Global metrics for terrestrial biodiversity

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Abstract

Biodiversity metrics are increasingly in demand for informing government, businesses, and civil society decisions. However, while there are many metrics available, it is not always clear to end-users how they differ or for what purpose they are best suited. This confusion undermines uptake. Here, we seek to clarify these questions by reviewing and presenting a database of 573 biodiversity-related metrics, indicators, indices and layers (hereafter 'metrics'). Of these metrics, 227 are spatial data layers and 272 are temporal indicators. Assessed in relation to the pressure-state-response-benefits framework, 213 address only state, 118 address only pressures, 124 address only responses and 8 address only benefits. The remaining 110 relate to combinations of the four. Among the state indicators, 217 are bottom-up metrics (aggregated from individual components), 57 top-down (compiled through extrapolation), 8 are neither, and 1 is both; while 61 measure significance ('biodiversity importance') 86 intactness ('biodiversity condition'), 5 both, and 131 are neither. These metrics address aspects of genetic diversity (19), species (106) and ecosystems (214), with 38 covering more than one aspect and 196 being general metrics. Considering complementarity across these characteristics, we recommend a small number of metrics considered most pertinent for use in decision-making by governments and businesses. We conclude by highlighting five future directions: increasing the importance of national metrics, ensuring wider uptake of business metrics, agreeing a minimum set of metrics for government and business use, automation of metric calculation through use of technology, and generating sustainable funding for metric production.

Contents

1 Introduction

In recent years, governments, civil society, and business have made a series of pledges and commitments to address the dual climate and biodiversity crises. These have been seen at the 15th meeting of the Conference of the Parties (COP15) to the Convention on Biological Diversity (CBD), the UN Framework Convention on Climate Change (UNFCCC), the 2030 Agenda for Sustainable Development and its Sustainable Development Goals (SDGs), as well as at private sector-facing events like the World Economic Forum (WEF).

At CBD COP15, Parties to the CBD adopted a package of decisions related to the Kunming-Montreal Global Biodiversity Framework (GBF), which contains 4 goals, 23 targets and an associated monitoring framework comprising a suite of headline indicators, component and complementary indicators (Box 1). The GBF complements mechanisms under the other biodiversity-related conventions and adds specificity to SDG 14 (life below water) and SDG 15 (life on land) and their associated 24 indicators. Together, these form the political basis for international action to conserve biodiversity and its contributions to people, driving progress towards implementation of actions by 2030 and achievement of goals by 2050 (1).

The GBF goals focus on outcomes (e.g. the state of biodiversity) while the targets focus on actions (e.g. to reduce the threats to biodiversity, how it can be sustainably used to provide equitable benefits for people, and how to ensure that there is sufficient finance and capacity to deliver the adopted decisions) (1). To guide implementation and measure progress towards the goals and targets, robust biodiversity metrics are required for the monitoring framework of the GBF (2), and the SDG indicators framework (3), with both aiming to measure progress towards global sustainability aspirations.

Box 1: The Kunming-Montreal Global Biodiversity Framework and associated package of decisions

The Kunming-Montreal Global Biodiversity Framework (GBF) (Decision 15/4) was adopted during the fifteenth meeting of the Conference of the Parties (COP 15). This historic Framework builds on previous strategic plans under the CBD, and sets out an pathway to reach the global vision of a world living in harmony with nature by 2050.

The implementation of the GBF is supported through a package of decisions adopted alongside the GBF, at CBD COP15. The package includes a monitoring framework (Decision 15/5), an enhanced multidimensional approach for planning, monitoring, reporting and review of implementation of the GBF (Decision 15/6), a series of decisions relating to the means of implementation that will be necessary to enable an effective implementation of the framework (resource mobilization – Decision 15/7-, capacity building and development and technical and scientific cooperation –Decision 15/8), and finally, an agreement regarding the fair and equitable sharing of benefits from the use of digital sequence information on genetic resources (Decision 15/9).

Parties to the CBD committed to implementation of the GBF and related decisions through aligned national targets in their revised national biodiversity strategies and action plans (NSBAPs). A global analysis of national targets submitted by the next meeting of the Conference of the Parties (CBD COP16) will be made available for discussion. Later on, at CBD COP17, a global review of collective progress in implementation of the Framework will be discussed. In this context, the monitoring of implementation by governments, and other stakeholders will be essential to understand the progress that has been made towards the 2030 targets. Robust metrics, used by Parties and non-state actors will be key input to the global review of collective progress.

Furthermore, the need for business and financial institutions to measure their impacts and dependencies on biodiversity continues to grow in response to investor, regulatory and societal pressure (4, 5). Increasing numbers of businesses are calling for greater ambition from governments and have made commitments to implement the agreements made at climate and biodiversity COPs, with over 5,800 businesses setting climate targets aligned to the Paris Climate Agreement and over 1,400 calling for action on biodiversity at CBD COP15. Several voluntary and mandatory frameworks and standards are emerging to support nature-related assessments, disclosures and target-setting by businesses. Examples of voluntary frameworks and standards include the Taskforce on Nature-related Financial Disclosures (TNFD) (focused on nature in general), the Science Based Targets Network (focused on freshwater and land),the IUCN Nature Positive Initiative (focused on biodiversity) and the Global Reporting Initiative (GRI) Standards (focused on sustainability including dedicated standards for selected environmental issues).

Mandatory regulatory requirements, which apply to business and the trade system between governments, are also emerging. These can be seen, for example, in the European Union (EU) Due Diligence Directive, Deforestation Regulation, Corporate Sustainability Reporting Directive, and France's Article 29. The International Finance Corporation's Performance Standard 6 on Biodiversity, widely adopted by the regional development banks and the Equator Principles financial institutions, adds momentum by making access to capital dependent on biodiversity metrics and reporting. The International Sustainability Standards Board (ISSB) general sustainability disclosure and climate disclosure standards are expected to be mandated in jurisdictions across the globe over time. The International Standards Organisation (ISO) has now established a Technical Committee 331 on Biodiversity.

As political and business commitments have been established, and scientists have increasingly engaged in these processes, numerous metrics (systems or standards of measurement) for biodiversity have been proposed and conceptualised. Many of these have been developed into readily available tools and data layers for application by users. This proliferation of metrics (and tools delivering them) makes it difficult for end users to know are the most reliable, scientifically robust and appropriate for different use cases (6). This problem is exacerbated by the complexity of many metrics, and the inaccessibility of their methodologies and/or underlying data.

In this review, we present an assessment of available biodiversity metrics, indicators, indices (collectively termed "metrics" from now on), which have been developed for use in decision-making by governments, businesses, financial institutions and civil society (Annex 1). We distinguish these metrics from the scientific discussion on the different ways of quantifying biodiversity change (e.g., 7).

All metrics were reviewed against the causal-chain State, Pressure, Response and Benefit (SPRB) framework, widely used for identification and reporting against indicators (8–10) (Box 2; Figure 1).

Box 2: State, Pressure, Response and Benefit (SPRB) framework

The SPRB framework was adapted from the Organisation for Economic Co-operation and Development (OECD) ”Pressure-State-Response” model (11, 12), and was adopted by the CBD to guide indicator development (13). This framework links changes in the **state** or condition of biodiversity (e.g., habitat extent, species’ extinction risk), with the **pressures** resulting from human activities (e.g., agriculture, pollution, invasive alien species, species utilisation). Society then **responds** to these by implementing environmental and economic policies or actions, intended to reduce or mitigate the pressures, and this recover the state of the natural resource. These responses should in turn improve the **benefits** that humans derive from the environment (e.g., pollination, air quality, scenic beauty), also known as “ecosystem services” or “nature’s contributions to people”. The inclusion of this fourth category is important in the context of biodiversity policy and practice and justifies our use of the SPRB framework rather considering only State-Pressure-Response. However, we did not use the expanded “drivers, pressures, state, impact and response” (DPSIR) model as drivers and pressures are hard to separate Among metrics of the state of biodiversity, we also classify those derived from bottom-up relative to top-down approaches, and those measuring significance relative to those measuring intactness (14).

Box 3: Definition of key terms

Data: The structured information used to create metrics, indicators and indices.

Metric: A system or standard of measurement. For example, biodiversity observations, collected over space and/or time can be used to form a metric that tells us something about biodiversity – either directly (e.g. number of species observed), or indirectly (e.g. habitat extent). **In the context of this paper, we use “metric” to include indicators, indices and spatial data that provide information on pressure, state, responses or benefits.**

Indicators: Indicators are measures that are based on verifiable data that convey information beyond their own context. An **indicator** requires an external context, as they are purpose-dependent and so their interpretation depends on the issue being examined. To become an indicator, a **metric** must either a) be presented in the context of progress towards a target (e.g. the metric shows progress towards a target to increase forest extent by x%), or b) be used to assess the effectiveness of an intervention (e.g. changes in forest cover inside protected areas can be used to indicate the effectiveness of protected areas at maintaining or delivering greater forest extent).

Index: A numerical scale used to compare variables with one another or with some reference number. An index can be made from an aggregation of data, metrics or indicators (although aggregating data is recommended). Indices aim to reduce complexity into individual measure(s).

Platforms: These are systems, typically available online, that bring information to users. They may (or may not) have an associated metric. For the purposes of this review, we have focused on platforms with a biodiversity metric included. A sample of biodiversity-related platforms are listed in Annex 2.

