Global biodiversity measurement to meet scale-dependent needs and opportunities

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Abstract:

In the face of rapid ecological decline, biodiversity information is essential for safeguarding life on Earth. Although this information is increasingly valued by governments, businesses, and other stakeholders, it remains insufficiently accessible and usable. Because the rarity and functions of biodiversity vary greatly across land- and seascapes, the global and local ecological and social significance of biodiversity change within and among regions can differ greatly. Measuring biodiversity at both scales is therefore critical for effective monitoring and conservation—an expectation embedded in global frameworks. We review the challenges and opportunities in biodiversity measurement, examining key users, producers, and use cases, and the role of emerging technologies. As catalysts for a more robust, efficient, and collaborative global measurement system we highlight Essential Biodiversity Variables (EBVs) as a flexible foundation to integrate across scales by linking local data into global significance assessments. EBVs also underpin indicators, geospatial data products, and an evolving 'bag of metrics' required by different users. We call for improved incentives and organization around thematic and regional networks to produce EBVs and structured end-to-end initiatives and workflows as a blueprint for the next phase of coordinated biodiversity measurement globally.

Main text:

Land- and seascapes worldwide are increasingly affected by human activities and are undergoing rapid change, resulting in declining ecosystem health and/or wholesale losses of species populations and the functioning ecosystems they support (*1-4*). These losses not only impact countless communities locally but also regionally and globally depending on a range of benefits that biodiversity provides (*5*). Biodiversity—defined in the Kunming-Montreal Global Biodiversity Framework (GBF) (*6*) as "the diversity of life at genetic, species and ecosystem levels, and the ecological and evolutionary processes that sustain it"—is the foundation of human well-being and a healthy planet. Some initiatives use the term "Nature" as a synonym for biodiversity. Biodiversity as mentioned in the GBF is essential to the well-being and prosperity of people, as well as to the planet's life-support systems, since humanity depends on biodiversity for food, medicine, energy, clean air and water, protection from natural disasters, and cultural and recreational inspiration. The GBF (adopted under the United Nations Convention on Biological Diversity, CBD in 2022), recognizes these values and dependencies alongside a monitoring framework (*7*) that includes specific indicators for tracking both national and global progress toward defined biodiversity targets.

The framework adoptions have accelerated and focused momentum among actors worldwide to advance measurement of the status and trends of biodiversity (*8, 9*). Biodiversity data collection and derived information products (biodiversity measurement) are central to a basic understanding of drivers and consequences of biodiversity loss, specifically under anthropogenic change (*10*). They take on specific relevance for biodiversity management and conservation, and the associated shifting of financial flows to halt and reverse nature loss (*11*). Biodiversity measurements are needed by a large group of users who share many commonalities but also differ, not least in their geographic scope. Their interests include assessment of progress towards policy goals and targets, reporting to national and international bodies, legal compliance and tracking of business risks and dependencies across single or portfolios of locations. To address any of these use cases requires biodiversity status metrics to be integrable and comparable within and across scales, times, or domains, necessitating some form of standardization. At present, despite important scientific advances and biodiversity observation activities, these needs are insufficiently met, and producers and consumers of biodiversity measurements remain ineffectually connected (*12*). Our review assesses the current state and opportunities around global production and use of biodiversity measurement. We set out to characterize the key innovations in data production and monitoring that allow explicit understanding of biodiversity significance and change, the central use cases for this information, and their respective scale dependence. The review thereby aims to show how lingering gaps within and between the producers and end users of biodiversity information can be closed. We identify ways forward that ensure all actors can rely on the scale-relevant biodiversity information they need to implement action to meet the goals and targets of the GBF.

Measurement of biodiversity significance for conservation

In contrast with climate change, where emissions (or sequestration) at all locations have equal impact on global greenhouse gas concentrations, the significance of biodiversity change is disproportionately concentrated in some parts of the world, with both local and global consequences arising from its loss. Recognition of this important issue of scale has implications for biodiversity measurement, how it is organized and coordinated, and used by networks of actors implementing conservation actions.

While some local benefits of biodiversity might be restored with effective local action this is not the case for global extinctions of species and destruction of ecosystems, which are irreversible. Given our limited understanding of the web of life's many connections, we may not fully know what the consequences of even just a few global biodiversity extinctions might be, now or in the future under different environmental scenarios.

The enormous cost and uncertain success of any local species or ecosystem replacement and recovery means the deteriorating health of biodiversity is incurring immeasurable ecological debt now and for future generations. To recognize the importance of biodiversity, to adequately measure its status and trends and to ultimately support decisions that safeguard it, the consideration of relevant scales is critical.

Measurement reveals scales of biodiversity significance

With some simplification, the biodiversity significance of any given place can be separated into two aspects (Fig 1). The first is the contribution biodiversity provides locally, i.e. in the local ecosystems and the surrounding land- and seascapes they are part of. Here, biodiversity conveys a range of geographically specific benefits to people that rely on the compound functional and structural elements and contributions emerging from the presence and interactions of locally co-occurring species (*13-15*). Maintaining these emergent benefits and supporting their resilience relies on sufficient levels of ecosystem integrity, e.g. adequate connectivity and minimum population sizes supporting healthy species and resilient communities. The exact spatial extent of this local scale varies with system and ecological processes – as small as a few hectares to several square kilometers for most terrestrial systems, but larger for processes including seasonal movements of species, and for large lakes and marine systems (*16*). A single location might convey a large portion of the same function (e.g. pollination) or benefits (e.g. climate regulation) found at another, and the combined value changes minimally as one is lost or restored. Notably, functions and benefits might require particular species to co-occur and might decrease or collapse entirely if key species populations or functions fall too low and the system is below a resilience threshold. These decreases, as arising from an unsustainable use biodiversity, are expected to impact the supply of ecosystem services and the many known and measured benefits to people (*17*). But as those species or functions are retained in the region and biodiversity is used sustainably, local biodiversity significance has the potential to recover.

The second part of a location's significance arises from the global-scale contribution of its biodiversity (*18, 19*). In short, locations might harbor geographically rare, evolutionarily or functionally unique or particularly valuable biodiversity assets that are of fundamental importance for their future survival globally. These are typically species or ecosystems that in addition to conveying local functions or benefits have narrow distributions (endemism), low populations sizes, insufficient protection and/or decreasing recent or projected trends in extent and condition (*20, 21*). In some cases, they might hold particular importance (flagship, umbrella status) due to their unique or outstanding functional, evolutionary, or cultural values (*22*). The units conveying this varying importance are biologically defined, in the case of species, or human-assessed, for ecosystem types, and each hold a distinct realized or potential geographic distribution that can be assessed for single spatial units, say 1km pixels.

Implications of scale dependence for measurement

The two scales of biodiversity values necessarily require different scales of measurement. For local values, measurements addressing occurring biodiversity functions and benefits require data collection at the local to regional scale, extending to land- or seascapes and watersheds, but not usually beyond. It is important for measurements to encompass all key functions and benefits to the extent possible.

In contrast, to gauge global significance arising from locally occurring biodiversity elements (species, ecosystems), the scope of assessment goes far beyond the location. It requires determining the extent of the elements' global distribution and of their status/condition at each of their occurrence locations (*23*). In simplified form, for a single location (and time) the significance value for a given biodiversity element can then be derived as Local Suitability / Sum (suitability of all pixels), and the compound total as aggregate across all elements (for species this is akin to 'endemism richness' or 'total range rarity' (*24*)). For the case of single species abundance (i.e. population size individuals/area) or ecosystem type prevalence, local significance is given as proportion of the global population or global ecosystem type an area holds. All metrics can be weighted by other attributes such as threat or distinctness. Here, accounting for each member of a biodiversity element group (e.g. species class mammals, ecosystems type of Global Ecosystem Typology Level 4) not just locally but globally is key. Insufficiently capturing status or condition for elements in some regions and missing their value would not only miss their importance but also wrongly upweight locations that are measured. For species populations the need to address all locations of all species across their full geographic scope was therefore recognized as essential (*25*).

