this is a call for interoperability and reliability, not homogeneity, which will be beneficial in all contexts where monitoring is used to support investment and conservation action (18). The World

Meteorological Organization (WMO) provides a successful model for this end-to-end approach. Its rigorous standards produce policy-relevant Essential Climate Variables (ECVs) that underpin global assessments like those from the IPCC. This structured approach is a strong precedent and is mirrored in how climate data informs corporate, business, and governmental emissions accounting.

We present a general Biodiversity Monitoring Standards Framework (BMSF; see Table S4 for acronyms used in this article). The BMSF recognizes the reality of a fragmented landscape of methods and standards but rather than advancing a single, rigid protocol, we propose a flexible structure that can harmonize these diverse existing efforts. The BMSF is modular, linking steps that integrate ethical principles like FAIR (19) and CARE (20), promote the use of Essential Variables (21–24) and other suitable data, and endorse standardized protocols. It also promotes accredited analytical workflows that produce reliable indicators with quantified uncertainty, ensuring data can be processed into comparable, high-confidence insights. The framework is designed to be global, inclusive, and adaptable for diverse users—including national governments, business and financial institutions, NGOs, and Indigenous-led initiatives (25–27)—implementing actions under the GBF. It suggests a tiered structure, a community-driven accreditation process, and is envisioned for operationalization through open tools and technology platforms that make sophisticated, standardized analyses accessible worldwide. The implementation of the BMSF is envisioned through a federated model, building on the strengths of existing organizations and observatories.

This article is composed of four parts. First, we define the core components of monitoring workflows. Second, we describe the BMSF and its modules. Third, we provide an example of how the framework applies to a connectivity indicator under GBF Target 3. Fourth, we discuss implementation challenges, the need for a federated standard body, and next steps.

[Box 1 HERE]

2. The core components of generalized monitoring workflows

A generalized monitoring workflow combines two systematic cyclical processes linking the planning and design of monitoring to its implementation. Monitoring begins with defining clear monitoring objectives and then moves to the planning, design, and resource allocation cycle. This “planning” cycle informs the “do” cycle of collection and quality-assured processing of observational data and analyses, translating this information into predefined and selected biodiversity indicators and other communication tools for reporting. This culminates in an assessment of progress towards the initial objectives to inform adaptive management and decision-making (28).

When viewed at the highest level we see seven interacting steps that are common to all biodiversity monitoring cycles where standards are necessary (**Figure 1**). The cycle starts (step 0) with Foundational Principles & Ethics that identify needs and guiding values, which leads into the cycle in which standards are sets for: 1) data collection (the "Sensing and Knowing" step); step 2) data processing and management (the "Curation" step), step 3) provenance and licensing (the "Trust" step); step 4) analytical methods and interpretation (The "Analysis" step); step 5) indicator calculation and interpretation (the "Insight" step); and finally 6) reporting and disclosure (the "Reporting" step). Below we discuss each of these steps in turn and then interlink them in a cycle that comprises the BMSF (see Table S2 for a typology of the terms used below).

2.1 Step 0: The "ethics" step: Foundational Principles & Ethics

This critical initial step (Step 0, Figure 1) establishes the overarching needs, values and guiding principles for all subsequent biodiversity monitoring activities. It defines the "why" and "how" monitoring should be conducted in an ethical, equitable, and just manner. Crucial here is the articulation of how the data will be used and by whom. In the context of the GBF, a foundational principle is national ownership, which recognizes that monitoring systems and data for reporting against international agreements and treaties are nationally owned and driven, reflecting national priorities and knowledge needs. Multiple principles come together in this step.

[FIGURE 1 HERE]

Adoption of Core Principles: There is a need for the formal adoption of principles analogous to IPCC's TACCC (Transparency, Accuracy, Completeness, Comparability, Consistency), adapted for the complexities of biodiversity monitoring (e.g., accuracy may refer to correct species identification, precise and unbiased population trend estimates, or reliable habitat mapping).

Ethical Guidelines: Develop and adopt ethical guidelines covering eight topics inherent to all monitoring activities:

1. Respect for Life & Ecosystems: Minimizing disturbance during data collection and non-destructive sampling wherever possible.

2. Indigenous Peoples and Local Communities (IPLCs): Ensuring Free, Prior, and Informed Consent (FPIC), full and effective participation, inclusion of traditional knowledge and rights (including data ownership) and go beyond FAIR to fully embrace CARE principles for Indigenous Data Governance, and equitable benefit-sharing from data and its use (aligned with Target 21 & 22 of KM GBF). The BMSF should explicitly state that the purpose of monitoring may be defined by non-Western objectives, such as holding the dignity of nature.

3. Data Sovereignty & Security: Especially important for sensitive data (e.g., locations of endangered species or sacred natural sites), where some countries, rightsholders and other organizations may not wish to share data publicly. Federated learning protocols have the potential to help actors participate in monitoring while maintaining privacy (29, 30).

4. Transparency of Data Use & Specification of Purpose: Clearly declare, prior to data collection, the intended primary uses of the monitoring data, how it will be shared to contribute to stated monitoring objectives, and any anticipated secondary uses or sharing. Establish mechanisms for reviewing and agreeing upon new uses not initially specified, particularly when involving data from Indigenous Peoples and Local Communities or sensitive information (e.g., location of species at risk).

5. Gender Responsiveness: Ensuring monitoring design and implementation consider gender roles and knowledge (Target 23).

6. Precautionary Principle: Guiding monitoring design and interpretation where scientific uncertainty exists about threats or effectiveness of interventions.

7. Sustainability: Designing monitoring programs that are financially and technically sustainable in the long term by being resilient to policy shocks and funding breaks.

Once the ethical framework for the monitoring program or network has been established, these standards are applied at each step along the monitoring workflow we described below. We describe these modules in turn and suggest what each module requires for implementation.

2.2 Step 1: "Sensing and Knowing" Step: Observations and data collection

Description: This module focuses on the systematic and ethical collection of primary data from multiple evidence streams—including scientific methods and Indigenous Knowledge systems—to assess biodiversity status, trends, and the causes of change.

Activities & Standards:

Development with Indigenous Knowledge Systems:

Actively create ethical space and culturally appropriate pathways for the respectful inclusion of Indigenous Knowledge (IK), innovations, and practices related to biodiversity monitoring and assessment (e.g. the principle of "Two-Eyed Seeing" (Mi'kmaq: Etuaptmumk, (25)), or the place-based *mātauranga* (the Māori knowledge system), which includes historical knowledge, culturally recognized indicator species, and intuitive, holistic assessments of environmental health. Māori communities recognize different indicators and monitoring approaches, and these differ to scientific monitoring systems (26, 27, 31). Within these worldviews the environment is a web of relationships to be nurtured.

This includes recognizing that the *purpose* of monitoring can be defined by non-Western objectives, such as upholding the dignity of nature as a relative, not just tracking resources for human use. Indigenous Peoples are knowledge and rights holders so participation must recognize their FPIC for any engagement and process. Protocols should be developed collaboratively (with CARE principles) that weave together IK biodiversity concepts with non-indigenous approaches.

Support Indigenous-led monitoring initiatives and ensure equitable benefit-sharing from any co-produced knowledge. The standards in Step 1 must be explicitly designed to accommodate and legitimize multiple evidence streams. The typology of data cannot be limited to quantitative metrics. It must include pathways for respectfully incorporating qualitative, narrative, and place-based knowledge. Standards should include qualitative and narrative data forms inherent in many IK systems (e.g. Indigenous-relevant biodiversity indicators) alongside quantitative scientific data.