For **State, Pressure, Response and Benefits** the following definitions are relevant:

Biodiversity state metrics quantify the condition of biodiversity (e.g., habitat extent, species extinction risk, ecosystem condition, genetic diversity).

Biodiversity pressure metrics quantify how and where biodiversity state is being impacted by pressures (e.g., agriculture, pollution, invasive alien species, species utilisation)

Biodiversity response metrics quantify policies or management actions that aim to reduce or mitigate the pressures or otherwise help recover the state of nature (e.g. establishment and management of protected areas, biosecurity, eradication, and management of invasive alien species, restoration interventions).

Biodiversity benefits metrics quantify what people derive from biodiversity (e.g., pollination for human crops, air quality for human health, scenic beauty for human enjoyment), otherwise known as ecosystem services.

Complementing these definitions, recent work has also introduced additional dimensionality to the classification of biodiversity metrics (14):

Bottom-up metrics are based on features measured at the level of an individual component of biodiversity (e.g. species within a class) and then aggregated.

Top-down metrics are measured by extrapolating or modelling biodiversity features from samples across a given ecological unit (ecosystem, habitat). Often the modelling includes the impacts caused by threats.

Intactness metrics measure biodiversity in a given place and time with respect to some pre-determined historical or spatial baseline (e.g. 1970, pre-human, when remote sensing data became available).

Significance metrics compare the relative importance of losses or gains in biodiversity across space and time.

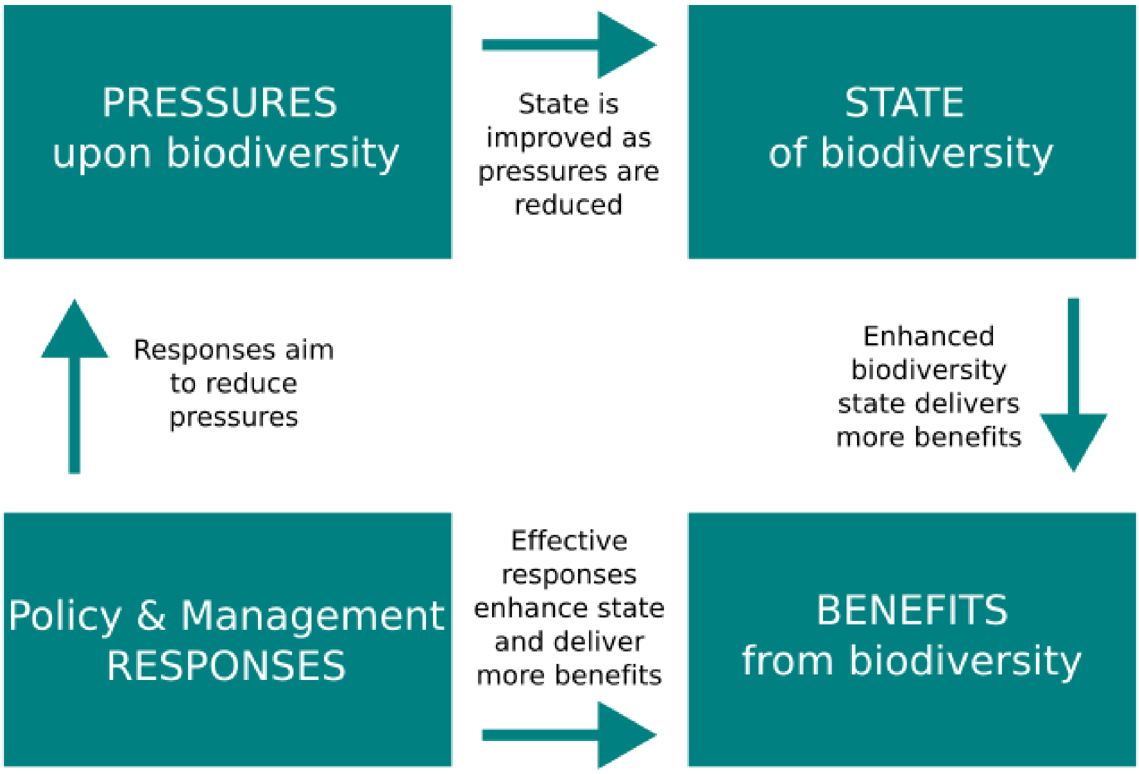

Figure 1. Graphical representation of the State-Pressure-Response-Benefits model often used in biodiversity measurement. Figure adapted with permission from Sparks et al. (8).

For this paper, we adopt the Convention on Biological Diversity (CBD) definition of biodiversity, which encompasses three different components: genetic diversity, species and ecosystems (Box 4). These components each contain a variety of different features that each requires different metrics to measure. For an overview of how biodiversity is defined across disciplines, as well as a review of the values, patterns and trends of biodiversity, see Díaz and Malhi (15).

Box 4: The three components of biodiversity and example features

According to the CBD: "Biological diversity" means the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems."

Components	Example features
Genes	Within species diversity, between species diversity (phylogenetic diversity)
Species	Extinction risk, Population abundance, changes in distribution
Ecosystems	Extent, condition, risk of collapse

We focus this review on terrestrial biodiversity metrics. This is partly because there are smaller bodies of work on metrics for freshwater (16–20) and for marine (10, 21–23). Nevertheless, many of the metrics we review do have application in these other biomes, sometimes with adjustments to the specific conditions in freshwater and marine systems.

2 Reviewing the Metrics

We compiled a database of biodiversity metrics (covering indicators, indices and relevant data layers: Annex 1). No formal literature search protocol was used.

Instead, we built our database from several existing lists. These included lists compiled of possible indicators to support the development of the monitoring framework for the GBF (24–27) based on information provided by the Biodiversity Indicators Partnership, an inventory of spatial datasets developed to support governments and business with spatial planning for biodiversity (28), an assessment of the role of remote sensing in spatial planning for biodiversity (29), and a review of top-down intactness compared to bottom-up significance metrics (14). These existing lists were first combined and standardised. We then added new metrics from an assessment of papers published in 2023 and early 2024. We removed platforms and databases that provide biodiversity data but lack an associated biodiversity metric (See Annex 2).

Each metric was assessed by NB and MH in terms of their relevance to spatial or temporal aspects of biodiversity state, pressure, response or benefits (Figure 1), and the biodiversity elements of genes, species or ecosystems (see Box 3). These comparisons yielded greater than 70% agreement, with the remainder harmonised through discussion. Each metric was further assessed in the current and potential use of the metric for the GBF, SDGs, and by businesses. Similarly, for biodiversity state metrics, the classifications of bottom-up/top-down and significance/intactness were assessed by FH and TB, yielding 96% agreement, and mismatches were harmonised through discussion.

In the process of our review, it became clear that some metrics that are most appropriately classified as state metrics (e.g., extinction risk of species) also provide information on measurement of pressures. We found that some also contain information relevant to responses. Others that were assessed as measuring benefits to people also created pressures on biodiversity where the use was unsustainable. These non-mutually exclusive classifications are documented in Annex 1. Through our review process, we identified 573 metrics that aim to measure different elements and features of biodiversity (Annex 1), within the frameworks of State-Pressure-Response-Benefits (Figure 2a; Table S1), genes-species-ecosystems (Figure 2b; Table S2), and top-down/bottom-up and significance/intactness (Figure 2c; Table S3).