A central distinction between local and global parts of biodiversity significance arises from their different geographic restriction/concentration, redundancy, and replaceability (*18, 19*). Different to the redundancy attributes of local biodiversity significance, for global significance we see additivity or uniqueness. The defined geographic distribution of global significance units implies geographic restriction, complementarity, and potentially irreplaceability, indicating that some locations have much higher portions of specific assets than others. It also means additivity, with a location's importance increasing linearly with the aggregate of the global significance of the biodiversity units it holds and their respective geographic restrictions. Single locations' global significance aggregates to compound regional and global biodiversity significance, with each part of the planet contributing a portion, and when apportioned in this way exact complementarity of these contributions. Systematic conservation planning leverages this information and supports spatial decision-making and optimized reserve design and sustainable development (*26, 27*).

Implications of scale dependence for conservation

These differences have direct implications for conservation outcomes. Consider Location A, for example, situated in a sub-/tropical region, that holds both high local and global biodiversity significance because it is home to several narrowly distributed species or ecosystems that also provide important local benefits and functions. Protecting the biodiversity of these locations from degradation or restoring them to their native state holds both global and local importance. It ensures progress around both local and global ecosystem health in GBF Goal A and delivers on the objectives of Target 3 on increased area-based conservation by 30% by 2030 (the "30x30" target) to address areas of biodiversity importance and ecological representativeness (Figure 2). In contrast, Location B holds very limited global significance but does deliver important functions and benefits locally. Here, deterioration or protection affects local but not global biodiversity significance and thus has relevance for local ecosystem health and services (Goal A components, B). But these changes have limited bearing for safeguarding species and ecosystems globally (Targets 1, 3).

These examples highlight how central goals and targets of the Kunming-Montreal Global Biodiversity Framework (GBF) are to addressing biodiversity status and threats and that they go beyond the jurisdictions of its signatories, let alone single locations (Figure 2). This situation is similar for metrics now stipulated for use by businesses under the Taskforce for Nature-related Financial Disclosures (TNFD) (*28*) and emerging jurisdictional disclosure regulations aligned with CBD Target 15 (*29*), as well as with emerging voluntary guidance such as from the Science Based Targets Network (*30*), the Nature Positive Initiative (*31*), and the Align Project.

In the GBF, this applies most obviously to the commitments to reduce species extinction risk and support healthy species populations and their genetic diversity (Goal A, Targets 1, 3, 4). As the species and their populations extend beyond, and in cases seasonally move beyond, the borders of single landscapes and countries, gauging the adequacy of local actions to support conservation goals requires large-scale context. Information on the status and site condition for species is obviously critical. But only additional information on respective population status and trends (and existing protection measures) everywhere else allows for quantification of the location's full significance. As species and their interactions with a particular environmental setting define ecosystems, the same applies to GBF commitments around ecosystem status and trends. Assessing the extent and status of ecosystems relies on a full global delineation (atlas) with single elements going beyond single locations and landscapes. And evaluating a location requires measurement of the health of locally occurring ecosystem types including information about their global status, akin to species. Global significance underpins all elements of GBF Goal A, and the compound potential progress on these biodiversity commitments through avoidance of impacts or active conservation measures (Targets 1, 2, 3, 4) is greatest in places of high global biodiversity value. In the current Nature Positive Initiative draft guidance (*32*), both species indicators and at least one ecosystem indicator rely on the capture of both local and global biodiversity significance of areas of interest to business (Fig. 2).

In contrast, for other threat-related GBF targets addressing nature benefits and use and for the Nature Positive Initiative draft indicators addressing local ecosystem conditions, local biodiversity values are sufficient (albeit in cases larger landscape integrity and connectivity of surrounding land- and seascapes requires consideration).

Biodiversity measurement users and their types and scopes of need

Key users of biodiversity information span geographic scales and domains (Fig. 3). They are united by their interest in including biodiversity in their decision-making and monitoring and assessing change, in some cases tracked against specific targets. Human society as a whole benefits from biodiversity measurement, as a means of protecting the multiple values we attach to nature: whether intrinsic ("Nature for Nature"), instrumental ("Nature for Society") or relational ("Nature as Culture")(*33*). While ensuring sufficiency of local biodiversity benefits, human society is charged especially with the global safeguarding of biodiversity and access to information is key for it to hold governments accountable. Valuation of the global status of species and ecosystems and of a location's relative contributions to support it are thus central. A range of global initiatives use this information to support global status assessments, including the Half-Earth Project (*34*), the Global IUCN Red List (*35*), the Planetary Boundaries initiative (*36*), and reports and trackers provided by international NGOs such as WWF (*37*)(*38*).

In international policy frameworks, national governments formalize these commitments toward global progress in the form of national targets and track them in their jurisdictions. As illustrated in the GBF (Fig. 2), both local and global biodiversity values are key, while the overarching vision mirrors the large societal obligation toward minimizing global losses. This applies similarly to other conventions that focus on particular parts of biodiversity or loss drivers, such as CITES for traded species and CMS for migratory species.

Businesses rely on global and local biodiversity value information to evaluate, act on, and disclose nature-related impacts, dependencies, risks, and opportunities across their value chain, extending from single or multiple locations of their own direct operations to upstream and downstream processes, including commodity sourcing. The global economy, and individual businesses, are significantly reliant on biodiversity– with over 55% of global GDP (US$58 trillion) moderately or highly dependent on nature (*39*). Biodiversity-related dependencies include ecosystem services and functions that business operations might rely on, such as those affecting crop or fishing yields, material quality, tourism and others and typically centered on values at local to regional scales. Businesses are also key contributors to the major global drivers of biodiversity loss, e.g. through land-use and climate change, exploitation, pollution, and invasive non-native species. Related to both dependencies and impacts are the resulting nature-related risks, which can be characterized as physical, transition, or systemic (*40*). Businesses require biodiversity information to accurately assess nature-related dependencies, impacts, risks, and opportunities, commit to specific targets to address them, take action accordingly, and disclose their progress (*41*). A major lift in guidance on identifying exposure to nature-related risks and opportunities has recently been delivered by TNFD. Its LEAP framework recommends businesses to Locate how they geographically interface with nature (including biodiversity) and Evaluate both global and local biodiversity values in those places. These steps are followed by Assessment and Preparation around their risks and opportunities, with management and planning requiring additional information at both global and local scales. Multiple corporate nature frameworks are currently evaluating suitability of Nature Positive Indicators (Fig. 2) for assessment for reporting inclusion in disclosure guidance. How much corporates' activities intersect Areas of sort A rather than B (Fig. 1) will affect the balance between global vs. local biodiversity information needed. As lenders and investors, the same information needs extend to financial institutions, which, like corporations with complex value chains, may have limited traceability to specific locations. Interestingly, through the TNFD's Transition Planning guidance, the Science Based Targets Network methodology, and other guidance, there is specific emphasis on ensuring the biodiversity efforts in a specific place align with, and can be reported against, jurisdictional and global objectives. An additional particular relevance exists for a rapidly emerging group of business operations around high-biodiversity nature-based solutions (e.g. carbon credits) and direct biodiversity credits which may be either required for permitting compliance or voluntary (e.g. easements, restoration). Nascent voluntary biodiversity credit measurement standards remain variable, but credit pricing is poised to converge around local and global biodiversity contributions achieved which in turn will guide planning and site management.

At the level of countries and their component governments and agencies, needs for biodiversity information are cross-cutting and cover all areas of their jurisdiction. Governments need biodiversity information to inform the development and monitoring of national policy, to monitor compliance with existing regulations and to guide new legislation. In order to develop national policy, countries rely on biodiversity information to assess their own biodiversity dependence- and impact-related risks, value their nature assets and support their spatial planning. In the context of international agreements, such as the GBF, Parties to the Convention (i.e. countries) need to set national biodiversity targets and they are legally obligated to report on progress towards those targets, including reporting on progress towards the indicators in the GBF monitoring frameworks. And they rely on biodiversity information to assess their own biodiversity dependence- and impact-related risks, value their nature assets and support their spatial planning. For example, national targets include the targets that many governments have committed to area-based conservation actions in support of the '30x30' GBF Target 3.