Indicator-Driven Design: Monitoring protocols should be designed to directly inform specific KM GBF headline, component, complementary or national indicators (e.g., habitat extent for Target 1, species population trends and genetic diversity for Target 4, protected area coverage and effectiveness for Target 3). This is needed for existing indicators and those under development to be included in the future. At this time 12% of the elements of the GBF lack an indicator (8). As gaps in indicators are addressed, there's a need to ensure that they are responsive to actions taken to mitigate biodiversity loss. They may also, in some cases need to be modified to address the needs of other subnational actors (Indigenous Peoples, local communities, regional governments, and businesses).

Standardized Protocols (Tiered Approach):

A tiered approach (like IPCC Tiers for greenhouse gas inventories) allows countries to start with simpler methods and progressively adopt more sophisticated ones as capacity grows. A similar approach primarily but not only directed to businesses is adopted by the Nature Positive Initiative with its associated nature metrics.

Development of internationally recognized, yet nationally adaptable, field protocols for “basic” observations used to estimate Essential Biodiversity Variables (EBVs; (21) and Essential Ecosystem Service Variables (EESV; (22, 23)) that are required by indicators used to track progress to some of the Targets of Goal A and Goal B of the KM GBF. Essential Ocean and Essential Climate Variables provide critical complementary information about the system and recognized drivers. Other protocols are required for assessing drivers and impact variables (e.g., socio-economic data on pressures and benefits: EEIV, Essential Environmental Impact Variables; (24).

Technology Integration:

Sampling Strategy: Guidance on statistically robust sampling designs (e.g., balanced, stratified random, systematic) appropriate for particular EBV classes (e.g., occurrences, genetic samples, etc.).

Remote Sensing: Standardized methods for using satellite and drone imagery to estimate habitat and ecosystem extent, condition, connectivity, and land-use change.

In-situ Technologies: Guidance on using camera traps, acoustic sensors, GPS tracking, etc., with standardized calibration and validation, deployment and data extraction from sensors.

IPLC Monitoring and Citizen Science: Protocols for integrating data from validated citizen science programs and weaving community-based observations (two-eyed seeing), ensuring FPIC, and ethical engagement.

2.3 Step 2: "Processing and Curation" Step: Data Processing and Management

Description: This step builds a module that deals with the transformation of raw acquired data into validated, organized, and accessible datasets ready for analysis, ensuring data quality and longevity.

Activities & Standards:

Data Validation & Quality Assurance/Quality Control: Standardized procedures for data cleaning, error checking, de-duplication, outlier identification, and quality assurance/quality control for different data types.

Data Formatting & Interoperability: Adoption of common data standards and formats (e.g., Darwin Core for species occurrences, standardized metadata schemas like ISO 19115 for geographic information) to ensure interoperability between national systems and global repositories (e.g., GBIF) for particular needs (e.g ., Environmental Impact Assessments, (32)). This interoperability should be operationalized through well-documented, public APIs that allow both humans and machines to submit, query, and retrieve data in a standardized manner, facilitating automated data flows from collection devices and platforms into curation workflows.

Multimodal Integration: Combination of diverse sources (species observations, movements, environmental DNA, habitat maps, bioclimatic variables) into calibrated spatial and temporal datasets of varying granularity (e.g. BioCube, (33)).

Database Management: Guidance on establishing and maintaining biodiversity databases (potentially using open-source platforms) capable of storing diverse data types (spatial, tabular, genetic, media).

This activity applies whether the focus is national datasets or more local community-based monitoring and information systems.

FAIR Data Principles: Commitment to making data Findable, Accessible, Interoperable, and Reusable, within the bounds of ethical, commercial, and security considerations (19).

Indigenous Knowledge: The standards for data models and ontologies must be flexible. While technical interoperability (e.g., Darwin Core) is important, the framework must also allow for data to be structured and aggregated according to culturally defined relational frameworks, not just Western scientific taxonomies. The data storage must be designed to capture both automated sensor data and insights directly provided by Indigenous communities.

Versioning & Archiving: Protocols for data version control and long-term secure archiving.

2.4 Step 3: The "Trust" Step: Provenance and Licensing

Description: This module ensures transparency and credibility by meticulously tracking the origin and processing history of data and clearly defining rights and permissions for its use.

Activities & Standards:

Metadata Standards: Comprehensive metadata capture for all datasets, detailing data collection methods, processing steps, quality assurance and quality control, personnel involved, temporal and spatial coverage, and any constraints to access.

Data Lineage Tracking: Systems to track the "chain of safekeeping" for data from collection to final product, allowing for reproducibility and auditability.

Clear Licensing: Adoption of clear data licensing frameworks (e.g., Creative Commons licenses) that balance open access with the need to protect sensitive information or respect IPLC data sovereignty.

Attribution: Standards for proper attribution of data sources when data are reused or integrated.

Security Protocols: Measures to protect sensitive data from unauthorized access or misuse.

Indigenous data Sovereignty: Standards must provide explicit guidance on co-designing data access and governance protocols with IPLC partners. It must support tiered access levels and recognize that not all data in a monitoring system will be "open". The principle of guardianship should be a core concept within this "Trust" step.

2.5 Step 4: The "Analysis" Step: Analytical Methods

Description: This step involves the application of open, discoverable, and reusable scientific and statistical methods to process data to derive meaningful information about biodiversity patterns, trends, and the effectiveness of interventions.

Activities & Standards:

Standardized Analytical Approaches (where appropriate): For common analyses like population trend estimation, species distribution modeling, habitat change analysis, connectivity analysis, ecosystem condition assessment. Standardization does not require use of a single analysis or method but rather agreed-upon – and regularly peer reviewed – workflows reflecting best practices.

Uncertainty Quantification: Mandatory assessment and reporting of uncertainties associated with estimates and trends, drawing from IPCC and IPBES standards (34).

Model Validation & Calibration: Protocols for validating and calibrating models used for extrapolation or prediction (e.g., creating spatial/temporal training, validation, sensitivity analysis, and training-test data splits for robust model evaluation)

Models & software: Standardized and reproducible approaches for modeling and artificial intelligence, including the documentation of algorithms, and assumptions used (e.g., ODMAP and ROBBIT (35, 36)), and the provenance of artificial intelligence (AI) algorithms (e.g. training set used, training recipe, architecture, DOI for the evaluation of the algorithm). Promotion of free and open-source analytical software (Open Source Initiative (2007); e.g., software libraries, QGIS, platform for biodiversity analytics such as BON in a Box) and provision of training, although methods should be documented such that they can be implemented independently of specific software choices.

Indigenous Knowledge: standards for "accredited analytical workflows" should be expanded to include methodologies for IK-informed and trained AI algorithms and machine learning models (37). This implementation of "Two-eyed Seeing" (25) means that AI models see the world through both scientific and Indigenous lenses, potentially revealing insights neither could find alone. The framework must also address the ethical need for AI interpretability and explainability, avoiding "black box" models that are not transparent to the communities using them.

Integration of Diverse Data: Methods for integrating ecological data with socio-economic data, pressures, and response data to understand drivers and impacts.

Gap Analysis: Methods for synthesizing uncertainty, validation and calibration data to identify priorities for collecting more or different data to improve performance.

2.5 Step 5: The "Insight" Step: Indicator Calculation and Interpretation

Description: This module focuses on translating analytical outputs into indicators (including those required by the KM GBF), interpreting their meaning in the context of targets, baselines, and ecological understanding.

Activities & Standards:

Indicator Calculation & Protocols: Open, documented, and repeatable methods for calculating indicators from the analyzed data. These methods should guide aggregation protocols to facilitate assessments and regional and global levels. Crucially, these protocols must be updated to reflect changes to methods and input data, but this review is conducted in Steps 2 - 4.