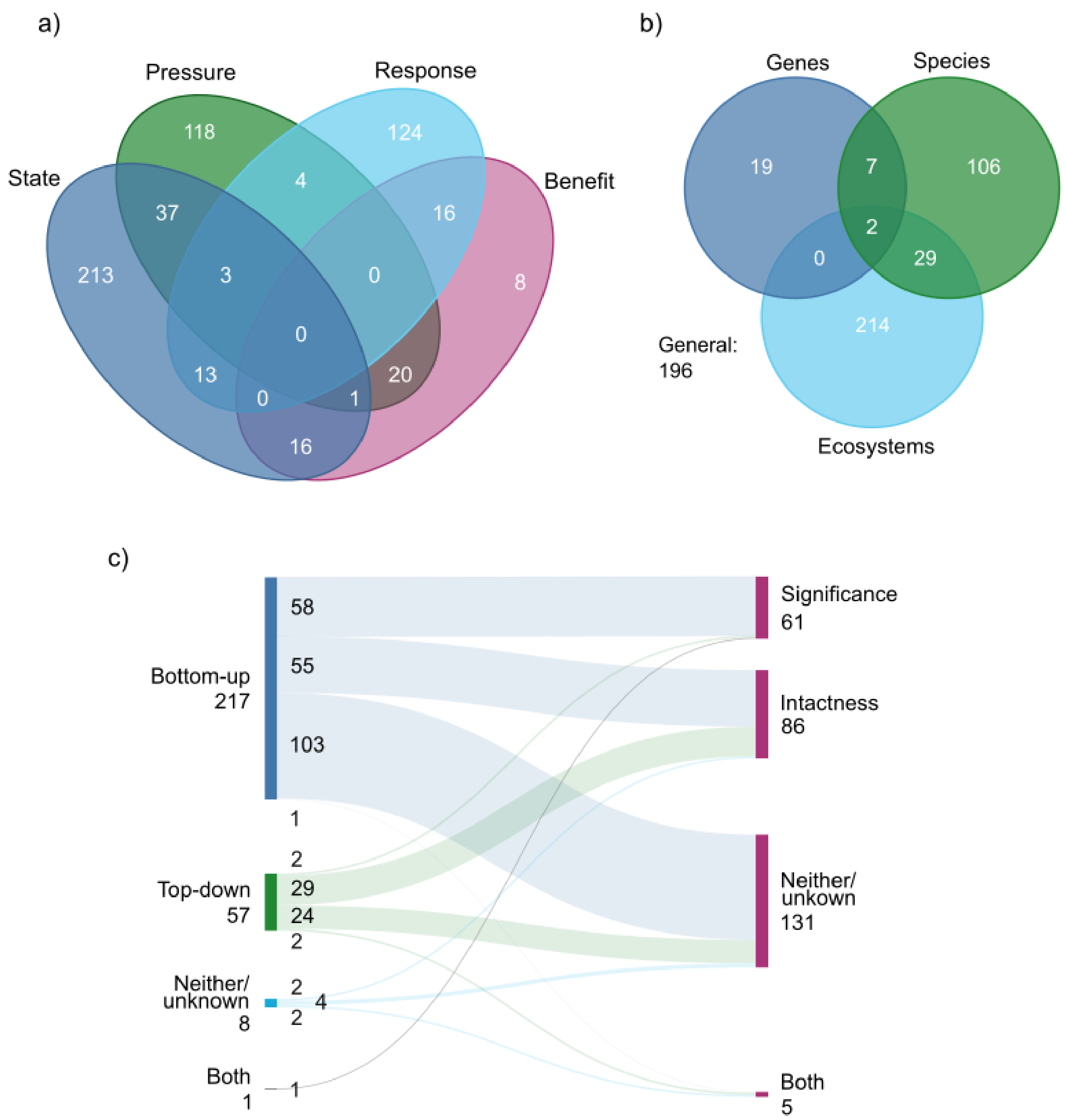

Figure 2. Overview of the 573 metrics reviewed and presented in Annex 1. (a) Number and overlap between metrics classified within the State-Pressure-Response-Benefit framework; (b) Number and overlap between metrics classified within the Genes-Species-Ecosystems framework; (c) Top-down/Bottom-up & Intactness/significance. Diagram created using SankeyMATIC. For tabular data see Tables S1-S3.

3 Aligning metrics to users

Biodiversity metrics are required by different user communities. The main user groups of these metrics are governments (including policy makers and public bodies/authorities at national, subnational and even city levels), business and trade-related bodies (corporations with supply chains, financial institutions, credit ratings agencies, trade organisations and intergovernmental trade agreements), technical agencies (international organisations, NGOs, universities), and civil society encompassing local communities and citizens (indigenous people, general public, resource users). We use information in Annex 1 to highlight metrics, indicators and indices proposed for use by governments (Table 1) and provide examples of how they are being used.

	State	Pressure	Response	Benefit	**All**
GBF	56	41	81	22	155
Headline	4	0	9	2	14
Component	16	13	11	4	32
Complementary	47	32	64	17	124
SDG	13	12	43	9	66

Table 1: Numbers of metrics agreed for use under the GBF and SDGs that were included within our analysis. The sum of headline, component and complementary indicators does not add up to the total GBF indicators as some indicators are classed as more than one if they are under different targets.

3.1 Governments

Biodiversity metrics for use by governments in relation to international and national policies and laws may be politically agreed at various scales (global, regional, national and sub-national). For example, the Parties to the CBD adopted a set of 26 headline indicators to track progress towards the goals and targets of the GBF, along with a further 58 component and 230 complementary indicators that governments can use subject to national needs (30). Similarly, 24 biodiversity-related indicators have been adopted by the world's governments to track progress towards the Sustainable Development Goal 15. These metrics are highlighted in Annex 1. We provide a shortened list of options for government and civil society use (Table S4, S6) and indicate online sources for these metrics, with other online platforms listed in Annex 2.

3.2 Business and trade-related bodies

There is a growing recognition that biodiversity is associated with significant financial risks and opportunities for businesses (4, 5). There are also emerging regulatory requirements for businesses to report on their climate- and nature-related risks (31). Target 15 of the GBF, and to some extent Target 16, provide a political impetus for CBD Parties to encourage businesses to assess biodiversity risks, disclose those risks, dependencies and impacts on biodiversity and develop targets to reduce negative impacts (1).

Various initiatives provide or are developing guidance on biodiversity metrics for corporations and finance bodies across value chains, for example, through the TNFD, GRI, SBTN, EU Business@Biodiversity Platform, the Align project, Natural Capital Protocol, the IUCN Measuring Nature Positive approach, and the World Economic Forum (WEF) 'measuring stakeholder capitalism' initiative. An emerging trend across these initiatives is a growing recognition that businesses need to contextualise the pressures that they place on nature using information on the state of nature, which should be measured by assessing the extent and condition of ecosystems, alongside population size and extinction risk of species (e.g., 14, 31).

Corporate biodiversity 'footprinting' tools often rely on the use of modelled pressure-state relationships (i.e., top-down intactness metrics) to estimate impacts across the business value chains. For example, the tools Global Biodiversity Score (32), Corporate Biodiversity Footprint (33) and the Biodiversity Impact Metric (34) use the Mean Species Abundance (MSA) metric. The latter, weights MSA by species range rarity derived from the IUCN Red List (35). The widely used life cycle impact assessment (LCIA) method ReCiPe (36) applies the potentially disappeared fraction of species (PDF) metric (37) for biodiversity impact assessment. The ReCiPe method is further utilised in business-oriented Life Cycle Assessment (LCA) approaches such as the Biodiversity Footprint for Financial Institutions (38) and Bioscope (39). These approaches need to be complemented with bottom-up significance metrics such as STAR (40, Box 3), not least to ensure their alignment with and track their contributions towards global goals such as the GBF and SDG 15. A shortened list of options of metrics for business use is presented online (Table S5) which also indicates online sources.

Whilst global metrics are most applicable for screening processes, metrics based on primary data are often needed to calculate actual, realised footprints on the ground and track outcomes of management decision making, for example in Environmental Impact Assessment processes. These metrics tend to be precise for local application, but can be challenging to apply at scale as different metrics tend to be used for different locations and activities, creating challenges of aggregation for reporting and disclosure (41). Methods to assess site scale impacts have been developed for development corridors and linear infrastructure, extractives (42), agriculture (43) and forestry (44, 45), for example.

4 Detailed Review of Metrics

4.1 Biodiversity State

Biodiversity state metrics describe the status and changes in status of components of biodiversity (genes, species and ecosystems). State measures are critical for understanding the health of the biosphere and the balance between the negative impacts of pressures and positive impacts of responses. However, measuring changes in the state of biodiversity does not necessarily reveal *why* it is changing. Therefore, it is crucial to explore the links between state metrics and those for pressures and responses to inform decision-making.

4.1.1 Genes

The CBD definition of this component of biodiversity covers the ‘within species’ aspect of genetic diversity (Box 4). Intraspecific genetic variability is critical not only intrinsically, but also to ensure species are resilient to environmental change (46). The importance of genetic diversity and sharing its benefits is also recognised under Target 13 of the GBF.

Despite its importance, few datasets are available to assess the within-species genetic element. Metrics of genetic diversity within wild mammal and amphibian species (47) complement work on metrics of genetic diversity within domesticated species by the Food and Agriculture Organisation of the United Nations (48). In the GBF Monitoring framework, the proportion of populations within each species with an effective population size of more than 500 individuals has been adopted as headline indicator A4. It acts as a proxy for loss of genetic diversity but is recognised as insufficient (49). Hoban et al. (50) also proposes a further metric of “the proportion of populations maintained within species,” which reflects the loss of genetic distinctiveness of each population. Most of the above are bottom-up metrics of biodiversity intactness. Significance metrics have yet to be developed for genetic biodiversity.

The ‘between species’ element of genetic diversity (see Box 2) can be assessed using phylogenetic diversity metrics, which are bottom-up metrics of biodiversity significance. These measure the shared ancestry of taxonomic groups and the breadth of evolutionary history. They represent the evolutionary distance between coexisting taxa (51). A number of phylogenetic diversity metrics are available for vertebrate groups (52–55) and flowering plants (56) on land and can be used to identify (and maintain) areas of greater genetic diversity in terms of distance between taxa (i.e. maintaining the results of evolutionary history). However, work to date suggests that these do not add substantial information content over and above that provided by species-level significance metrics (55).

4.1.2 Species

Many metrics of the state of species use either data on birds, mammals, amphibians and reptiles, largely due to a shared reliance on International Union for the Conservation of Nature (IUCN) Red List of Threatened Species (16, 35) or data on selected vascular plant groups (57–61). Vertebrates and vascular plants are therefore often used as surrogates for wider biodiversity (e.g., 62) applications which have been shown to be rather robust (63), despite the fact that plants, invertebrates and fungi sometimes differ in their distribution patterns (e.g., 64). The IUCN Red List contains information on species distributions, population size, structure and trends, habitat preferences, threats and actions needed and implemented for over 150,000 species (35). These data are applied to a set of criteria (65) to classify species' risk of extinction, with 42,100 classified as threatened with extinction.