National planning efforts, such as those supported by SPACES Alliance, require both intra- and extra-territorial biodiversity information. Local biodiversity values that citizens rely on in the land- and seascapes they inhabit have particular importance for government. But the larger societal and international commitments along with the ‘beyond-borders’ distribution of biodiversity require a strong consideration of global biodiversity values.

The goals and information needs of non-governmental organizations supporting biodiversity conservation overlap with many of those already listed. The geographic scope of their own direct activities and those of their partners might span single locations or large regions across the globe. Among organizations, conservation goals include outcomes for both local and global biodiversity and require information addressing both. Organizational target setting and tracking is variable, with some using internal tools and others following GBF-inspired metrics with no cross-cutting frameworks or reporting tools.

Indigenous peoples and local communities (IP&LCs) are both dependents and key custodians of biodiversity worldwide. They are keen to monitor compliance of institutions active in their areas and deeply value information about not just local but also global biodiversity significance of their land- and seascapes. IP&LC knowledge holdings are often richer than those derived by outside actors but may lack the context necessary to detect a location’s outstanding global value. Democratizing access and use of this information as IP&LCs navigate outside interests is a key priority for producers and consumers of biodiversity information.

Addressing information needs with biodiversity measurement

The above characterization of use cases highlights key commonalities among all consumers of biodiversity measurements and the need for common and shared solutions (*42*). We note that temporal and spatial metrics might be calculated by stakeholders internally one-off, or through the development or use of internal or through partnerships with external tool providers. Decision-support use cases such as comprehensive asset valuation, target setting, spatial planning (*43*), or site management are often more complex. They might require additional information or assumptions around biodiversity pressures and response, and any planning usually relies on spatially comprehensive and contiguous information (e.g. detailed regional to global maps across time) and benefits from future scenario assessment.

Field data collection

Collection of biodiversity data in the field is the core, albeit on its own insufficient, means to address these information needs. Some but not all of the key information user groups (Fig 3) are also central producers of biodiversity data and are using a growing suite of technologies to collect it (Box 1). Many government agencies have field survey programs or bring together data from regional actors in their jurisdiction, with coverage often closely related to wealth. Along with some commercial ventures, some high-GDP governments undertake satellite and airborne remote sensing campaigns that can deliver near-global data addressing biodiversity indirectly

(*44, 45*). For compliance, and due to an increasing recognition of risks and opportunities related to biodiversity, businesses are a nascent but rapidly growing collector of biodiversity data in their own areas of interest. With their local partners, conservation organizations undertake myriad surveys in their activity areas addressing particular species, ecosystem, and impact interests. In academia, including museums and herbaria, data collection is usually project-driven around incidental areas of interest, often near university or research stations. Together with government, conservation NGO, and IP&LC partners, academic researchers have an outsized importance for locating and assessing under-sampled or describing new biodiversity. And alongside the same peers, they are central to advancing new sampling methodologies and technologies. Finally, IPLCs hold key knowledge for their locations with use guided by appropriate consent. More broadly, local people have become key to advancing community-based information and addressing past data inequities, and in terms of record counts have become the largest contributors.

Either directly or through additional means of identification, these primary data address the status of ecosystems, species, and their functional and genetic attributes. Comprehensive (and rare) community time series and atlas surveys excepting, these data are sparse across space, time and biodiversity units. And they are subject to well-known but heterogeneous biases, associated with access, wealth, detectability, identifiability, and other factors (*46, 47*). They are dominated by presence data, with evidence on condition, local abundance or absence collected much more rarely (*48*). Earth surface signals from orbiting satellites are spatiotemporally more dense, contiguous and less biased, but limited to specific types and derivation of biodiversity-relevant metrics constrained by spatiotemporal data grain and available ground training data.

Data processing and harmonization

These primary, and mostly unstructured data require standardization to make them interoperable and sharable. Here a mostly academic community along with Global Biodiversity Information Facility, a sharing infrastructure for spatial biodiversity data, have advanced the Darwin Core and its recent Humboldt extension as standard to serve this central purpose (*48-50*) along with taxonomic standardization initiatives (*51, 52*). For ecosystems, the Global Ecosystem Typology and Atlas efforts serve a similar role, as do natural capital accounting guidelines for ecosystem services. For this primary evidence to be fit for further use requires extensive additional harmonization and quality assessments, a service provided by expert networks in academia, agencies, NGOs, and the public. These networks are organized loosely under different structures and contributing volunteer time or linked to project-focused initiatives. Intersecting and overlapping with thematic axes of expertise are regional networks, such as biodiversity observation networks. Challenges in this space are obstacles to data sharing, quality control and fitness for purpose, and others.

In combination, the above steps result in a structured and curated primary data ‘cube’, addressing the observed status/condition of biodiversity in select instances of time, place and biodiversity element. In rare instances, e.g. for a densely sampled location or expert-assessed categorical threat status, basic interpretation of these data would be sufficient to address a measurement use case. But typically, for the information to be fit for purpose, additional statistical or machine learning-driven models are necessary which leverage environmental data, e.g. from remote sensing, and can link in other ancillary information.

From data to Information Products and Insights

As an example, for use cases only addressing assessment or monitoring of Local Biodiversity Significance, traditional time series or occupancy models can capture status for a subset of biodiversity at single locations. In practice, for small portfolios these analyses could be completed by stakeholders fully in-house, and they would not necessarily require going through communal warehousing and quality refinement steps.

The situation is different for many decision-support use cases and all those requiring Global Biodiversity Significance of any sort. Here, more comprehensive information that addresses a full geographic scope, ideally over multiple time scales, is key.

This is best encapsulated in the ‘Essential Biodiversity Variable’ (EBV) concept (*53*) (and its extension, Essential Ecosystem Service Variables, ESSVs (*54*)), conceived as a space - time - biodiversity element cube (Fig 1), where space and time are represented as single pixels of standard size and models provide standardized quality predictions across all pixels. EBVs are typically made possible through remote sensing, addresses the status and condition of all members of a defined group of biodiversity entities, functions, or services (e.g. all mammals, trees, Typology Level 5 ecosystems, canopy structural attributes, or net primary productivity, etc.). When completed at appropriate quality and scope and sufficiently fine spatial grain, EBVs are foundational to any biodiversity information use case. By definition, pixels in the EBV cube are fully comparable, ‘apples to apples’, for different places in space and time, and EBVs can thus be used to flexibly assess few or many single locations or to provide support planning and decisions over large areas and global portfolios. For each biodiversity element, aggregated across all its locations, EBVs directly deliver a quantitative estimate of the global status and trends. And for each location, aggregated for all biodiversity elements, EBVs provide the status of each element. EBV production requires massive data harmonization and integration, across e.g. thousands of species or ecosystem types, and appropriate statistical computational methods to be derived at a fine scale along with uncertainty capture. Finally, EBVs directly support mapping and spatial planning across large regions.

An existing qualitative approach to delineating Global Biodiversity Significance or Status can exist through expert-driven threat assessments, such as those conducted by Red List efforts globally in 5 to 15-year intervals. These assign high-priority biodiversity elements to threat categories (that are static in space) and in binary form delineate high-priority places. Such assessments are limited in spatiotemporal detail and miss critical nuances within and beyond priority cases, limiting their effectiveness and fitness for many measurement and decision purposes. But they are sufficient for several use cases, mobilize important information on threat drivers, and represent a helpful engagement of experts that leverages and in turn can contribute to EBV-based information development. Threat assessment and EBV approaches are thus complementary and synergistic, and there is strong potential for realizing synergies and maximizing the impact of expert knowledge. Global EBVs provide a structure for pooling data and limiting duplication (*55*), and delivering both Local and Global Biodiversity Values and supporting all measurement cases. EBVs unlock the enhanced availability of, and access to, consistent, global, location-specific, up-to-date biodiversity data which has been identified as a key technical priority needed for the private sector to play its role in halting and reversing biodiversity loss (*56*).