This step must support the development and use of holistic, composite indicators that can integrate both quantitative and qualitative data. The BMSF should promote Indigenous indicator frameworks which provide a culturally-grounded way to interpret the overall "picture" of ecosystem health (37). This moves beyond single-variable trend lines to holistic assessments of well-being.

Baseline Establishment: Expert guidance on establishing robust baselines and reference conditions against which progress can be measured.

Trend Interpretation: Frameworks for interpreting observed trends (e.g., stable, declining, improving) in the context of uncertainty (e.g. due to short, noisy, time series) relative to targets and ecological thresholds (38, 39).

Attribution Analysis (where feasible): Methods to assess the extent to which observed changes can be attributed to particular direct and indirect drivers, including conservation actions or policies (17, 40, 41). Here, clearly-defined counterfactuals are needed for robust attribution (42).

Synthesis & Narrative Development: Guidance on synthesizing multiple indicators to provide a holistic picture of progress, such as towards the KM GBF Goals and Targets.

2.7 Step 6: The “Reporting” Step: Reporting and Disclosure

Description: This module covers the communication of monitoring results at subnational (i.e., by companies reporting under the CSRD) and national levels. At the national level, a reporting authority submits findings to the CBD Secretariat (as per Article 26), in a consistent, and timely manner. This communication is framed against the ambition set out in National Biodiversity Strategy and Action Plans (NBSAPs).

Activities & Standards:

Standardized Reporting Formats: Development of common reporting formats and templates, for example for National Reports to the CBD, aligned with the KM GBF monitoring framework, or for companies towards the TNFD or similar (in line with Target 15).

Regular Reporting Cycles: Adherence to agreed reporting timelines.

Public Accessibility: Making reports and (non-sensitive) supporting data publicly accessible through national clearing house mechanisms (maintained by UN CBD) and potentially a global biodiversity monitoring portal and dashboard followed dashboard design standards (43).

Verification/Review Mechanism: Establishment of a supportive ongoing technical review process (analogous to UNFCCC's international consultation and analysis) to enhance transparency, credibility, share lessons learned, and identify capacity-building needs.

Communication Products: Guidance on developing diverse communication products to reach different audiences. The standard in this step must provide guidance on developing a wide range of communication products (dashboards, policy briefs, summaries for policymakers, public-friendly reports), including visual, narrative, and interactive platforms that can communicate a relational worldview. Instead of just showing charts, the User Interface should embed stories, audio clips, and images from the Indigenous Knowledge Workspace directly alongside the scientific data, providing a richer, more contextual understanding of what the numbers mean. The goal of reporting is not just to inform, but to connect and reflect the values established Step 0.

2.8 A specific instance of the general workflow

These general steps are the framework for guiding the assembly of specific monitoring workflows (as per Figure 1) can be articulated as follows:

Step 1 *Sensing & Knowing*: Field Measurement (Raw Observation Record) of "N individuals of species X sighted at GPS_Coord_XYZ on Date_ABC by Observer_A using TransectMethod_X." This RawObservationRecord has_value_for the BiodiversityVariable "Species Occurrence" and "Count" (which are inputs to EBV_Species Populations). Stored in a RawDataset.

Step 2 *Curation*: RawDataset is processed. The observation is validated, species ID confirmed. It becomes part of a Curated Dataset (e.g., Species Occurrence Dataset_Verified).

Step 3 *Trust*: Metadata Record created for Species Occurrence Dataset_Verified, detailing who, what, when, where, how, and the data use license. A digital Data Lineage Record traces it back to original field notes kept in digital or physical form.

Step 4 *Analysis*: Species Occurrence: Dataset_Verified (along with other relevant driver datasets) is used as Model Input Data for a Model (e.g., a Species Distribution Model) used to estimate an EBV using best practice methods and reporting protocols. This produces a DerivedDataset (e.g., EBV_Dataset_SpeciesDistribution - a habitat suitability map for Species X). An Uncertainty Estimate (e.g., confidence map) is also produced.

Step 5 *Insight*: The EBV_Dataset_SpeciesDistribution is used as Indicator Input Data. An IndicatorCalculationProtocol calculates the BiodiversityIndicator "*Area of Suitable Habitat for Species X*." This is compared to a Baseline Value and Target Value. A Trend Assessment is made.

Step 6 *Reporting*: The Biodiversity Indicator value and Trend Assessment are included in a Monitoring Report following reporting guidelines provided by a national authority following the guidelines of the requesting organizations (e.g. CBD secretariat).

The assembled workflows can be shared and updated and thus represent a resource for other monitoring efforts by (a network) of participants in the same area or elsewhere in the monitoring network (**see Table S1** presenting this among network benefit). The automation of these workflows can produce a pipeline used by monitoring analysis platforms, thereby serving the broader community contributing to the implementation of monitoring standards.

3. An example

To illustrate how these steps create an auditable "chain of evidence," we provide a detailed example of a workflow for an indicator assessing the *Area and connectivity of natural forest ecosystems* (relevant to GBF Target 3). This indicator involves diverse methodologies and data streams—from remote sensing to ground-truthing and connectivity modeling—that benefit greatly from the standardization the BMSF provides. The complete, step-by-step application of BMSF standards, including objectives, necessary steps, and evidence for certification at each stage, is detailed in **Table S1**. This example demonstrates how overarching certification ensures that decisions informed by the indicator are based on high-quality, comparable, and scientifically credible information.

4. Towards implementation:

We now outline the approach required to implement the BMSF, including key elements and the need for an implementing organization. We draw parallels with the process adopted by the IPCC, WMO, and FAO and other organizations for the development and implementation of international monitoring standards in other domains (Box 1).

Operationalizing the BMSF Across a Monitoring Network: collaboration across diverse monitoring networks can be envisioned through a federated, network model (a Biodiversity Observation Network (6, 44)), fostering both local site engagement and national (or global) synthesis (**Table S1**). In this model, the network is comprised of numerous site-level participants (actors)—such as field teams (e.g. academia, consulting companies, government agencies), community monitors, and Indigenous Knowledge holders—responsible for data acquisition and initial curation at their respective locations, guided by BMSF-standardized protocols (Step 1, Step 2) disseminated by a coordinating group following FAIR, CARE and FPIC principles. These locally generated, standardized datasets and knowledge records then flow into a national or regional hub (e.g., a National Biodiversity Monitoring Agency, a national GBIF node). This national hub undertakes data integration, applies standardized analytical workflows for essential variable derivation (EBV, EESV, EEIV) and indicator calculation (Step 4, Step 5), ensures comprehensive provenance and trust (Step 3), and ultimately produces aggregated assessments and reports for national commitments (Step 6). Crucially, this structure allows for a form of "federated learning": insights derived from the synthesized national picture can be fed back to refine methods and guide local actions, enhancing the entire network's effectiveness over time (29). This model does not require all raw local data to be shared. This federated approach underpinned by the BMSF ensures scalability, comparability, and local trust and relevance while building a robust, evolving understanding of biodiversity status and trends.

A Phased and Tiered Approach to Adoption: An implementation should start with a needs assessment, followed by capacity building focused on foundational modules (e.g., Principles, basic Data Acquisition protocols, Curation standards) and key, easily measurable indicators. Subsequent phases would progressively introduce more complex monitoring techniques and indicators under a tiered approach. The first tier would recognize the value of standards not requiring sophisticated and costly technical and technological capacity. Support to phase in subsequent tiers would focus on building and maintaining human capacity and the adoption of methods and technologies that allow scaling of monitoring effort across a broad set of sectors responding to targets under subnational and national biodiversity strategies and actions plans.