Measurements of species extinction risk from the IUCN Red List can then be aggregated to yield bottom-up metrics of biodiversity significance, such as STAR (40) and LIFE (66). STAR specifically, for example, is a wholly scalable and additive measure of global specific risk reduction opportunity. Further, repeated assessments of species' extinction risk over time enable calculation of the Red List Index (9, 67) for complete suites or random samples of species, showing how their aggregate extinction risk has changed over time. This is adopted as GBF headline indicator A3 and SDG indicator 15.5.1. These are all bottom-up metrics of biodiversity significance. Meanwhile, the IUCN green status of species (68, 69) aims to measure different dimensions of species recovery. It is meant to be used in tandem with the assessment of extinction risk.

Metrics relating to distribution and diversity are also becoming available to cover biodiversity patterns of non-vascular plants or invertebrates, e.g. for soil biota such as fungi (70), earthworms (71) and soil nematodes (72). Nevertheless, the lack of data on some of the most speciose groups (71, 73–75) means that for the foreseeable future, species level biodiversity metrics will need to be based on surrogacy and samples of all species on Earth. This has been known for decades and is only slowly being addressed.

The Global Biodiversity Information Facility (GBIF, https://www.gbif.org/) brings together 2.38 billion (as of 9 October 2023) occurrence records from museums, herbaria, citizen scientists, and environmental impact assessments. The main metric generated using GBIF is the number of records available for use, as a proxy for availability of biodiversity data, but GBIF data are fed into many other metrics on biodiversity state, including the IUCN Red List assessment process.

Species range data from the IUCN Red List and point locality data from GBIF and other sources are often paired with land cover and topography, and sometimes distance to water and other factors, to model species' distributions and changes in these resulting from loss or gain of habitat. Range polygons (showing distributional boundaries) can be refined using data on species' elevation and habitat preferences in combination with land-cover maps to estimate bottom-up metrics of Area of Habitat (AOH) (76, 77). With its higher spatial resolution, AOH is more useful for spatial analyses of biodiversity values than the underlying range maps (see 77, 78) and is used to underpin STAR, LIFE, and other metrics (examples in Figure 4).

The Living Planet Database brings together more than 38,427 geolocated species population datasets (61) and is used to generate the Living Planet Index (LPI). The LPI is a measure of the state of population trends of vertebrate species, as a bottom-up intactness metric.

There are different aspects of connectivity including structural and functional connectivity. Areas where the flow of species movement is concentrated are places with the potential to disproportionally reduce connectivity (79) (Brennan et al. 2022). The Protected Area Isolation (PAI) is a metric that quantifies the connectedness of each protected area through the lens of moving mammals, using mammal movement data.

4.1.3 Ecosystems

More than 100 years' work to classify ecosystems underpins the creation of ecosystem metrics reflecting area and condition, with the most recent advance in ecosystem classification being the development of the IUCN Global Ecosystem Typology (80, 81).

The most common metrics of ecosystem state are those linked to land cover and land use maps, especially those that measure changes over time, incorporated into the GBF as headline indicator A2 on the extent of natural ecosystems. Bottom-up intactness metrics that assess individual ecosystems extent across the world are increasingly available – such as forests (82–84), mangroves (85), seagrass (86), saltmarsh (87), coral reefs (88), peatlands (89), wetlands and water bodies (90, 91). Challenges remain to measure the extent of some ecosystems – for example, in differentiating natural grasslands from pasture or croplands, differentiating natural forest from plantations or tree crops (e.g., rubber, palm oil, 92), distinguishing peatland ecosystems from similar vegetation and identifying mixed-use land – such as mosaic habitats or shade-grown crops. At finer scales, the gradual emergence of standardisation in land use and land cover classifications, and the creation of national land cover and land use maps for most countries, facilitates using satellite remote sensing data to measure changes in ecosystem area and condition at local to national scales (29).

Metrics of ecosystem condition directly calculated using remote sensing are difficult, so they are often appraised indirectly to generate top-down intact metrics through proximity to pressures (e.g., 83). However, measures such as tree canopy height (93), or radar-based forest condition assessments (94), can deliver metrics of condition for forest ecosystems (83, 95). Another way to calculate ecosystem condition uses the intactness of species assemblages. The PREDICTS database contains 376,992 records of site level species assemblages, which is used create a Biodiversity Intactness Index (BII; 96, 97) that presents an estimated percentage of the original number of species and their abundance that remains following changes in land use. A similarly modelled index of biodiversity assemblage intactness is the mean species abundance (MSA) metric (98, 99).

One of the largest programmes for assessing ecosystem condition that uses a nationally driven approach and that links to a globally agreed methodology is the IUCN Red List of Ecosystems (100–103). This is gradually developing worldwide assessments of the state of ecosystems, in terms of their risk of collapse and was incorporated into the GBF as headline indicator A1. In turn, these will allow derivation of bottom-up metrics of biodiversity significance at the ecosystem level (e.g., 104).

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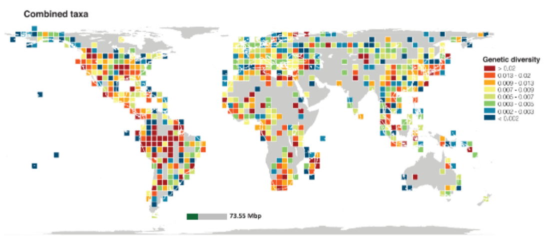
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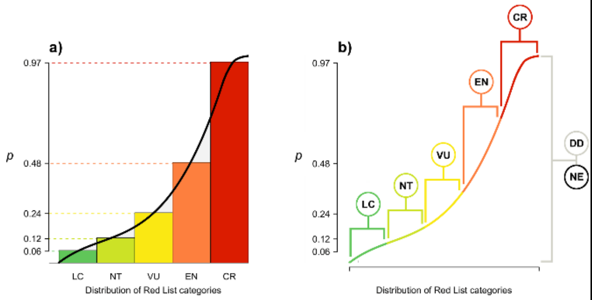
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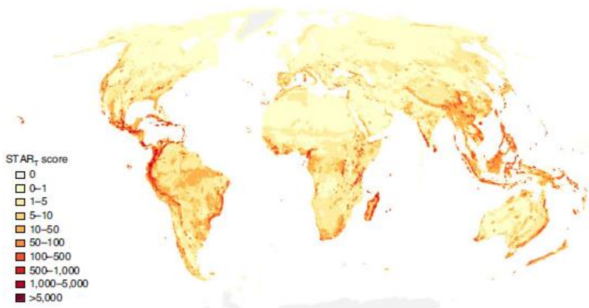
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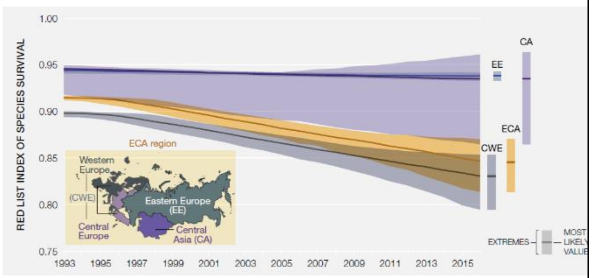
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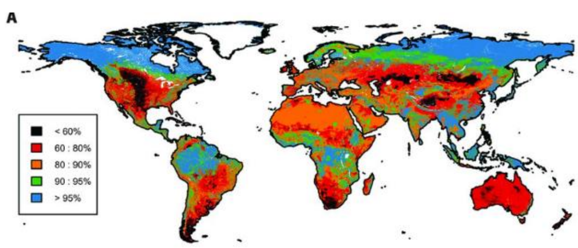
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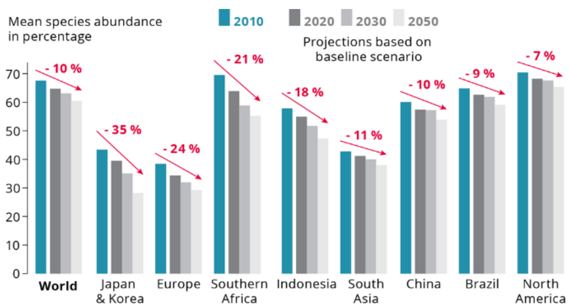

</td></tr>
<tr><td>g. ecosystems distribution in South Africa</td><td>h. Rates of tree cover loss</td></tr>
</table>

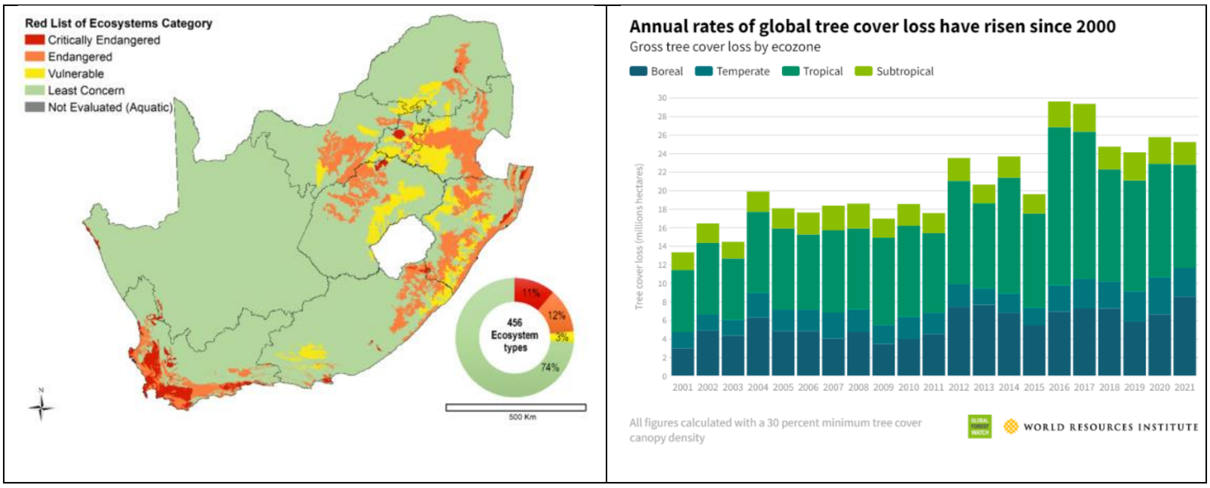


Figure 4: Spatially mapped and temporal metrics of the three elements of biodiversity state.