Challenges and Opportunities

1. Unlocking field data for Global Biodiversity Valuation

Global Biodiversity Values, and global EBVs in particular, deliver the quantitative, standardized common good required by all users and many use cases. Yet, no single entity collects even a small percentage of the field data required to address this need, and its compilation relies on data sharing and collaboration. While most beneficiaries of biodiversity information, perform data collection, their realized contributions to overall information are heterogeneous. Publicly shared data contributions are numerically vast in citizen science and have grown in academia thanks to journal and funding requirements, and many governments publish data through GBIF. GBF Target 21 commits parties to grow and make available biodiversity information, but the CBD and other international agreements do not directly require data sharing. IPLC-related data collection and sharing is guided by free, prior, and informed consent and requires consultative approaches. Businesses are rapidly growing collectors of biodiversity data in their locations, but to limit exposure, retain competitive advantage, and save costs, many prefer to keep data private. Although the TNFD stipulates transparency and disclosure and includes accessibility as data principle (*57*), it stops short of mandating data sharing and specific data standards. And while some jurisdictions require submission of biodiversity data into public repositories, e.g. for surveys required for permitting, this is inconsistent and often the exception. The commercial arena therefore stands out as key user and beneficiary of global data, but with limited stipulations to contribute.

Mechanisms to encourage or require appropriate contribution and standardization of data to the common good can help address these issues. Any local data producer, specifically those also requiring information on global significance, should be requested to contribute their data to global information production in some form. Secure digital sharing mechanisms and infrastructure allow for sensitive or otherwise private data to contribute to model-supported EBV development needing fully public data access. Mechanisms include requirements by industry regulators and business disclosure frameworks, legislation, and philanthropic funding to support better data capture and sharing structures.

2. Advancing Global Biodiversity Valuation and EBV Production

As with data collection, even though all information consumers are beneficiaries of Global Biodiversity Information, none are in a place to be producers of the compound information required. Global EBVs address both monitoring and decision-support use cases across scales of valuation and areas of interest. EBV implementation is gaining traction in near-continental contexts such as the European Union (*58*), and is advancing globally for species and ecosystem distributions. EBV's versatility comes with the requirement of immense data, expert, computational and methodological inputs and coordination in their production.

EBVs are a central common good and digital infrastructure and shared resourcing can support a more direct participation of information users and producers. Growing computational capabilities, AI-supported data integration, and advances in secure digital cloud infrastructure that enable more direct links to data production and expert engagement can now support a much stronger and concrete vision of global EBVs and Global Biodiversity Valuation than well over a decade ago when originally conceived. Incentives could be put in place to better link up qualitative global significance valuation (e.g. threat classification) approaches and quantitative EBV production efforts which currently are separate or even competing, despite obvious potential synergies.

3. Rewards, optimization, and sharing of expert engagement

Regional and thematic experts and their networks play a central role by curating data structures (such as taxonomies), standards, and quality and guiding both collection and integration. Usually, this work is delivered ad hoc for specific initiatives and sometimes more ongoingly in working groups. In almost all cases it is voluntary without financial rewards and often also with limited attribution and credits as data moves through to further integration and modelling. When experts are financially supported, e.g. contracted to prepare and analyze data, they tend to be kept private and detract rather than contribute to information advancements benefiting the public.

Expert contributions are also marked by inefficiencies, with data expert review and quality control and for the same biodiversity elements and locations conducted repeatedly and redundantly by different stakeholders, e.g. to produce species or ecosystem maps. Finally, due to their ad hoc and voluntary nature, expert contributions are often not captured in sufficiently standardized ways to most effectively benefit production of fit-for-purpose information.

Mechanisms to address this issue include a more direct recognition of expert service contributions in their own professional systems for career advancement, avenues to support a more explicit and consistent attribution of their work in downstream products, and targeted philanthropic support for expert networks and societies that aims to optimize contributions and limit redundancy.

4. Efficient data collection guided by information gaps and needs

When not required for environmental compliance purposes, the collection of field biodiversity data is largely untethered from information need and tends to follow collector group interests and the sociology, expertise, and locational and other preferences of their contributors (*59, 60*). Collectors tend to use metrics such as counts of records, area covered, or similar to measure and report data collection effort. The biodiversity data collection landscape is an evolving system of ongoing citizen science activity, readily deployed automated remote or local and increasingly AI-supported sensors, and focused data capture on specific locations or biodiversity of high interest. In this context, valuable data are those that strongly complement these existing data flows and address the most glaring gaps in the raw data cube of space, time, and biodiversity elements. More quantitatively, the most helpful data address pixels in the EBV cube with greatest uncertainty, as arising after the model-based combination with ancillary information such as remote sensing. Finally, it might instead be locations with the greatest projected change under different scenarios or those of interest to the greatest number of users that should receive data collection priority. In all cases, communication, coordination and direct collaboration between information user, information producer, and data collector communities is a hitherto mostly untapped opportunity to increase collection efficacy and biodiversity information at large. With immense redundancy in current local biodiversity collection, there is potential to steer at least a small portion of ongoing collection efforts to be more effective, thus radically increasing its value. EBVs enable a credible re-envisioning of the “same metrics, same methods, everywhere” approach to biodiversity measurement that has gained some traction in private sector space, instead focusing effort and resources where they are needed most.

Next steps

Several opportunities for concrete initiatives within the scope of science-policy and funding organizations emerge that leverage new science and technology and add key capacity to unlock progress.

Collaborative infrastructure for national and regional hubs. Countries are the sovereigns in charge of their nature assets with a direct interest and activities addressing their measurement. Especially in smaller nations and marine systems much of biodiversity crosses borders, and thus larger, regional-scale perspectives are needed to address a more complete biodiversity scope and bring together relevant data collectors, information producers, and users. Regional center could serve such a purpose (e.g. (*61*)) and be catalysts for ensuring data collection networks are supported and incentivized around overall knowledge needs. At present, the compound contribution of sub-global nodes is limited by variable and insufficient capacity and lack of structures for effective and standardized biodiversity data and information capture. The vision of Biodiversity Observation Networks organized under a global system offers the potential for more coordinated data collection (*9*). We suggest extending this to include shared and streamlined digital infrastructures that allow data collection to directly tie into and benefit from thematically focused and larger-scale monitoring efforts. While retaining ownership and privacy when necessary, distributed infrastructure linked to common backbone can provide the efficiencies in data collection, preparation, harmonization and information production and help unlock benefits through effective decision-support tools.

Formalized support for thematic integration hubs. We suggest that regional centers be directly partnered with cross-cutting global hubs that bring together relevant technologies and expertise. These have a focus on standardized data integration and co-development and curation of information products with end-users. Overarching themes could follow the major classes of EBVs, such as species populations or ecosystem structure etc. and further organized into expert networks and technology initiatives that in partnership provide the knowledge and solutions to the steps leading to biodiversity information products. Thematic hubs support biodiversity measurement from local to global scale and significance and support a feedback loop between national and regional data collection and global progress and needs. A key goal of thematic hubs is to support experts with structures that increase the efficacy and recognition of their central recognition.

End-to-end initiatives. We suggest rapidly conducting several projects that fully address select biodiversity dimensions and biodiversity information use cases end-to-end. These would at a minimum serve as a “proof of concept” or become fully-fledged missions or initiatives to effectively link biodiversity data from providers to end users and institutions at local, regional or global scales. The efforts could address several different use case types to demonstrate specifications and enabling conditions unique to different user groups (e.g., local communities, agricultural companies, government agencies). They would help identify: best practices for operationalizing the “data to impact” value chain; lessons learned for how to connect different institutions and systems operating within jurisdictions; possible new “lynchpin” data sets needed to unlock impact; processes to coordinate, consolidate, and align data collection process with user needs.