Capacity Building: This is the cornerstone for supporting adoption. The subregional Technical and Scientific Cooperation Support Centres recently selected by the UN CBD could provide training, technical backstopping, and facilitate South-South cooperation. This will involve training on remote sensing, field survey design, data management tools, analytical software, and reporting as per the cycle (Figure 1).

Governance: For monitoring frameworks like REDD+ MRV, a centralized, top-down body like FAO makes sense given the direct link to the UNFCCC and IPCC and the coupling of climate observing systems to carbon stock and emissions models and assessments. However, the multifaceted nature of biodiversity and the existing landscape of key organizations, makes a federated governance model, with national ownership at its heart, more appropriate and likely to succeed for the BMSF. This model is similar to structures (e.g. the Inter-agency and Expert Group on SDG Indicators) developed by the UN Statistics Commission for monitoring progress to the SDGs (45). The intent is to build on the progress made to date, which is being achieved via distributed networks and bottom-up modes of governance.

This federated organization (e.g., a Global Biodiversity Monitoring Partnership (GBMP)) would have a mission to collaboratively and inclusively develop, maintain, and promote the global adoption and implementation of the Biodiversity Monitoring Standard Framework (BMSF) to enable effective tracking of progress towards the KM GBF via its monitoring framework, as well as towards biodiversity goals encoded in other Multilateral Environmental Agreements. It would also provide the foundation for other users and stakeholders to engage, e.g., businesses, IPLCs and civil society.

Functions and Responsibilities of a Global Biodiversity Monitoring Partnership:

This standards body should oversee six core functions:

1 Standard Development & Maintenance: This would involve the development, review, and periodic updating of the BMSF steps and associated technical guidance through technical working groups. Ensure standards are scientifically robust, practically implementable, and adaptable to national contexts, and promote harmonization and interoperability of methods and data.

2 Capacity Building & Technical Support: Here the objective is to catalyze and coordinate capacity-building initiatives (training workshops, webinars, e-learning, technical assistance missions) in collaboration with implementing partners. Develop and disseminate training materials and best practice guides and support the development and dissemination of open-source tools and platforms for biodiversity monitoring (e.g., expanding existing tools or fostering new ones). Additional guidelines will be needed to evaluate capacity to deliver training.

3 Knowledge Sharing & Community of Practice: The key role of this function is to work with organizations that facilitate a global community of practice for biodiversity monitoring, organize international conferences, workshops, and webinars. A central knowledge portal would ensure open access to documents, tools, case studies, and contact points for using the standards.

4 Resource Mobilization & Coordination: Advocate for increased investment in national biodiversity observation and monitoring networks based on a needs assessment given the monitoring objectives. Help coordinate funding efforts to support BMSF implementation, avoiding duplication and maximizing impact. Provide guidance to funding agencies, investment banks and other financial investors, and philanthropy on priority areas for investment.

5 Alignment & Harmonization: Work to ensure alignment between the BMSF and other relevant global and regional initiatives (e.g., Sustainable Development Goals monitoring, other MEAs, industry initiatives). Promote harmonization with existing data standards (e.g. an ISO for biodiversity data) and infrastructures.

6 Review & Quality Assurance Support: Develop guidelines and potentially a roster of experts for a voluntary technical review process for national biodiversity monitoring reports, designed to improve quality and sharing lessons (akin to UNFCCC's International Consultation Analysis or technical assessments).

A federated model offers numerous advantages. It would leverage existing expertise and infrastructure from organizations like GEO BON, GBIF, and IUCN, increasing legitimacy and buy-in by involving a diverse range of rightsholders and stakeholders from the outset. This decentralized structure fosters flexibility, responsiveness, and innovation within a common global framework, allowing the GBMP to act as a crucial orchestrator providing the common language and tools to strengthen global assessments of progress.

5. Discussion

The pressing need to halt and reverse biodiversity loss, as articulated by the Kunming-Montreal Global Biodiversity Framework, demands a commensurate revolution in how we monitor, report, and act upon changes in the state of nature (8, 46, 47). We proposed a Biodiversity Monitoring Standards Framework as a comprehensive, multi-step system to guide the standardization of the entire monitoring workflow. The realization of high-quality monitoring workflows under a BMSF would transform disparate data into actionable, globally comparable knowledge, thereby enabling aggregation of evidence and more effective tracking of progress towards conservation targets set at organizational, national, and global levels.

5.1 Strengths and Potential Impacts of the BMSF

The adoption of the BMSF promises several transformative impacts by directly addressing longstanding gaps that prevent disparate monitoring data from becoming actionable knowledge. Its strength lies in creating a standardized and auditable "chain of evidence" that links field observations to high-level decisions.

First, the BMSF fills the methodological gap between data collection and data aggregation. Currently, data from different projects are often incompatible due to varying field protocols, data formats, and analytical choices. By promoting standardized protocols for data acquisition (Step 1), curation (Step 2), and provenance (Step 3), the BMSF creates interoperable datasets. This enhancement is crucial for national reporting, allowing for the robust aggregation of data from diverse actors—including subnational governments, businesses, and local communities—to generate a credible national picture of biodiversity trends. This is also crucial for understanding broad-scale trends, identifying priority areas for action, and evaluating the collective progress towards the GBF targets. It is vital that Parties have the means to consistently and robustly monitor, report, and verify progress while fostering national ownership, capacity, and global comparability.

Second, the BMSF addresses the analytical gap between observing a trend and attributing its causes (17). Understanding *why* biodiversity is changing is essential for effective management. By promoting accredited analytical workflows (Step 4) and guidance on attribution analysis (Step 5), the framework supports more rigorous assessments of the drivers of change. This directly informs critical conservation decisions, such as prioritizing investments in policies that mitigate key threats or assessing the effectiveness of specific restoration actions against a clear counterfactual.

Third, the framework's emphasis on transparency, standardized and traceable protocols, provenance tracking, and uncertainty quantification will build greater trust and confidence in biodiversity assessments by businesses (e.g., via TNFD alignment), investors and the public. Subnational governments and communities (e.g., municipalities) also require credible monitoring workflows to mobilize funding directed toward protection and restoration of nature and the climate risk mitigation and ecosystem service benefits they receive from (i.e., nature-based solutions).

Fourth, the proposed tiered structure, coupled with the promotion of open-source tools and capacity-building initiatives, aims to empower a wider range of actors, including those in resource-limited settings, to participate in and benefit from robust monitoring. This inclusivity is vital for ensuring national ownership and for integrating diverse knowledge systems, including those of Indigenous Peoples and Local Communities, as emphasized by the CARE principles and specific ethical guidelines within the BMSF. Furthermore, by streamlining reporting processes and clarifying methodological expectations, the BMSF can lead to greater efficiency and reduce duplication of effort, allowing resources to be focused more effectively. Ultimately, the high-confidence biodiversity insights generated through the BMSF will be critical for supporting adaptive management strategies and achieving tangible global conservation goals.

The BMSF is designed to complement and integrate with other key global initiatives, including the UN's System of Environmental-Economic Accounting (SEEA), the Natural Capital Protocol, and serves as a robust basis for disclosures under the Taskforce on Nature-related Financial Disclosures (TNFD) and Science Based Targets for Nature (SBTN). For example, the BMSF aligns well with the Accounting for Nature framework, conceptualized by the Wentworth Group of Concerned Scientists (2016), which offers a rigorous, transparent, and verifiable approach to environmental accounting. Grounded in reference ecosystem condition benchmarking, it enables the standardized measurement of biophysical asset condition across various scales. The BMSF, therefore, does not compete with frameworks like CSRD, CSDDD, or TNFD; it underpins and enables them (Table S3).