Figure 4a adapted from (47); reprinted with permission from AAAS. Figure 4b adapted from (105). Figure 4c reproduced with permission from (40); copyright Nature Ecology & Evolution. Figure 4d reproduced from (106); copyright IPBES. Figure 4e adapted from (97); reprinted with permission from AAAS. Figure 4f adapted from (107); copyright OECD. Figure 4g adapted from (108); CC-BY. Figure 4h reproduced from Global Forest Watch (82, 109); CC BY 4.0. The boundaries and names shown and the designations used on these map do not imply official endorsement or acceptance by the United Nations.

Metrics of state of genetic diversity. a. Within species genetic diversity (47), showing that sampling of within species genetic diversity is patchy globally and the available data are not really sufficient to be used for decision making or the creation of indexes or for conservation planning. b. EDGE phylogenetic index (105), showing that there is a lot of unique genetic history in species of increasing risk of extinction

Metrics of species state. c. Species Threat Abatement & Restoration metric (40), showing the location of numbers of species whose extinction risk can be reduced by actions to reduce threats d. Red List Indices for Europe & Central Asia (106), showing how changes in the threat status for species can be used to determine progress towards (or away from) extinction.

Metrics of ecosystem state based in indices: e. Biodiversity Intactness Index (BII) (97), showing how the assemblage of biodiversity has changed from a historical baseline situation. f. Projected trends in Mean Species Abundance (MSA) over time (107), showing how changes in assemblage composition has changed (negatively) over time in various regions of the world

Metrics of ecosystem state based on assessments of area and condition of individual ecosystems. g. Risk of ecosystem collapse for different ecosystems in South Africa (108), with ecosystem classification based on (110), showing regions of that country where the ecosystems are threatened and on a progression to collapse. h. Global trends in tree cover loss (82, 109), illustrating one of the ecosystems that can be monitored from space to illustrate global declines in cover in different parts of the world.

4.2 Biodiversity pressure metrics

Conservation efforts often focus on reducing pressures to reduce biodiversity loss and ultimately facilitate improvements in the state of biodiversity (111). The creation of biodiversity pressure metrics facilitates decision-making in two ways: (i) To assess the kinds of pressures that need to be addressed to improve the state of biodiversity (i.e. planning) and (ii) to assess how effective actions have been in reducing pressures (i.e. monitoring). Some metrics include a combination of state and pressure elements; notably, many metrics and indicators of biodiversity state can be disaggregated to yield indicators of specific pressures. Annex 1 contains many examples of metrics of pressure that affect all aspects of biodiversity. These include metrics of hunting, pollution, greenhouse gas emissions, air pollution, expansion of invasive alien species, logging or many other human activities.

4.2.1 Pressure on genetic diversity

No distinct metrics have been developed to measure pressures on biodiversity at the level of genetic diversity.

4.2.2 Pressure on species

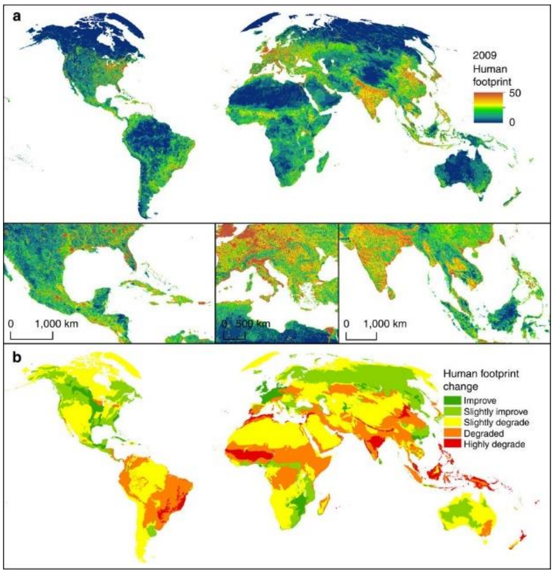
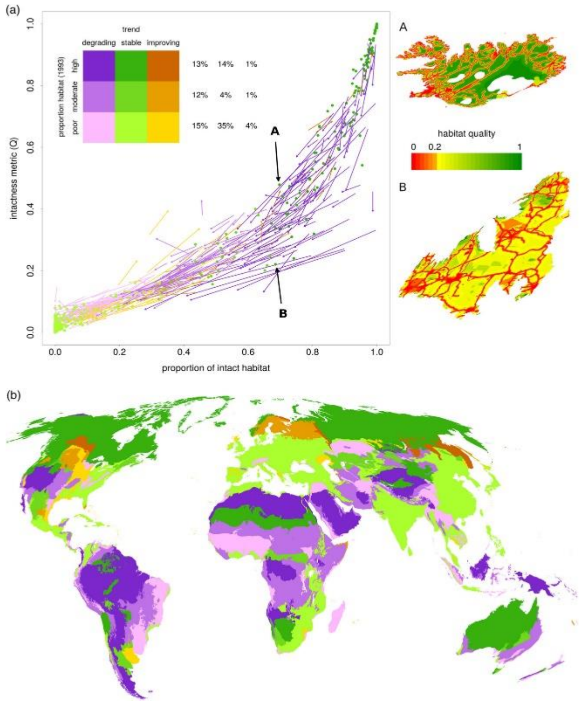
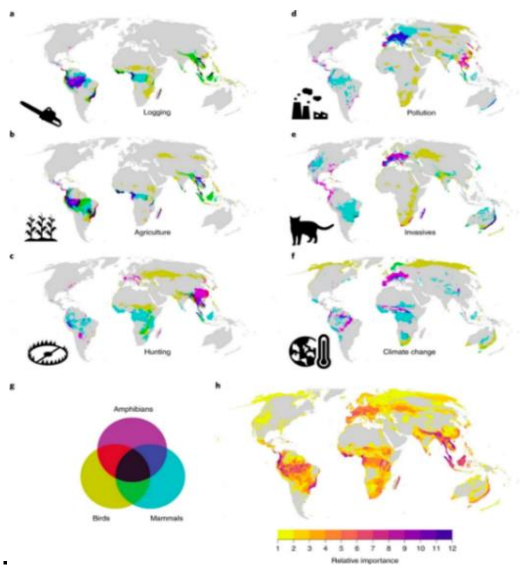
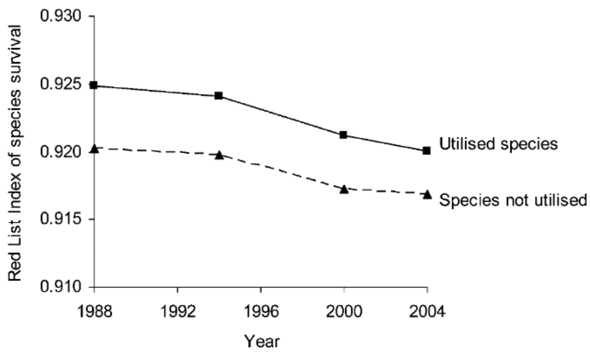
Metrics of pressures on species can be disaggregated from IUCN Red List database derived metrics (112, 113) (Figure 6), for example the Species Threat Abatement and Recovery (STAR) metric (40, 114). Documentation against the standard Threats Classification Scheme (115) is required for all IUCN Red List assessments, and so STAR can be perfectly disaggregated as a metric of the opportunity to reduce extinction risk by mitigating any given threat. Another approach to measuring the impact of land use change pressure on species within the IUCN Red List is the “persistence score” or LIFE metric developed by Duran et al. (66). This uses IUCN Red List data, but extinction risk is calculated in relation to both the original extent of habitat and the extent of remaining habitat, rather than from the IUCN categories directly, and all species (including those classified as Least Concern (LC)) are included (116). The list can be disaggregated to provide a pressure metric for the threats contributing to land use change.

Specific pressures, such as sustainable and unsustainable use of species from hunting, fishing, harvesting and wildlife trade, can also be measured using the IUCN Red List (117), while metrics of species in trade can be calculated using UNCTAD databases through the Biotrade Initiative (Annex 1). IUCN Red List data can also be used to create maps of the spatial variation in extinction risk globally, which provide a proxy measure of the pressures facing species (78, 118). Specific disaggregation of the Red List Index (RLI; 67) show trends in aggregate extinction risk to species driven by particular pressures, such as unsustainable utilisation, pollution or invasive alien species, using data on the factors causing individual species to improve or deteriorate in status sufficiently to qualify for lower or higher Red List categories.

4.2.3 Pressures on ecosystems

The most common metrics of pressure on ecosystems are those that measure a decline in ecosystem area due to land use change. Metrics that measure a decline in ecosystem condition due to pressures are also commonly developed.