A global biodiversity warning system. We suggest producing near real-time alarm systems coupled with initiatives that support activism and campaigning. Infrastructure developed with technology and remote sensing partners could provide short-term information or forecasts on specific biodiversity elements (*62*). This can include warning systems and local biodiversity ‘alarms,’ a ‘Biodiversity Watch’ system akin to the World Resource Institute’s Global Forest Watch, which highlights places of particular global concern with recent or expected impact. Such a system would replicate or scale existing efforts which combine the best available remote sensing and aerial data to make timely reports and be most powerful when directly linked to related efforts for advocacy and intervention in policy, business and other societal areas. Such initiatives could collaborate with local organizations to mobilize around hotspots, launch targeted campaigns, and mobilize the local public around local verification and advocacy.

BOX 1: Innovations in biodiversity sensing

A range of recent innovations in science and technology transform data collection and integration.

Novel acoustic and visual sensors and monitoring devices, increasingly with remote data access and onboard processing, are bringing about a new era for local biodiversity sensing (*63, 64*). Combined with AI- supported avenues for biodiversity detection and identification, this offers a scalable solution for collecting biodiversity data through more actors and from more locations, time points, and taxa or ecosystems (*65*). Hyperspectral and lidar sensors that can directly capture structural and functional biodiversity data are becoming more accessible. Deployment, data and metadata standardization and sharing, obstacles to AI-supported identification, and restriction to audiovisual detection remain limitations.

Citizen science, although often reporting on much of the same accessible locations and readily identified species (*66, 67*), is reaching ever more people, places, and ultimately biodiversity (*68*). Important next developments include: - the scaled-up use of emerging sensors and devices to capture data beyond species presences to address quality and potentially functional aspects of biodiversity and include genetic dimensions; - new computational tools and field-guide apps for improved and quantified quality of identification; - collection campaigns and incentives that are directly linked to data needs and remain uncertainties as emerging biodiversity information products such as EBVs. Collaborations between the citizen science and information production communities will be key.

Environmental DNA (eDNA) combined with next-generation sequencing is rapidly growing powerful means of regional to local species detection (*69, 70*). Sample processing requirements and costs continue to fall, and first fully effective in-field workflows using nanopore sequencing have been successfully demonstrated. Key remaining constraints include: incomplete and biased libraries for species identification (*71*); - a restriction to taxa, conditions and environments that provide readily accessible eDNA; - in cases such as samples derived from water or airborne DNA lack of spatial specificity (*71*); and lab processing logistics. Yet, further innovations here are likely to support a scaled-up use of eDNA for local biodiversity sampling in a way that complements other data types.

New satellite- and UAV-based data flows are poised to contribute ever greater and more relevant data for biodiversity measurement. New earth observation missions are offering expanded and more highly resolved radar and hyperspectral data (*45*). And UAVs are rapidly growing means to collect data at spatial resolutions and extent in between ground-based and remote sensing with demonstrated ability to rapidly and cost-effectively capture biodiversity in complex and inaccessible environments (*72, 73*). With increasing training data and AI methodology, direct detection, identification and monitoring of select species and specific ecosystems and their functional and structural attributes, satellite-, UAV-based and other airborne sampling will strongly enhance biodiversity measurement (*74*).

AI-based and other computational advances in data mobilization, imputation, harmonization, and quality control. Rapidly growing amounts of data of different types and from heterogeneous sources represent an increasing challenge to prepare and validate. Computational tools with human-in-the loop and reinforcement learning can offer critical avenues to make limited expert capacity maximally effective. In data integration and modelling, innovations in deep learning hold immense promise for improving the coverage and robustness of biodiversity information (*75*). This includes foundation models to leverage vast remote sensing data (*76*) and ‘borrowing strength’ or imputation approaches to support the inclusion of under-sampled biodiversity in EBV production (*77*). Dedicated capacity and innovative partnerships are needed to identify, transfer, and adapt the most promising of emerging methods and technologies to benefit the development of biodiversity information products.

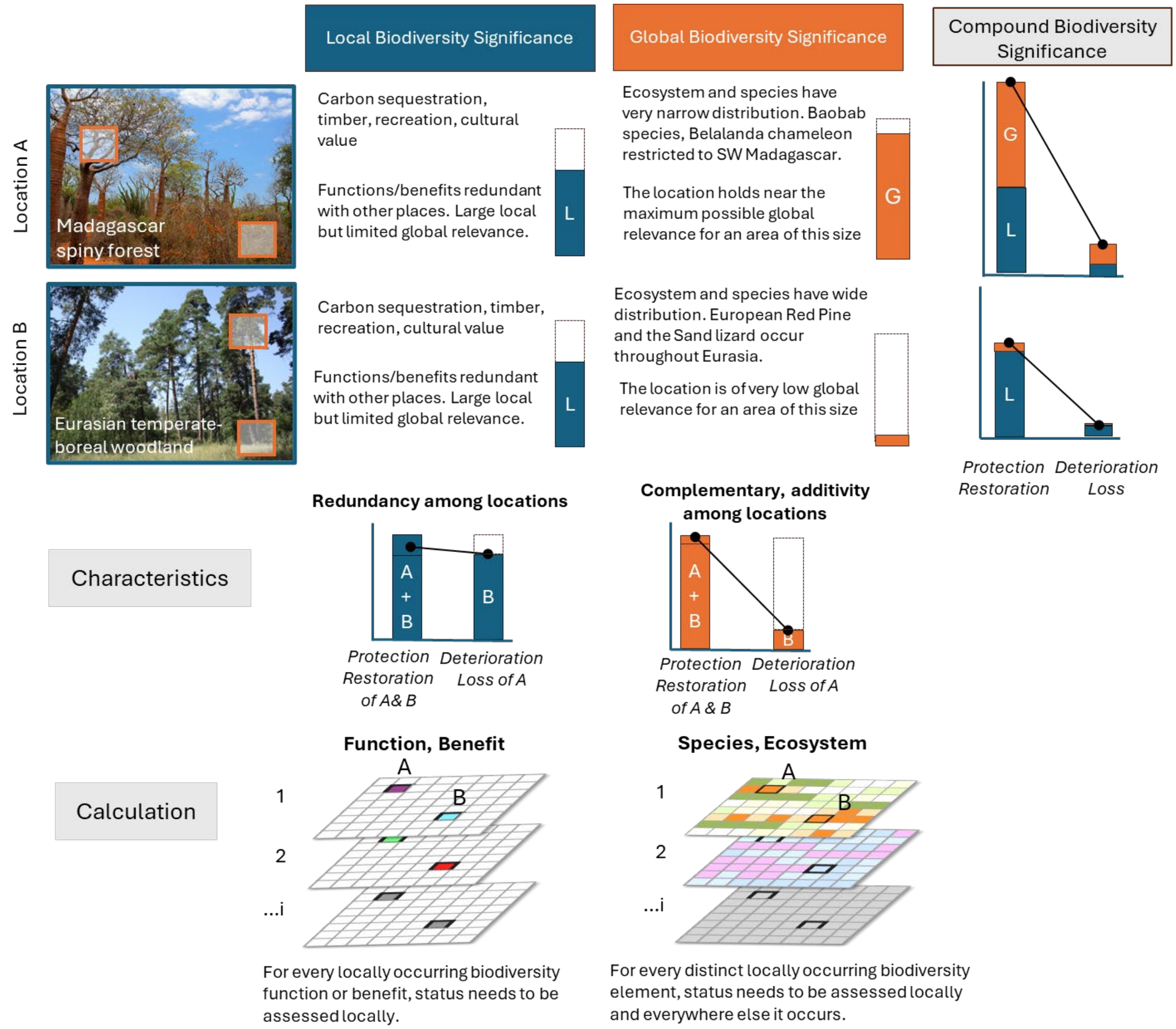


Figure 1: Biodiversity significance of locations is composed of local and global values. Their absolute and relative amounts differ geographically and determine the compound impact any change in condition will have. High-integrity locations deliver greater functions and benefits, and greater suitability for species and ecosystems. Photo credits: Anna Kuzemko (FloraVeg.EU), JialiangGao (www.peace-on-earth.org).