Generally, the BMSF’s flexibility and grounded approach would enable it to support monitoring to meet the needs of a range of different end-user groups: citizen networks and the significant data they are gathering and contributing (48), governments for their NBSAPs, Indigenous groups to enable them to integrate their data and knowledge systems into national and global structures on their own terms, and businesses, which are both data providers (e.g. the datasets they generate to fulfil regulatory requirements such as Environmental Impact Assessments, as well as those generated to understand their biodiversity impacts), and users - for example in understanding how their contributions support national and international priorities, and in generating reports for shareholders, investors and bodies such as TNFD.

5.2. Navigating the Path to Implementation: Challenges to Consider

The BMSF is made tractable through the phased and modular implementation model. A country or organization need not adopt the entire framework at once. It can begin with Tier 1 standards focused on foundational principles and easily measurable indicators. As capacity and resources grow, it can progressively adopt more sophisticated Tier 2 and 3 methods for more complex analyses and EBVs, ensuring the framework is both accessible and aspirational. Crucially, adoption will be facilitated by a commitment to open-source principles for all core components, including analytical workflows and technology platforms (e.g., BON in a Box, UNBL). This approach lowers financial barriers, fosters a global community of developers and users, and ensures the tools can be transparently validated and adapted for diverse needs.

There are compelling reasons to be confident that historical hurdles can now be overcome. The political and technological landscape has fundamentally shifted, creating a powerful window of opportunity. First, the GBF provides the clear, high-level international mandate for standardized monitoring that was previously lacking. Second, the private sector is now a major driver of action, with frameworks like the TNFD creating unprecedented demand for credible, comparable biodiversity data, unlocking new streams of investment and innovation. Third, the technological barriers have been dismantled; accessible cloud platforms, AI-driven analytics, and open-source tools make the operationalization of a sophisticated framework like the BMSF technically feasible at a global scale. Finally, a growing global recognition of Indigenous rights and knowledge systems provides a more just and effective foundation for the co-development of monitoring solutions. It is within this new, synergistic context that the following challenges must be addressed.

A primary hurdle will be achieving broad consensus and sustained commitment from multiple international organizations, regional bodies, national governments, scientific bodies, and other stakeholders. A federated governance model for a Global Biodiversity Monitoring Partnership is designed to facilitate this, but navigating diverse interests and ensuring coordinated action will require a dedicated commitment to collaboration.

Resource mobilization is another critical challenge. The development and widespread adoption of the REDD+ MRV system were underpinned by substantial, multi-year financial investments (Box 1). Similar long-term financial commitments from governments, multilateral funds (e.g., Global Environment Facility), and philanthropic organizations will be indispensable for developing BMSF standards, building global capacity, supporting national implementation, and maintaining the necessary technological infrastructure. A key priority for this investment must be the development and long-term maintenance of a core suite of open-source software and tools that operationalize the BMSF workflows. While proprietary solutions may arise, a foundation of free and open-source tools is essential to ensure equitable access, enable transparent peer review of methods, and foster a collaborative community that can sustain and improve the framework's components over time. Without dedicated funding for this open-source infrastructure, the BMSF risks remaining an aspirational framework rather than an operational reality.

We recognize that monitoring and the mainstreaming of biodiversity data into decisions requires deep involvement of sub-national governments, NGOs, business and industry and many other societal actors. A robust system for incentivizing the adoption and use of the BMSF is needed. There are several ways to do this. First, link the standards to the national reporting required by the monitoring frameworks of the Multilateral Environmental Agreements (KM GBF, SDGs, CMS). Second, initiatives such as the TNFD could align with the BMSF by requiring private sector disclosures to be based on the guidance offered by this framework. Third, encourage governments to require adherence to standards in publicly funded projects and environmental regulations (e.g., impact assessments). Lastly, explore the potential for voluntary certification schemes for organizations demonstrating adherence to high-quality monitoring standards.

Capacity development is a cornerstone of the model we propose for the BMSF, particularly for enabling participation from developing countries. Significant regional variation in resources and capacity exists and should be recognized when allocating effort to enabling the BMSF. This requires more than short-term training workshops; it necessitates sustained investment in institutional strengthening, local technical expertise and infrastructure, tailored to national and regional contexts. A tiered approach allows for progressive engagement, but moving countries up the tiers requires dedicated long-term support. Here the CBS subregional Technical and Scientific Cooperation Support Centres could play a key role.

Furthermore, balancing the need for standardization with the inherent diversity of species and ecosystems and national monitoring priorities will be a long-term task. Standards must be adaptable enough to be relevant in different contexts without losing the core elements that ensure comparability. The development and maintenance of accredited analytical workflows and tools will also require continuous innovation, technical support, and community engagement to ensure they remain fit-for-purpose and widely accessible. Finally, the governance of the GBMP itself will require careful design to ensure it is efficient, transparent, accountable, and truly representative of its diverse constituents in all parts of the world.

5.3. Future Work and the Road Ahead

This introduction of a BMSF is a call to action. Immediate next steps should focus on initiating pilot implementations of the framework in diverse national and regional contexts, potentially focusing on a subset of GBF targets and indicators (as exemplified in Table S1). These pilots will be crucial for testing the practicality of the proposed linking of standards across the steps, refining the tiered approach, identifying implementation bottlenecks, and demonstrating tangible benefits.

The formal establishment and operationalization of the Global Biodiversity Monitoring Partnership (GBMP) is a critical institutional step for implementing the BMSF. This involves securing support from national governments and from key partner organizations and networks designed to provide support. A plan defining its governance structure and securing initial operational funding will also be needed. The GBMP will then need to actively build and nurture a global community of practice around the BMSF, fostering knowledge sharing, collaborative problem-solving, and communication of the advantages to all actors seeking to mainstream the monitoring framework.

Simultaneously, effort is needed to begin the detailed development of specific standards via technical working groups dedicated to each step of the BMSF, engaging relevant expert communities (e.g. GEO BON, IUCN, TDWG, UNEP-WCMC) and technical working groups maintained by partner organizations. This includes elaborating on standardized protocols for translating data into EBVs and EESVs, and then onto indicators, developing suites of accredited analytical workflows, and providing clear guidance on implementing ethical principles. Further research will also be essential. This includes developing methodologies for assessing the performance and impact of the BMSF itself, ensuring that the investment in standardization leads to demonstrably better conservation outcomes. Investigating innovative financing mechanisms, including how robust monitoring could provide powerful incentives for investment in nature restoration.

The BMSF represents a major undertaking, requiring significant investment of time and resources. However, the urgency of global biodiversity declines and the proximity of GBF targets, mean we cannot afford a slow, sequential adoption. Fortunately, a powerful window of opportunity exists to catalyze this process through a strategic "grand collaboration" between the scientific community, public bodies, the private sector, and, critically, IPLC groups. This will complement existing frameworks and standards like SBTN who have already built standardized approaches to driving credible science-based action and TNFD’s framework for guiding biodiversity disclosures. A groundswell of private sector investment is now being directed towards biodiversity monitoring, sparked by GBF Target 15 and driven in part by new regulatory frameworks, green financing, and market-based imperatives such as the emerging biodiversity credit economy. We argue that this momentum should be channeled and leveraged to drive the formation of public-private partnerships to align corporate monitoring efforts with the standards and principles of the BMSF. Such a collaboration would enable the private sector to invest with confidence, knowing monitoring will be credible and comparable, while simultaneously providing the scientific and conservation communities with the resources, technology, and scalable implementation pathways needed to make the BMSF a reality—particularly in countries currently lacking sufficient capacity. By creating a standardized pathway from private-sector action to nationally aggregated data, the BMSF allows corporations to demonstrably align their nature-related reporting with the indicators of the GBF, and by consistent use of standardized methods for aggregation of evidence allow measurable assessment of the contribution of corporations to national and international goals.