Combinations of different remotely sensed data layers on human pressures on biodiversity have allowed the development of indices of pressure, for example the Human Footprint Index (119–122) (Figure 5), and Human Modification Index (123), which can be disaggregated into their component threats. Other metrics categorise land based on their extent of pressure, such as Low Impact Areas (124), Natural and Modified Habitat (125) and anthropogenic biomes (126, 127). The GLAD alerts (128) are pressure indicators for deforestation events available on the Global Forest Watch platform are used by non-government and civil-society organisations (as well as governments) to target interventions to address illegal deforestation and forest degradation.

<table>
<tr><th>Spatial</th><th>Temporal</th></tr>
<tr><td>a. distribution of human footprint index

</td>
<td>b. changes in human footprint within ecoregions

</td></tr>
<tr><td>c. distribution of pressures on species

</td>
<td>d. trends in species populations due to different pressures

</td></tr>
<tr><td>e. fire intensity in Africa as a potential pressure on ecosystems and species</td>
<td>f. trends in deforestation linked to agriculture</td></tr>
</table>

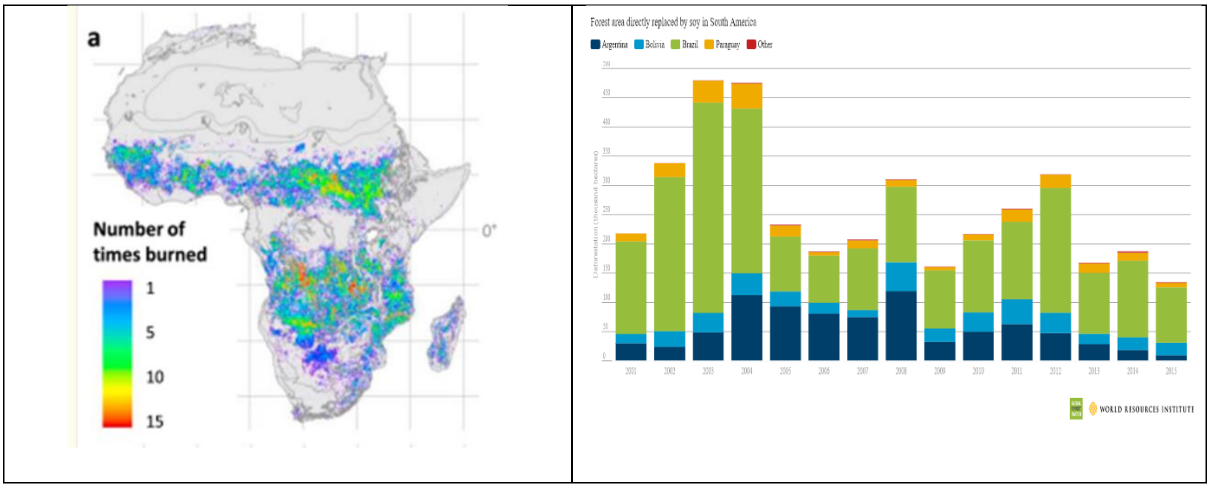


Figure 5. Spatial and temporal examples of biodiversity pressure metrics.

Figure 5a adapted from (149, 150); CC BY 4.0. Figure 5b adapted from (129); CC BY. Figure 5c adapted from (113); CC BY 4.0. Figure 5d reproduced with permission from (130); copyright Cambridge University Press. Figure 5e reproduced from (131); CC-BY-NC-ND. Figure 5f reproduced from Global Forest Watch (132); CC BY 4.0. The boundaries and names shown and the designations used on these map do not imply official endorsement or acceptance by the United Nations.

Pressures on ecosystem condition. a. Human Footprint Index (119), showing how a series of remotely-sensed layers can be combined to give a spatial metric of the degree of human pressure on nature (noting that some pressures like hunting or climate change are not included in this metric). b. Changes in pressure within ecoregions (129), showing how human footprint change data can be used to measure changes in pressure across the more than 800 ecoregions in the world.

Pressure on species. c. Distribution of pressures on species using data derived from the IUCN Red List of threatened species (113), showing that there are spatial patterns in how pressures on species are distributed globally – facilitating conservation decision making to reduce these pressures. d. Red List Indices for utilised bird species in comparison to those that are not utilised by people (130), showing that there is a similar progression towards extinction for species that are both used or not used.

Pressures on ecosystems. e. Number of times areas in Africa burned 2002–2016 (MODIS 500-m) (131), showing areas of Africa where vegetation is naturally fire-prone but also showing that some areas are burning almost every year which is a higher frequency than the natural situation without human-set fire. f. trends in the loss of forest cover due to the pressure of agriculture in some South American countries (132), showing large annual variation in the amount of forest lost to agriculture in different countries.

4.3 Biodiversity response metrics

Most of the response metrics listed in Annex 1 relate to the GBF, and many consist of counts of the numbers of countries or other entities that have developed a policy or otherwise responded to the biodiversity crisis. While essential, these metrics are necessarily simplistic and contain limited information for further decision-making. Here we focus on metrics that facilitate a richer understanding of how responses might affect biodiversity state or reduce pressures.

Metrics of responses to the conservation of genetic diversity typically relate to the numbers of species in long term storage facilities (seedbanks and tissue banks) or in botanical gardens or zoos. These are further elaborated for domesticated species where the genetic diversity of crops and domesticated animals is carefully monitored. Hoban et al. (50) also proposed measurement of “the number of species (and populations) monitored using DNA-based methods”, as a response metric (i.e., through measurement of knowledge).

The World Database on Protected Areas (133) and on Other Effective Area-based Conservation Measures (134) contains information on those areas set aside for conservation, sustainable use or other reasons that achieve biodiversity goals. Response metrics derived from these databases include the area of ecosystems and Key Biodiversity Areas protected over time (135) – used as GBF headline indicator 3.1 – and the condition of ecosystems within protected areas (136).

There are a suite of diverse metrics on protected area connectivity (i.e., ProtConn, ProNet, PAI, PARC, ConnIntact). Theobald et al. (137) explains some of the differences between these metrics and how they can be used. Gaps remain in our understanding of where connectivity conservation is most critical including measuring key aspects of connectivity related to migratory connectivity across terrestrial, coastal/marine, and inland waters.

The World Database on Key Biodiversity Areas contains species, site, threat and habitat data from over 16,000 sites of significance for the global persistence of biodiversity (138) (Figure 6). KBA data underpin metrics on the conservation responses at more than 4000 sites and on the degree to which KBAs are covered by protected areas and Other effective area-based conservation measures (OECMs), which is used by the SDGs – specifically tracking protected area coverage of KBAs for marine (SDG indicator 14.5.1), terrestrial and freshwater (SDG indicator 15.1.2), and mountains (SDG indicator 15.4.1) – and also by the CBD and other MEAs as a response measure.

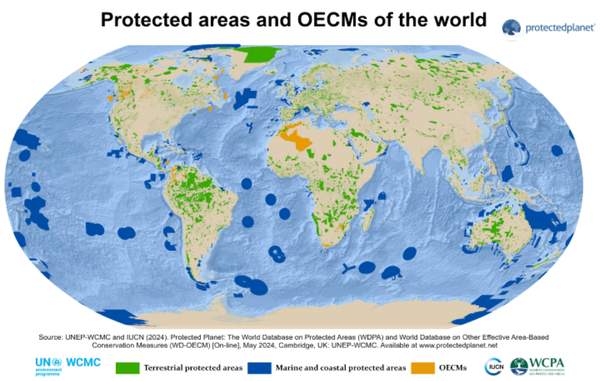
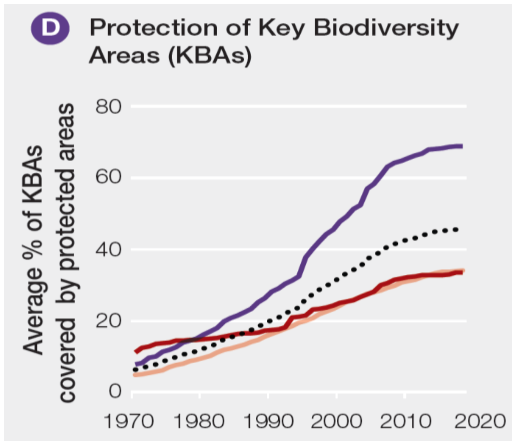
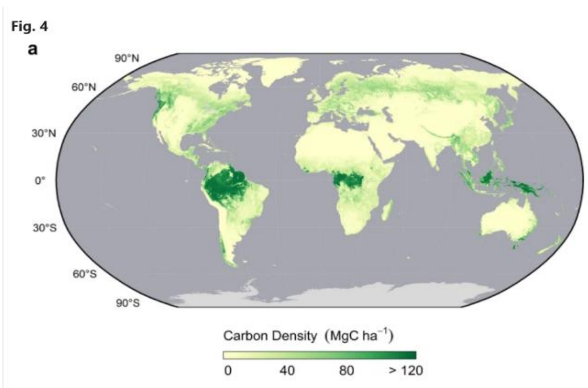
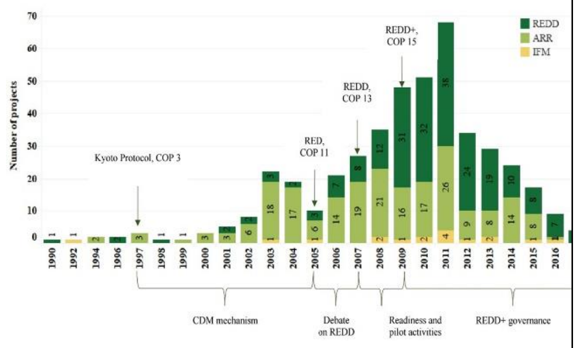
Although more typically used to measure species state, and to understand pressures on species, indices derived from the IUCN Red List can also be informative about the potential or actual outcomes from responses. For example, the Realised STAR scores (40) quantify the reduction in global extinction risk achieved through implementation of responses. Similarly, the LIFE metric (66, 116) can be used to measure species responses resulting from restoration.