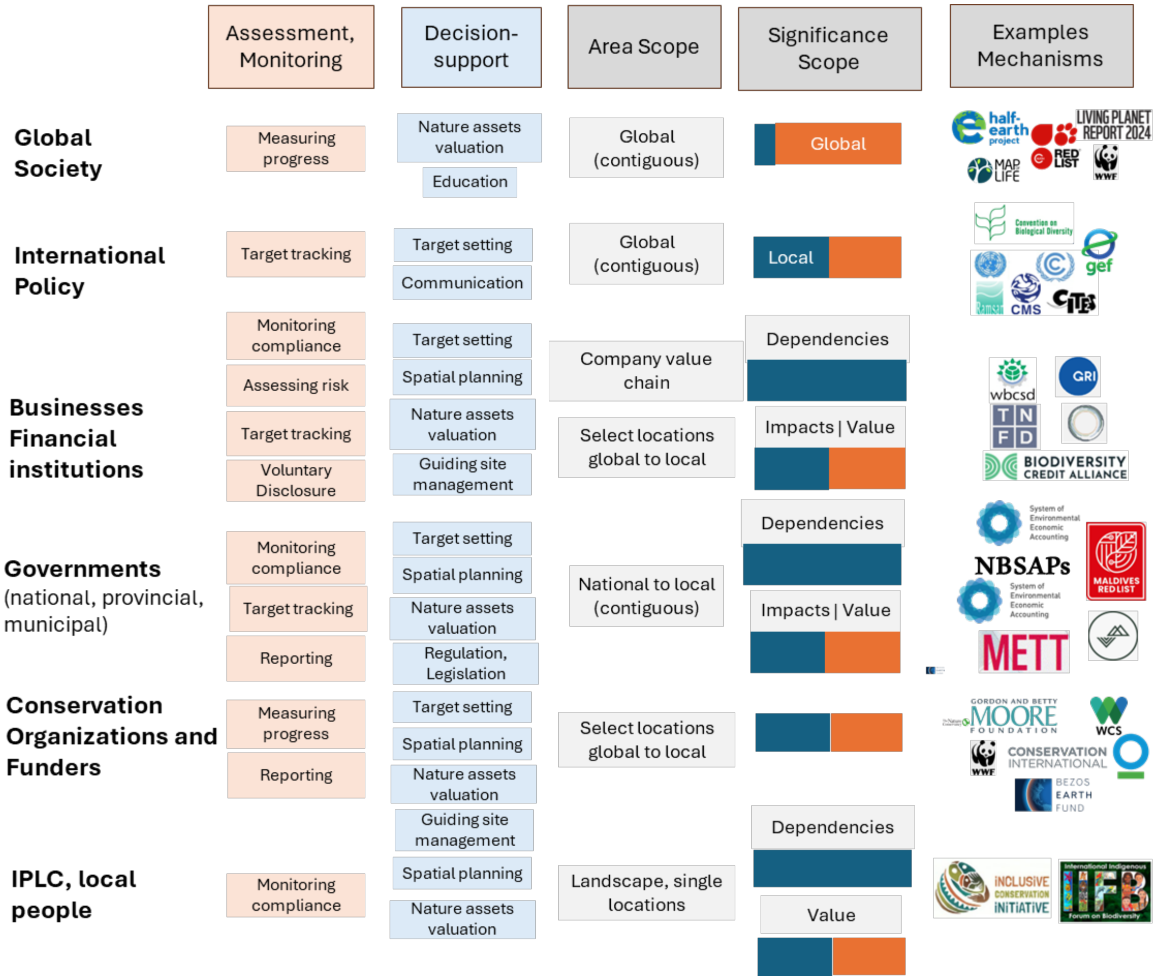
Species		
GBF	**Goal A**	Species extinction rate and risk Health and resilience of abundance levels* Genetic diversity, adaptive potential*
	Target 4: Species recovery	Species extinction risk | Species threats | Genetic Diversity* Human-wildlife interactions and conflict
	Target 5: Exploitation of species	Harvesting sustainability, safety, legality| Non-target species and ecosystem impacts | Ecosystem Approach*
Nature +	Indicator 6	Extinction risk
	Indicator 7	Priority and Population Abundance

Ecosystems		
GBF	**Goal A**	Ecosystem integrity, connectivity, resilience* Area of natural ecosystems
	Target 2: Ecosystem Restoration	Restoration effectiveness | Ecological integrity and connectivity* | Biodiversity and ecosystem functions and services
Nature +	Indicator 1	Extent: Extent by class and priority
	Indicator 2	Extent: In intensive land-use areas: Prop. of semi-/natural habitat
	Indicator 3	Condition: Condition of each ecosystem by class and priority
	Indicator 4	Condition: Condition of landscape: landscape intactness*, structural connectivity*, functional connectivity*
	Indicator 5	Condition: In intensive land-use areas: condition of semi-/natural habitat

Reducing threats		
GBF	**Target 1:** Spatial planning and effective management	Integrated and biodiversity inclusive | High ecological integrity * High biodiversity importance
	Target 3: Protected and conserved area (30x30)	Important for biodiversity and ecosystem functions and services | Ecological representativenes Effectiveness of Conservation and Management | Use Sustainabiltiy | Connectivity*
	Target 6: Invasive alien species	Invasive alien species | Prioritization | Pathway Identification and Management Preventing introduction and establishment | Eradicating or controlling
	Goal B	Sustainability of biodiversity use and management Nature benefits: Ecosystem functions and services*
	Target 7: Pollution and biodiversity	Harm on biodiversity and ecosystem functions and services*
	Target 8: Climate Change and biodiversity	Climate change/action impacts on biodiversity

Sustainable use and benefit-sharing		
GBF	**Target 9:** Sustainable use and management of wild species	Species use sustainability
	Target 10: Sustainable managemeny of key productive sectors	Biodiversity-friendly practices | Nature benefits: Ecosystem functions and services*
	Target 11: Ecosystem services and functions	Nature benefits: Ecosystem functions and services* | Nature-based solutions and/or ecosystem-based approaches
	Target 12: Urban blue and green spaces	Biodiversity-inclusive planning

Figure 2: Varying needs for information on global (red) vs. only local (blue) biodiversity value (status) metrics across elements of the Global Biodiversity Framework (GBF) and the draft Nature Positive Indicators. * denotes potential need for land-/seascape information beyond focal locations.



	Assessment, Monitoring	Decision-support	Area Scope	Significance Scope	Examples Mechanisms
Global Society	Measuring progress	Nature assets valuation Education	Global (contiguous)	🟦🟧🟧🟧 Global	half-earth project LIVING PLANET REPORT 2024 RED LIST MAP LIFE WWF
International Policy	Target tracking	Target setting Communication	Global (contiguous)	Local 🟦🟦🟧🟧	Convention on Biological Diversity gef CMS CITES
Businesses Financial institutions	Monitoring compliance Assessing risk Target tracking Voluntary Disclosure	Target setting Spatial planning Nature assets valuation Guiding site management	Company value chain Select locations global to local	Dependencies 🟦🟦🟦🟦 Impacts | Value 🟦🟦🟧🟧	wbcsd GRI TNFD BIODIVERSITY CREDIT ALLIANCE
Governments (national, provincial, municipal)	Monitoring compliance Target tracking Reporting	Target setting Spatial planning Nature assets valuation Regulation, Legislation	National to local (contiguous)	Dependencies 🟦🟦🟦🟦 Impacts | Value 🟦🟦🟧🟧	System of Environmental Economic Accounting NBSAPs MALDIVES RED LIST METT
Conservation Organizations and Funders	Measuring progress Reporting	Target setting Spatial planning Nature assets valuation Guiding site management	Select locations global to local	🟦🟦🟧🟧	GORDON AND BETTY MOORE FOUNDATION WCS WWF CONSERVATION INTERNATIONAL BEZOS EARTH FUND
IPLC, local people	Monitoring compliance	Spatial planning Nature assets valuation	Landscape, single locations	Dependencies 🟦🟦🟦🟦 Value 🟦🟦🟧🟧	INCLUSIVE CONSERVATION INITIATIVE International Indigenous Forum on Biodiversity IIFB

Figure 3: The information type and scopes associated with different users and use cases for biodiversity information.