5.4. Conclusion

The Biodiversity Monitoring Standards Framework proposed here offers a structured pathway to address the longstanding challenges of fragmentation and inconsistency in biodiversity monitoring. The BMSF should enable credible comparison of findings by promoting consistent data capture, quality assurance, and validated analytical pathways with uncertainty reporting. This framework should empower local actors, streamline national reporting to the Convention on Biological Diversity, enhance corporate accountability, and ultimately provide high-confidence biodiversity insights for adaptive conservation management. The implementation of the BMSF can be guided by a federated partnership, drawing lessons from established successes in the biodiversity standards community. The BMSF will be essential if the global community is to effectively mount a response that is appropriately scaled to track progress towards the KM GBF targets. The journey from disparate data to decisive, evidence-based action requires a shared commitment to building this common language for understanding biodiversity change and how action can be implemented most effectively to “bend the curve” of biodiversity (49). We hope the global biodiversity community will embark on this collaborative endeavor.

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Box 1: Lessons learned from the Measurement, Reporting, and Verification (MRV) framework for REDD+ (Reducing Emissions from Deforestation and Forest Degradation; GFOI. 2020).

The FAO has supported countries with the development and adoption of MRV systems for REDD+ (Reducing Emissions from Deforestation and Forest Degradation). The goal was to ensure estimates of anthropogenic forest-related greenhouse gas (GHG) emissions by sources and removals by sinks, forest carbon stocks, and forest area changes were comparable. This information is crucial for countries to access results-based payments for REDD+ activities and the role of conservation, sustainable management of forests, and enhancement of forest carbon stocks in developing countries. As of 2025, 71 countries have registered on the REDD+ web platform and are using comparable data and methods (50). The MRV framework builds from clear climate relevant measures (e.g. tons of carbon) to provide a repeatable workflow to monitor carbon stocks and greenhouse gas emissions from deforestation and forest degradation. Many lessons have been learnt from the implementation of the MRC (51) :

First, there was a **clear international mandate and framework**. The UNFCCC provides the overarching goals, reporting requirements, and verification process. This creates a strong incentive for countries to adopt standards.

Second**,** the **IPCC methodological guidelines are widely accepted**. These guidelines are endorsed by the UNFCCC and are considered essential for establishing robust and credible MRV systems for REDD+ initiatives because they ensure comparability and transparency across different countries and projects.

Third, the **tools needed are free and open source**. FAO's Open Foris and SEPAL which are used to calculate emissions lower the barrier to entry, promote transparency, allow customization, and facilitate collaboration and consistency across countries. They facilitate cost-effective and accurate monitoring of forest cover and other land covers, thus accelerating the development of operational National Forest Monitoring Systems.

Fourth, the FAO and partners have **invested substantially in training and technical support**, enabling countries to build national ownership and technical expertise. FAO's training programs (e.g. the eLearning Academy) address both national-level needs, such as strengthening institutional structures and developing regulatory frameworks, and local-level needs, such as training and certification on data collection and emission factor calculations.

Fifth, there has been a **phased and iterative improvement of the workflows**. Countries can start with simpler methods (Tier 1) and gradually improve their systems and move to higher tiers (Tiers 2 and 3) as capacity and data improve allowing them to choose approaches appropriate for their national circumstances and capacities, ranging from simpler methods to more detailed and data-intensive ones.

Sixth, **there has been a strong focus on national ownership**. The FAO supports countries in building their own National Forest Monitoring Systems, rather than imposing a single external system. This fosters agency and sustainability.

Figure 1: The Biodiversity Monitoring Standards Framework is a linked sequence of steps defined by the standards that each step adopts within a set of well-defined needs, principles and ethical guidelines (center). Every monitoring workflow would achieve an overall standard rating (potentially tiered) based on the standards adopted in each step. The monitoring workflow is implemented (right) once the necessary resources, human capacity, technologies, and data architectures have been adopted. A tiered approach allows countries to start with simpler methods and progressively adopt more sophisticated ones as capacity grows. These standards need not be costly or infeasible to adopt, but they do need to be defined a priori to create trust and confidence in the trends reported.

Supporting Information

Table S1: A national agency in "Country X" tasked with reporting one of the (component or complementary) indicators for the change over time in the connectivity of natural forest ecosystems for Target 3 of the GBF**.** The table illustrates how the BMSF might be implemented to ensure the report on this indicator is of high quality and internationally comparable. Certification of a step may require certification of previous steps that produce necessary information. Some workflows in this table already exist and are used to estimate connectivity.

Step in cycle	Objective	Implemented steps	Evidence documents for certification
Step 1: Planning and design of observations and data acquisition	To define precisely the resources invested, what will be measured, and how, ensuring the result is fit-for-purpose recognizing the rights (FPIC) of forest-dependent communities.	**Define "Natural Forest" and reference state:** The agency formally adopts a national definition based on an international standard (e.g., FAO), but with specific criteria to exclude plantations (e.g., minimum patch size, species diversity criteria). **Define Connectivity Metric:** A metric is chosen (e.g., Integral Index of Connectivity, IIC;(52)) from a peer-reviewed and approved publicly available source that supports and updates the methodology. Reviewed code or software used to calculate it and the counterfactual is specified (e.g., Conefor, BON in a Box). **Stakeholder/Rightsholder Engagement:** Documented consultations are held with the national forestry department and Indigenous community representatives to validate the "natural forest" map layers and understand data sensitivities.	**BMSF S1-Certified Design** **Evidence:** A publicly available "Design and Analysis Plan" with a DOI. **Criteria:** The document should contain the explicit definitions, the chosen metric, and evidence of stakeholder consultation (e.g., approved by stakeholders and rightsholders). **Outcome:** Anyone using the final data knows exactly what was intended and what "forest" means in this context, relative to the reference.

Step 2: Data acquisition, processing and management	To gather the raw spatiotemporal and ground-truth observations and data required for analyses.	**Acquire Satellite Imagery:** The agency acquires freely available Sentinel-2 Level-2A surface reflectance imagery for the entire country for the years 2020-2025. **Acquire Ground-Truth Data:** Collate data from the National Forest Inventory (NFI) plots and recent, quality-graded citizen science observations (e.g., research-grade iNaturalist records of forest-indicator species).	**BMSF S2-Certified Acquisition** **Evidence:** A metadata document listing all raw input data sources indicating which abide by data standards. **Criteria:** Each source must be cited with a persistent identifier (e.g., DOI for NFI data, specific query URL for satellite data). The protocol for collecting the NFI data must be included. **Value:** Ensures the sources and processes for data acquisition are known and traceable.
Step 3: Data provenance and licensing	To process raw data into an analysis-ready, FAIR & CARE land cover map.	**Image Processing:** Use a documented, version-controlled script to create cloud-free national mosaics from satellite imagery or available satellite knowledge product. Ensure updates to data layers are described and conducted across time periods. **Classification:** Train a machine learning model (e.g., Random Forest) using the ground-truth data to classify the mosaic into land cover types, including "natural forest." The model, its training data, and its accuracy assessment are all saved. **FAIR & CARE Publication:** The resulting 10m resolution "Natural Forest Map 2025" is published in the national data repository. It has a DOI,	**BMSF S3-Certified Data Product** **Evidence:** The publicly accessible, derived land cover map dataset. **Criteria:** The dataset must have a DOI, a complete metadata file describing its full provenance (including the classification model version), a clear license, and a statement on CARE implementation. **Value:** Creates a trustworthy, reusable asset (the map) that others can build upon.