4.4 Biodiversity benefits

People benefit from biodiversity through the ecosystem services (nature's contributions to people) that it provides, such as regulation of water supply, provision of food, pollination of crops, etc. (139–141). These benefits are the direct and indirect contributions from ecosystems (underpinned by natural capital (e.g., 142). The potential ecosystem service is the benefit that could be obtained, but there are no people to use the service, while the realised service is the actual benefit experienced or delivered to people.

Metrics exist to measure both potential and realised ecosystem service benefits and help understand the consequences of biodiversity loss on people (examples in Table S6). Ecosystem service assessments often use land use / land cover (LULC) maps that are then linked to attributes of value to people to develop models of realised ecosystem services flows (143–147). This means that many ecosystem service metrics broadly reflect the patterns of land cover, land use and human population density and consumption preferences. Changes in land cover, human population, use of natural capital, and sustainability of supply can all determine how ecosystem service flows continue over time. If the benefit realised is not sustainable, it will degrade the underlying natural capital leading to a loss of benefits over time. For species, abundance metrics in combination with demographic data can help determine the numbers of wild animals or plants that can be harvested for human use.

Few global ecosystem service layers are temporal. Indeed, it is rare for ecosystem service provision to be tracked over time. An exception is the tracking of change over time in biomass carbon as this has been linked to temporal land cover maps allowing carbon sequestration and emissions to be calculated (148), which are relevant for the ecosystem service of climate regulation. Detailed ecosystem service status updates are available at regional to local scales, for example for Africa (149), Europe (150), USA (151), and numerous papers for countries or parts of countries, such as Uganda (152), Mozambique (153), Tanzania (154) (Table S4, Figure 6)

Spatial	**Temporal**
a. Protected area on land and in the sea 	b. protected area coverage of KBAs across different regions 
c. Carbon density in living vegetation 	d. Trends in carbon projects benefiting people 

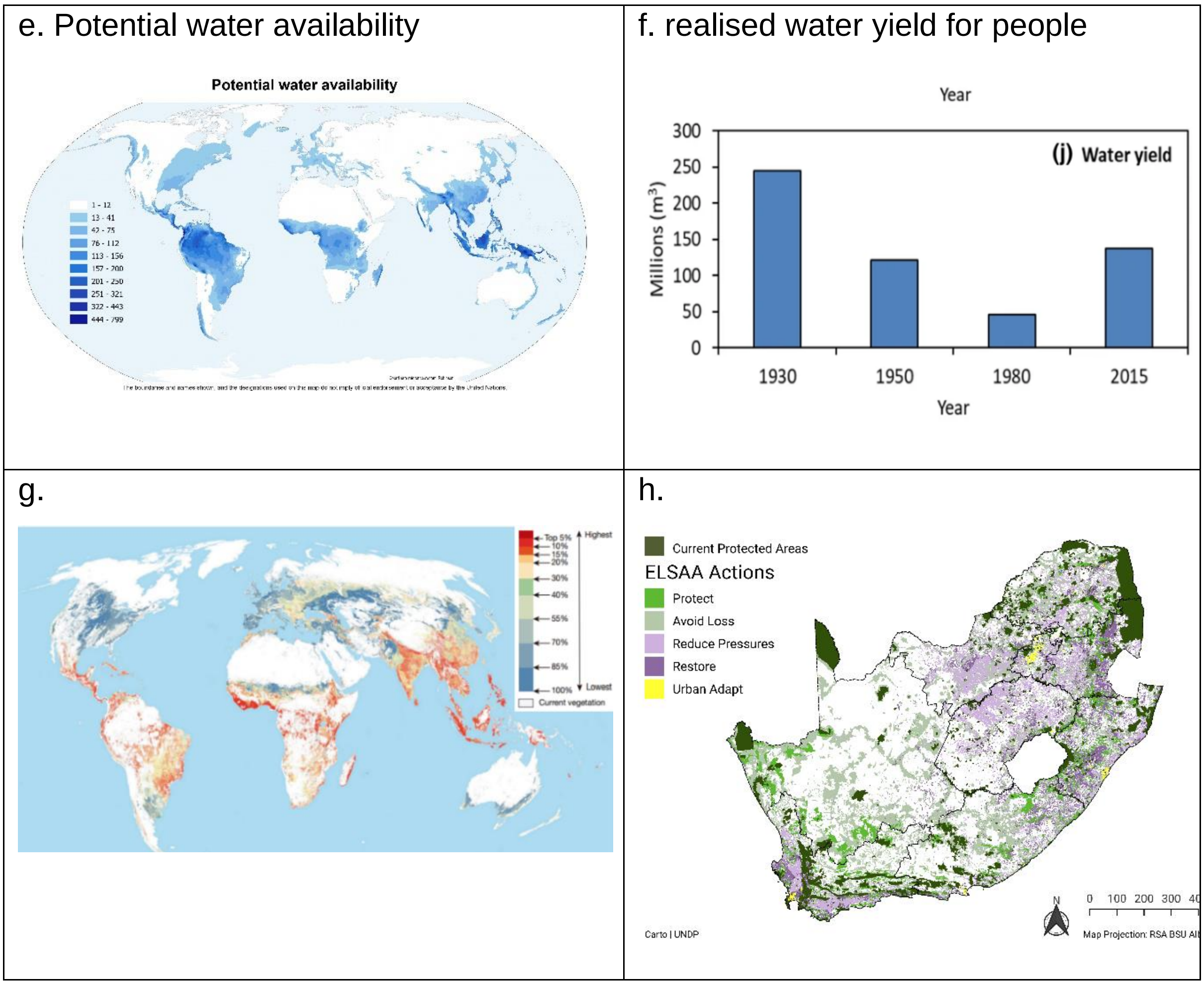


Figure 6: Examples of response and benefits metrics

Figure 6a adapted with permission from Protected Planet (135). Figure 6b reproduced from (141); copyright IPBES. Figure 6c adapted from (155); CC BY 4.0. Figure 6d reproduced from (156); CC-BY-NC-ND. Figure 6e data provided by (157). Figure 6f adapted from (158); CC BY 4.0. Figure 6g adapted with permission from (159); copyright Nature. Figure 6h adapted from (160); copyright UNDP. The boundaries and names shown and the designations used on these map do not imply official endorsement or acceptance by the United Nations.

Response metrics (protected areas). a. Protected areas globally (135), showing those areas of land and sea that have been declared mainly by governments for conservation purposes, facilitating a calculation of the area of land and sea protected. b. Changes in the percentage protection of Key Biodiversity Areas by protected areas for developing and developed countries, compared to globally (dotted line) (141), showing that key sites for biodiversity conservation are increasing being conserved within protected areas over time but with difference between developed and developing countries

Ecosystem service metrics. c. Biomass carbon distribution globally (155), showing a concentration of biomass carbon in the world's forests, especially tropical forests. d. Trends in biomass carbon projects benefiting people (REDD+ and others) (156), showing a peak in new projects focusing on carbon around 2010 with an apparent decline after then. e. Water availability (157) showing those areas where there is at least a seasonable abundance of water, especially in some temperate regions and tropical wet areas. f. changes in realised water for people following agricultural intensification and partial reforestation in Dorset, UK, 1930-2015 (158), showing a decline in realised water availability due to agricultural intensification up to the 1980s, followed by a recovery since that time.

Response metrics (restoration and planning). g. Ranked restoration priority areas (159), showing that there are parts of the world of a much greater priority for restoration to achieve nature outcomes than other areas. h. Systematic plan of nature positive areas in South Africa (160), highlighting a ranked set of areas according to different measures that are conservation priorities for that country.

4.4.1 Multidimensional indices

Some metrics are multidimensional as they seek to present information covering biodiversity state and pressure, and sometimes also responses or benefits (Annex 1; Figure 7). An ecosystems example is the Ecosystem Integrity Index (161) that contains measures of ecosystem condition and pressure. Another index measures the capacity of ecosystems to retain species under the pressure of climate change - the Bioclimatic Ecosystem Resilience Index (BERI; 162). Similar metrics have been developed within the framework of ecoregions globally (129, 163), and regionally (e.g., 164).

Further efforts have also been made to try and simplify the problem of multiple metrics —by developing complex indices that represent different dimensions of pressure, state, response within a single index. Examples of tools and stand-alone indices that are being used by governments or business include the Local Ecological Footprint Tool (LEFT), which takes 7 input data layers and processes them into a map of "relative ecological value" (165) (Figure 7).