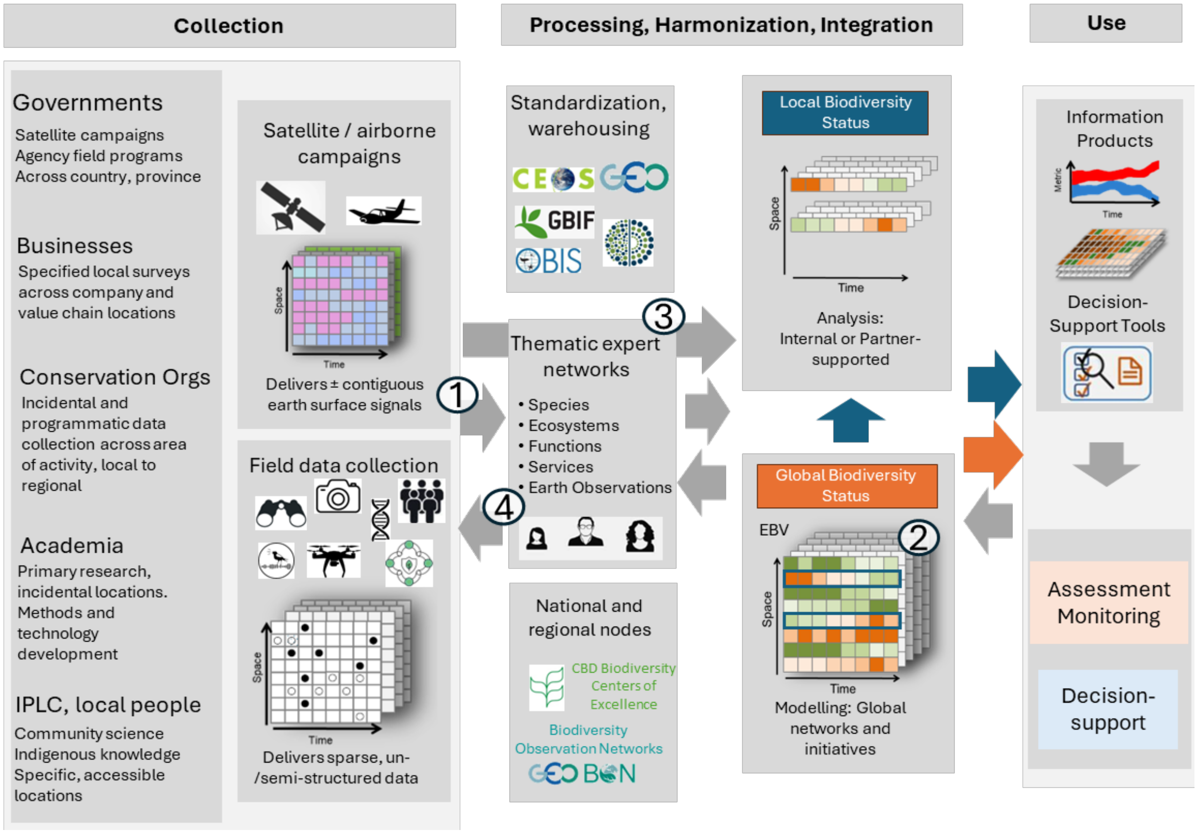


Figure 4: Addressing biodiversity information needs through data collection, and integration. Numbers refer to highlighted challenges and opportunities: 1. Unlocking field data addressing both Local and Global Biodiversity Status; 2. Advancing Global Biodiversity Valuation and EBV Production; 3. Rewards, optimization, and sharing of expert engagement; 4. Efficient data collection guided by information gaps and needs.

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References

1. D. Leclère *et al.*, Bending the curve of terrestrial biodiversity needs an integrated strategy. *Nature* **585**, 551-556 (2020).
2. IPBES, "Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Service," (IPBES Secretariat, Bonn, Germany, 2019).
3. B. J. Cardinale *et al.*, Biodiversity loss and its impact on humanity. *Nature* **486**, 59-67 (2012).
4. S. M. Díaz *et al.*, The global assessment report on biodiversity and ecosystem services: Summary for policy makers. (2019).
5. H. M. Pereira *et al.*, Global trends and scenarios for terrestrial biodiversity and ecosystem services from 1900 to 2050. *Science* **384**, 458-465 (2024).
6. U. CBD, in *Fifteenth meeting of the Conference of the Parties to the Convention on Biological Diversity (Part Two) Decision 15/4.* (2022).
7. https://www.cbd.int/gbf/related/monitoring
8. J. E. M. Baillie *et al.*, Toward monitoring global biodiversity. *Conservation Letters* **1**, 18-26 (2008).
9. A. Gonzalez *et al.*, A global biodiversity observing system to unite monitoring and guide action. *Nature Ecology & Evolution*, 1-5 (2023).
10. V. Proença *et al.*, Global biodiversity monitoring: from data sources to essential biodiversity variables. *Biol Conserv* **213**, 256-263 (2017).
11. L. M. Navarro *et al.*, Monitoring biodiversity change through effective global coordination. *Current Opinion in Environmental Sustainability* **29**, 158-169 (2017).
12. H. S. Kühl *et al.*, Effective Biodiversity Monitoring Needs a Culture of Integration. *One Earth* **3**, 462-474 (2020).
13. G. C. Daily *et al.*, Ecosystem services in decision making: time to deliver. *Frontiers in Ecology and the Environment* **7**, 21-28 (2009).
14. C. K. Feld, J. P. Sousa, P. M. da Silva, T. P. Dawson, Indicators for biodiversity and ecosystem services: towards an improved framework for ecosystems assessment. *Biodivers Conserv* **19**, 2895-2919 (2010).
15. I. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Methodological assessment of the diverse values and valuation of nature of the

Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. *Zenodo*, (2022).