		rich EML metadata, and ideally a CC BY license. The metadata explicitly describes the CARE principles applied (e.g., data for sacred groves were aggregated to a coarser resolution in the public version as requested by Indigenous partners).	
Step 4: Analysis & Modeling	To execute the analysis to calculate the area and connectivity values.	**Area Calculation:** A script calculates the total area of pixels classified as "natural forest." **Connectivity Calculation:** The forest map is used as input into the specified software to calculate the IIC index. **Uncertainty Quantification:** The known classification accuracy from Step 3 (e.g., 92% accuracy) is used to calculate a confidence interval around the final area estimate (e.g., 45,210 km^2 ± 1,240 km^2). **Reproducibility Package:** The entire analysis workflow (code, software environment) is packaged into a Docker container ready for use in BON in a Box or similar platforms.	**BMSF S4-Certified Analysis** **Evidence:** A link to a Git repository (e.g., on GitHub) containing the analysis code and the Dockerfile. **Criteria:** The code must be well-documented. The repository must include instructions to reproduce the exact numerical results, including the uncertainty calculations. **Value:** Guarantees scientific reproducibility and transparency of the calculations.
Step 5: Indicator calculation and interpretation	Translate the numerical results into a formal indicator product.	**Indicator calculation:** The final results are compiled into a formal "Indicator Factsheet." **Visualization:** The factsheet includes a map of forest cover change and a time-series graph showing the trend in area and connectivity (with	**BMSF S5-Certified Indicator** **Evidence:** The final, version-controlled indicator factsheet, with a DOI kept in a national repository. **Criteria:** The factsheet must clearly state the

		uncertainty bands) relative to baseline and reference state. **Provenance Statement:** The factsheet includes a dedicated section linking back to the DOIs of the certified products from steps 1, 2, 3, and 4, creating a complete, clickable "provenance chain."	indicator values with uncertainty relative to baseline and reference state. Include visualizations, and provide a complete, linked provenance chain. **Value:** Creates a single, trustworthy "answer" that is fully auditable.
Step 6: Synthesis with standards for communication reporting & disclosure	To use the certified indicator for official reporting and to inform national action.	**CBD Reporting:** The agency submits the value and a link to the Step 5 Certified Indicator factsheet in its 7th National Report to the CBD. **Policy Briefing:** A summary is used to brief the Ministry of Environment on where connectivity is lowest, suggesting priorities for new ecological corridors. **Disclosure:** The indicator is featured on a public national biodiversity dashboard.	**BMSF S6-Certified Application** **Evidence:** A link to the official national report or policy document where the indicator is cited. **Criteria:** The indicator must be verifiably used to inform policy or meet an international reporting commitment. **Value:** Demonstrates that the monitoring effort was used in national reporting and made available to global assessments.

Table S2: An example of how implementing the BMSF at local and national levels allows aggregation of learning across sites. This requires supporting local needs and monitoring activities and, where permitted, to support information flows to national monitoring knowledge services. The

BMSF, through its emphasis on standardization, facilitates a process analogous to "federated learning" by enabling robust aggregation and synthesis of information without necessarily centralizing all raw data processing in its entirety.

Standardized inputs: Because all local sites use standardized field protocols c(Step 1) and data formats (Step 2), the data they submit to the National Data Hub are comparable and interoperable. This data flow should be mediated by standardized APIs, allowing diverse local systems (from mobile apps to sensor networks) to programmatically push data to the national hub. Metadata standards (S3) ensure each dataset is well-described, allowing local sites to understand its context and quality.

Consistent EBV Derivation: The national hub can apply peer-reviewed analytical workflows (Step 4) to either the site-specific curated data or to aggregated datasets. For example, if each site provides data on tree density and species, local sites can calculate site-level "Habitat Structure" or "Community Composition" EBV components. These site-level EBV "summaries" or "models" can then be aggregated. Alternatively, all raw data points (if shared) can be pooled at the national level to train a single national model for an EBV (e.g., a national species distribution model for a key mangrove species).

A federated model can be applied for indicator calculation (Step 5): Local Calculations, Global Synthesis: Site-level teams could potentially calculate certain local indicators or EBV summaries based on their data, using BMSF-standardized methods. These pre-processed results (like local model parameters or indicator values, rather than all raw data) could then be sent to the national body for aggregation.

Central Aggregation: The national layer aggregates the site-level EBV/EESV and/or indicator summaries to produce a national picture. For example, the national "trend in forest extent" would be the sum of changes across all sites, each assessed using comparable remote sensing and ground-truthing standards.

Distributed Learning and Refinement: The national hub analyzes the aggregated picture and identifies patterns, conservation successes or failures (e.g., "restoration technique X appears most effective in region Y," or “indicator threshold Z is too sensitive/insensitive").

This "learned" information is then disseminated back to all local sites. This might take several forms such as updated monitoring protocols (Step 1 data collection). Recommendations for improved local management based on national trends. Local site teams can then adapt their local practices based on this centrally synthesized, but locally derived, learning.

Privacy/Sovereignty (Implicit in Step 0, Step 3): While this example has data flowing to a national hub, a true federated model could, in some instances, allow insights to be generated without raw data leaving the local "custodian" (site level). Local participants could run standardized analyses and only share anonymized or aggregated results/model parameters. The BMSF's emphasis on provenance and data use agreements (Step 0, Step 3) would govern this.

Overall Monitoring Objective (S0)	To assess the status and trends of an ecosystem (e.g., forest, mangrove) nationally, identify areas of degradation, and evaluate the effectiveness of restoration interventions, aligned with National Biodiversity Strategy and GBF targets (e.g., Target 1 for ecosystem area, Target 2 for restoration, Target 4 for species within mangroves).
Monitoring layer 1	**Local / Site-Level Monitoring Teams & Communities**
Actors	**Field Teams (NGOs, University Research Groups, Local Community Monitors, Park Rangers):** Multiple teams responsible for distinct ecosystem sites or regions along the coastline. **Remote Sensing Analysts (Potentially centralized or regional):** Processing satellite imagery for ecosystem extent and condition.
BMSF Application at Site Level	**Step 0 (Ethics - Localized):** Adherence to national ethical guidelines, obtaining local community consent (FPIC) if applicable for site access or co-implemented using incorporating local knowledge. Clear communication of local data use. **Step 1 (Sensing & Knowing):** **Field Teams:** Execute standardized field protocols for selected EBVs (e.g., EBV_EcosystemExtent via ground-truthing, EBV_CommunityComposition via quadrat counts of ecosystem species, crab populations, bird surveys; EBV_EcosystemStructure e.g. canopy height, tree density). Use standardized methods for equipment. **Indigenous/Local Knowledge Holders:** If involved, share observations on changes in ecosystem condition, material ecosystem services (realized ecological supply EESV), or traditional uses, using co-developed protocols. **Remote Sensing Analysts:** Acquire and pre-process satellite imagery (e.g., Sentinel, Landsat) according to agreed national standards (e.g., specific bands, cloud masking). **S2 (Curation - Initial):** **Field Teams:** Perform initial data entry into standardized digital forms/databases, basic quality assessment (checking for outliers, completeness). **Remote Sensing Analysts:** Georeferenced imagery, perform atmospheric correction. **S3 (Trust - Initial):**

	Field Teams: Generate basic metadata for their collected field datasets (who, what, when, where, how). **Remote Sensing Analysts:** Document imagery sources and pre-processing steps.
Outputs from Layer 1:	Site-specific observations and curated datasets (e.g., plot data, species lists, local ecosystem extent maps from field data, pre-processed satellite scenes for their area of responsibility).
Layer 2:	**National / Central Coordinating & Synthesis Hub**
Actors	**National Biodiversity Monitoring Agency (NBMA) / Lead Research Institution:** The central coordinating body. **Data Management & IT Team (within NBMA):** Manages central database, IT infrastructure. **EBV & Indicator Specialists (within NBMA or contracted experts):** Experts in deriving EBVs and calculating national indicators. **Policy Analysts & Communicators (within NBMA):** Translate findings for policymakers and public.
Responsibilities & BMSF Application at National Level	**Step 0 (Ethics, Monitoring Principles):** Establishes national ethical guidelines, data sharing policies, and MOUs with local actors. Ensures overall program alignment with national and international commitments. Defines overall purpose specification. **Step 1 (Sensing & Knowing - Coordination & Standards Adopted):** Develops and disseminates the standardized field protocols and remote sensing processing guidelines used by Layer 1. Provides training and capacity building to Layer 1 teams. May directly manage national-scale remote sensing acquisition. **Step 2 (Curation - Centralized):** Receives datasets from all Layer 1 teams. Performs data de-duplication, integration, harmonization (e.g., resolving taxonomic inconsistencies, aligning spatial data). Manages the national biodiversity database. **Step 3 (Trust - Centralized & Aggregation):**

	Creates comprehensive metadata for aggregated national datasets. Manages data licensing for national products. Ensures provenance tracking from local collection to national product. **Step 4 (Analysis - Centralized):** **EBV Derivation:** Uses curated data from all sites to generate national-scale EBV products (e.g., National Mangrove Extent Map, National Mangrove Species Richness Trends, National Mangrove Canopy Height Change Map). This involves applying accredited analytical models and workflows. **Indicator Calculation (National):** Aggregates site-level information or uses national EBV products to calculate national-level indicators for ecosystem status. **Step 5 (Indicator Calculation & Interpretation - National):** Calculates national indicators for GBF reporting (e.g., total area of ecosystem, trend in status of ecosystem, number of degraded sites under active restoration). Interprets these indicators against national targets and baselines. Conducts attribution analysis (e.g., linking ecosystem loss to specific drivers like deforestation, fire, disease, or linking recovery to restoration efforts). **Step 6 (Reporting & Disclosure - National & International):** Prepares national reports for the CBD and other relevant bodies. Develops policy briefs for national decision-makers. Publishes national state of ecosystem (e.g., forest, mangrove) reports and makes data/indicators publicly accessible (e.g., via a national biodiversity portal). **Adaptive updating of monitoring activities:** Assesses overall program effectiveness, identifies data gaps, evaluates EWI performance. Uses insights to refine monitoring objectives, protocols (Step 1), analytical methods (Step 4), and indicator thresholds for the next cycle. This feedback flows back to Layer 1.

Table S3: Typology of the key terms used in this paper to describe the BMSF

Class of component	Definition
Actor/Agent	An individual, organization, or system performing a Process/Activity.
Data entity	Observation Record (e.g., a single species sighting, a plot measurement) Indigenous Knowledge Record (e.g., a documented piece of IK) Variable Value (a measurement or derived value for a variable) - Metadata Element
Essential variable	EssentialBiodiversityVariable (EBV) Essential Ecosystem Service Variable (EESV) Essential Ocean Variables (EOVs) Essential Climate Variables (ECVs) Essential Environmental Impact Variables (EEIV) Driver Variable (e.g., climatic data, soil type, human pressure data)
Ethical Consideration	A principle guiding conduct (e.g., CARE, FPIC).
Information Product	The tangible output at various stages (e.g., raw dataset, curated dataset, EBV layer, indicator value, report).
Method/Protocol	A specific, documented way of performing a Process/Activity.
Monitoring Objective	The knowledge need for conservation or policy goals driving the monitoring.
Process/Activity	An action taken within a BMSF step or module (e.g., data collection, data validation, model fitting, report generation).
Quality Criterion/Metric	A standard or measure used to assess an Information Product or Process.
Tool/Software/Instrument	A physical or digital implement used in a Process/Activity.

Table S4: the BMSF does not compete with frameworks like CSRD, CSDDD, or TNFD; it underpins and enables them.

Framework	Primary Role	Relationship with BMSF
CSRD	Mandates *what* must be reported on biodiversity.	The BMSF is the **Data Engine**, providing the standardized "how-to" for generating the credible, auditable data required by CSRD reports.
CSDDD	Mandates the *process* of identifying and mitigating impacts.	The BMSF is the **Operational Toolkit**, providing the monitoring workflows needed to both identify impacts (due diligence) and verify the effectiveness of mitigation actions.
TNFD	Provides a framework (i.e., LEAP) for how to frame and disclose nature-related issues.	The BMSF is the **Measurement Arm**, providing the methods to gather and analyze the robust data needed for the "Evaluate" and "Assess" steps of the LEAP approach.
SBTN	Provides a framework for *what to aim for* (setting science-based nature targets).	The BMSF is the **Progress Tracker**, providing the standardized monitoring workflows needed to reliably track progress against SBTN targets over time.

Table S5: The table of acronyms used in the main text of the paper.

Acronym	Full name
BIP	Biodiversity Indicators Partnership
BON	Biodiversity Observation Network
BMSF	Biodiversity Monitoring Standards Framework
CARE	Collective Benefit, Authority to Control, Responsibility, and Ethics data management principles
UN CBD	United Nations Convention on Biological Diversity
CMS	Convention on Migratory Species
CSRD/CSDDD	Corporate Sustainability Reporting Directive/ Corporate Sustainability Due Diligence Directive
EBV	Essential Biodiversity Variables
ECV	Essential Climate Variables
EESV	Essential Ecosystem Service Variables
EEIV	Essential Environmental Impact Variables
EOV	Essential Ocean Variables
FAIR	Findable, Accessible, Interoperable, and Reusable data management principles
FAO	Food and Agriculture Organization of the United Nations
FPIC	Free, Prior, and Informed Consent
GBIF	Global Biodiversity Information Facility
GBMP	Global Biodiversity Monitoring Partnership
GEF	Global Environment Facility
GEO BON	Group on Earth Observations Biodiversity Observation Network
ICA	International Consultation and Analysis process (of the UNFCCC)
IIC	Integral Index of Connectivity

IPLC	Indigenous Peoples and Local Communities
IUCN	International Union for Conservation of Nature
KM GBF	Kunming-Montreal Global Biodiversity Framework
MEA	Multilateral Environmental Agreement
MRV	Measurement, Reporting, and Verification framework
NBSAP	National Biodiversity Strategies and Action Plans
NFI	National Forest Inventory
REDD+	Reducing Emissions from Deforestation and Forest Degradation
SDG	Sustainable Development Goals
SEPAL	System for Earth Observation Data Access, Processing and Analysis for Land Monitoring
TACCC	Transparency, Accuracy, Completeness, Comparability, Consistency
TNFD	Taskforce on Nature-related Financial Disclosures
TDWG	Biodiversity Information Standards (formerly Taxonomic Databases Working Groups)
UNFCCC	United Nations Framework Convention on Climate Change
UNEP-WCMC	United Nations Environment Programme World Conservation Monitoring Centre