16. L. Hein, K. van Koppen, R. S. de Groot, E. C. van Ierland, Spatial scales, stakeholders and the valuation of ecosystem services. *Ecological Economics* **57**, 209-228 (2006).
17. R. Chaplin-Kramer *et al.*, Wildlife's contributions to people. *Nature Reviews Biodiversity* **1**, 68-81 (2025).
18. J. R. Prendergast, R. M. Quinn, J. H. Lawton, B. C. Eversham, D. W. Gibbons, Rare species, the coincidence of diversity hotspots and conservation strategies. *Nature* **365**, 335-337 (1993).
19. R. Chaplin-Kramer *et al.*, Global modeling of nature's contributions to people. *Science* **366**, 255-258 (2019).
20. W. Jetz *et al.*, Include biodiversity representation indicators in area-based conservation targets. *Nature Ecology & Evolution* **6**, 123-126 (2022).
21. K. Jantke, C. D. Kuempel, J. McGowan, A. L. M. Chauvenet, H. P. Possingham, Metrics for evaluating representation target achievement in protected area networks. *Divers. Distrib.* **25**, 170-175 (2019).
22. J. McGowan *et al.*, Conservation prioritization can resolve the flagship species conundrum. *Nature Communications* **11**, 994 (2020).
23. R. I. Vane-Wright, C. J. Humphries, P. H. Williams, What to protect?--Systematics and the agony of choice. *Biol Conserv* **55**, 235-254 (1991).
24. G. Kier *et al.*, A global assessment of endemism and species richness across island and mainland regions. *Proceedings of the National Academy of Sciences* **106**, 9322 (2009).
25. W. Jetz *et al.*, Essential biodiversity variables for mapping and monitoring species populations. *Nature Ecology & Evolution* **3**, 539-551 (2019).
26. C. R. Margules, R. L. Pressey, Systematic conservation planning. *Nature* **405**, 243-253 (2000).
27. A. Moilanen, K. A. Wilson, H. Possingham, *Spatial conservation prioritization: quantitative methods and computational tools*. (Oxford University Press, 2009).
28. https://tnfd.global
29. https://capitalscoalition.org/project/align/
30. http://sciencebasedtargetsnetwork.org
31. https://www.naturepositive.org
32. https://www.naturepositive.org/app/uploads/2025/02/Draft-State-of-Nature-Metrics-for-Piloting_170125.pdf
33. H. Kim *et al.*, Towards a better future for biodiversity and people: Modelling Nature Futures. *Global Environmental Change* **82**, 102681 (2023).
34. https://map.half-earthproject.org/
35. https://www.iucnredlist.org/
36. https://www.stockholmresilience.org/research/planetary-boundaries.html
37. https://livingplanet.panda.org
38. N. D. Burgess *et al.*, Global metrics for terrestrial biodiversity. *Annual Review of Environment and Resources* **49**, 673-709 (2024).
39. https://www.pwc.com/gx/en/strategy-and-business/content/sbpwc-2023-04-19-Managing-nature-risks-v2.pdf
40. https://tnfd.global/wp-content/uploads/2023/09/TNFD-Glossary-of-terms-V3.0-January-2025.pdf
41. https://www.businessfornature.org/high-level-business-actions-on-nature
42. R. J. Scholes *et al.*, Building a global observing system for biodiversity. *Current Opinion in Environmental Sustainability* **4**, 139-146 (2012).

43. H. Tallis *et al.*, Prioritizing actions: spatial action maps for conservation. *Annals of the New York Academy of Sciences* **1505**, 118-141 (2021).

44. C. F. Randin *et al.*, Monitoring biodiversity in the Anthropocene using remote sensing in species distribution models. *Remote Sensing of Environment* **239**, 111626 (2020).

45. J. Cavender-Bares *et al.*, Integrating remote sensing with ecology and evolution to advance biodiversity conservation. *Nature Ecology & Evolution*, (2022).

46. M. Chapman *et al.*, Biodiversity monitoring for a just planetary future. *Science* **383**, 34-36 (2024).

47. C. Meyer, W. Jetz, R. P. Guralnick, S. A. Fritz, H. Kreft, Range geometry and socio-economics dominate species-level biases in occurrence information. *Glob. Ecol. Biogeogr.* **25**, 1181-1193 (2016).

48. R. Guralnick, R. Walls, W. Jetz, Humboldt Core – toward a standardized capture of biological inventories for biodiversity monitoring, modeling and assessment. *Ecography* **41**, 713-725 (2017).

49. J. Wieczorek *et al.*, Darwin Core: An Evolving Community-Developed Biodiversity Data Standard. *PLoS ONE* **7**, e29715 (2012).

50. J. M. Heberling, J. T. Miller, D. Noesgaard, S. B. Weingart, D. Schigel, Data integration enables global biodiversity synthesis. *Proceedings of the National Academy of Sciences* **118**, e2018093118 (2021).

51. E. L. Sandall *et al.*, A globally integrated structure of taxonomy to support biodiversity science and conservation. *Trends Ecol Evol*, (2023).

52. A. e. a. Gonzalez, From Data to Decisions: Towards a Biodiversity Monitoring Standards Framework. *ecoEvoRxiv*, (2025).

53. H. M. Pereira *et al.*, Essential Biodiversity Variables. *Science* **339**, 277-278 (2013).

54. P. Balvanera *et al.*, Essential ecosystem service variables for monitoring progress towards sustainability. *Current Opinion in Environmental Sustainability* **54**, 101152 (2022).

55. G. M. Mace *et al.*, It's time to work together and stop duplicating conservation efforts. *Nature* **405**, 393-393 (2000).

56. E. J. McKenzie, M. Jones, N. Seega, J. Siikamäki, V. Vijay, Science and technical priorities for private sector action to address biodiversity loss. *Philosophical Transactions of the Royal Society B: Biological Sciences* **380**, 20230208 (2025).

57. TNFD, "A roadmap for upgrading market access to decision-useful nature-related data," (2024).

58. M. Lumbierres *et al.*, Towards implementing workflows for essential biodiversity variables at a European scale. *Global Ecology and Conservation* **62**, e03699 (2025).

59. C. Meyer, H. Kreft, R. Guralnick, W. Jetz, Global priorities for an effective information basis of biodiversity distributions. *Nature Communications* **6**, 8221 (2015).

60. B. H. Daru, J. Rodriguez, Mass production of unvouchered records fails to represent global biodiversity patterns. *Nature Ecology & Evolution* **7**, 816-831 (2023).

61. https://www.cbd.int/article/sbi4-regional-centres-implementation-2024

62. A. Antonelli, K. L. Dhanjal-Adams, D. Silvestro, Integrating machine learning, remote sensing and citizen science to create an early warning system for biodiversity. *PLANTS, PEOPLE, PLANET* **5**, 307-316 (2023).

63. D. Teixeira *et al.*, Effective ecological monitoring using passive acoustic sensors: Recommendations for conservation practitioners. *Conservation Science and Practice* **6**, e13132 (2024).

64. S. Pringle *et al.*, Opportunities and challenges for monitoring terrestrial biodiversity in the robotics age. *Nature Ecology & Evolution* **9**, 1031-1042 (2025).

65. T. Gadot *et al.*, To crop or not to crop: Comparing whole-image and cropped classification on a large dataset of camera trap images. *IET Computer Vision* **18**, 1193-1208 (2024).
66. F. A. La Sorte, J. M. Cohen, W. Jetz, Data coverage, biases, and trends in a global citizen-science resource for monitoring avian diversity. *Divers. Distrib.* **30**, e13863 (2024).
67. A. Johnston, E. Matechou, E. B. Dennis, Outstanding challenges and future directions for biodiversity monitoring using citizen science data. *Methods in Ecology and Evolution* **14**, 103-116 (2023).
68. M. Chandler *et al.*, Contribution of citizen science towards international biodiversity monitoring. *Biol Conserv* **213**, 280-294 (2017).
69. F. Altermatt *et al.*, Utilizing aquatic environmental DNA to address global biodiversity targets. *Nature Reviews Biodiversity*, 1-15 (2025).
70. K. Deiner *et al.*, Environmental DNA metabarcoding: Transforming how we survey animal and plant communities. *Molecular ecology* **26**, 5872-5895 (2017).
71. V. Marques *et al.*, GAPeDNA: Assessing and mapping global species gaps in genetic databases for eDNA metabarcoding. *Divers. Distrib.* **27**, 1880-1892 (2021).
72. M. R. Popp, J. M. Kalwij, Consumer-grade UAV imagery facilitates semantic segmentation of species-rich savanna tree layers. *Scientific Reports* **13**, 13892 (2023).
73. S. Ecke *et al.*, UAV-Based Forest Health Monitoring: A Systematic Review. *Remote Sensing* **14**, 3205 (2022).
74. M. Conciatori *et al.*, Plant Species Classification and Biodiversity Estimation from UAV Images with Deep Learning. *Remote Sensing* **16**, 3654 (2024).
75. L. J. Pollock *et al.*, Harnessing artificial intelligence to fill global shortfalls in biodiversity knowledge. *Nature Reviews Biodiversity*, (2025).
76. C. F. Brown *et al.*, AlphaEarth Foundations: An embedding field model for accurate and efficient global mapping from sparse label data. *arXiv preprint arXiv:2507.22291*, (2025).
77. S. Sharma *et al.*, No species left behind: borrowing strength to map data-deficient species. *Trends Ecol Evol*.