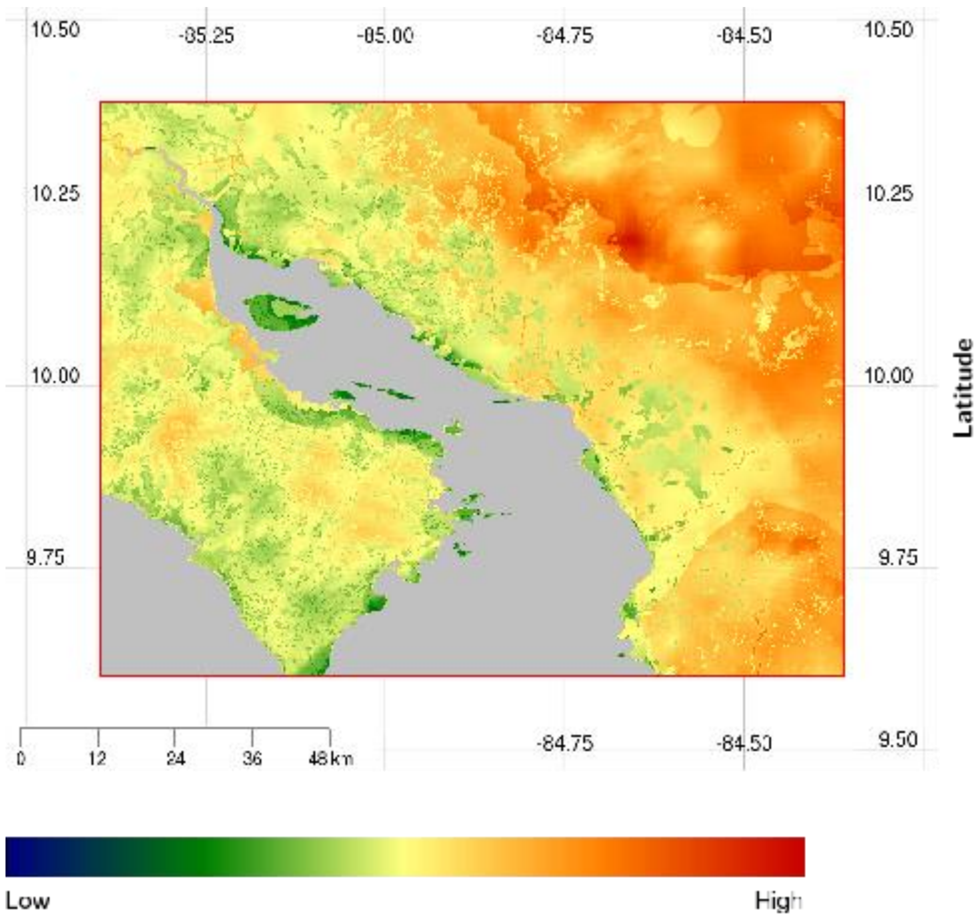
Another is the Multidimensional Biodiversity Index (MBI), which aims to combine measures of the biodiversity state and its contribution to people in a multidimensional ecological and social approach that considers the specifics of each national context. This allows countries to develop policies and take actions that consider the importance of safeguarding biodiversity for their sustainable development and well-being (166). This approach is analogous to indices such as the Human Development Index (HDI), the Multidimensional Poverty Index (MPI) and others. For business use, Environmental, Social and Governance (ESG) ratings are based on composite metrics that are built using different data inputs.

Multidimensional indices are often controversial. Such indices tend to treat different facets of biodiversity equally, are based on subjective weighting, are based on arbitrary scores, have an inconsistency in spatial scale, have inconsistency in the timescales of their datasets or may combine measures. This makes it nearly impossible to understand what drives trends without breaking the metric down into its constituent parts (167). Nevertheless, there remains a demand from both governments and business for such indices and they may play a role in communication or high-level decision making.

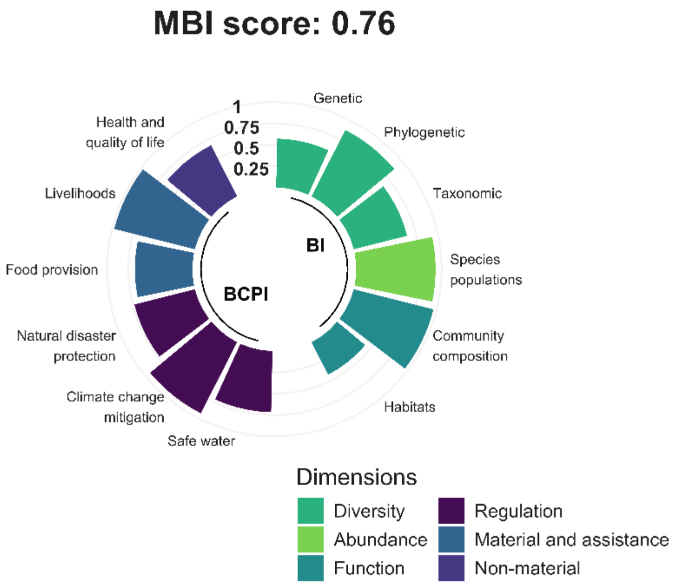
As examples, the Local Ecological Footprint Tool (LEFT) providing an example map of “relative ecological value” (165), showing a complex index of nature values that has been used by some companies for decision making (Figure 7).

Figure 7: Examples of multidimensional indices.

a) Visualization of the Local Ecological Footprint Tool (LEFT; 165), providing an example map of “relative ecological value” (168), showing a complex index of nature values that has been used by some companies for decision making. Figure reproduced with permission from (168).



b) A hypothetical example of a Multidimensional Biodiversity Index score (166). Each bar represents a biodiversity objective score ranging from 0 to 1, calculated from a series of indicators. The values can be considered separately or aggregated to obtain a country or region's overall score (in this case 0.76). The green bars show the Biodiversity State Sub-index (BI) dimensions and objectives, while the blue bars show the Biodiversity Contribution to People Sub-index (BCPI) dimensions and objectives. Unpublished figure by Ana Ramos Rodrigues.



5 Towards a minimum set of metrics

Some representatives of governments or business have highlighted the complexity of biodiversity metrics and requested simplification. These requests mirror those for the climate where the complexity of the climate system has been reduced to a focus on measuring the three goals of the Paris Agreement: greenhouse gas emissions (especially CO_2) and staying below a 1.5°C temperature rise above pre-industrial levels; climate change adaptation; and climate financing.

For biodiversity, a single metric is seen by many as scientifically indefensible (see 169). This is because a) we can measure biodiversity at different levels – e.g. genes, species and ecosystems - that are all unevenly distributed globally and undergoing different temporal trends; b) we can measure biodiversity in terms its benefits – for example, its direct contributions to people, its underpinning role in ecosystems, or its intrinsic value; c) we can prioritise biodiversity according to various measures of its rarity or extinction risk (or we can ignore that and measure it in absolute terms). There is no right or wrong choice in any of these and it depends upon the application as to which is the most suitable approach for measuring biodiversity value.

Thus, rather than proposing a single metric, which could not cover all aspects of biodiversity for all user groups, we have pooled our knowledge to identify a small number of metrics to address current needs (Table 2), building off previous papers (170, 171).

Criteria we used to identify this set were: a) ideally included as SDG 14 & 15 indicators and/or GBF headline indicators (highlighted in red in Table 2), b) published metric with available methodology and data, c) data flows exist to update the metric, d) responsible institution(s) committed to maintain and update the metric for at least 10 years, e) available for all countries and freely accessible for government decision making and f) established way to use the metric for commercial decision-making.

	Genes	Species	Ecosystems
State (significance)	EDGE[1]	STAR RLI	Extent of natural ecosystems[1] RLE
State (intactness)	-	LPI[1]	BII MSA/ PDF/cSAR
Pressure	-	STAR$_{T}$	HFI
Response	-	STAR$_{T \text{ and } R}$ GSSI[1]	PA coverage
Benefits	-	-	Forest Carbon Flux

Table 2. Proposed core set of metrics for measuring state, pressure, response and benefits aspects of biodiversity (species, ecosystems and genes).

Key:

Genes: EDGE = Evolutionarily Distinct and Globally Endangered Index

Species: STAR = Species Threat Abatement and Restoration metric; RLI = Red List Index and associated disaggregations; LPI = Living Planet Index and associated disaggregations, STARt = threat abatement component of STAR, which can be disaggregated by threats; STARr = restoration component of STAR; GSSI = Green Status of Species Index. Ecosystems: Extent of natural ecosystems = trends in habitat extent derived from remote sensing; RLE = Red List of Ecosystems Index; BII = Biodiversity Intactness Index; MSA = Mean Species Abundance; PDF = Potentially

Disappeared Fraction; cSAR = Countryside Species–Area Relationship; HFI = Human Footprint Index; PA coverage = protected area coverage and associated disaggregations; Forest Carbon Flux = biomass carbon flux.

In red and underlined: SDG and GBF headline indicators. In red, GBF headline indicators.

[1] = These metrics may not meet criteria (e) or (f)

6 Discussion

We have shown that a diverse array of biodiversity metrics is currently available, covering different aspects of biodiversity, which relate to measures of pressure, state, response and benefits. However, we have also shown that there are large numbers of metrics developed for different use cases and the field remains confusing for many users. Our summary of suggested metrics, drawing from existing intergovernmental decisions, boils the large numbers of metrics down to a handful. In this discussion we cover some of the issues that will affect the development and maintenance of metrics for decision-making over the medium term. We then conclude with some core findings and a way forward.

6.1 Data availability

For most metrics, the limited availability of field-level biodiversity data and data that are regularly updated are significant constraints to the quality of the metric. For the species data, most of the available metrics use a handful of data sources. These are typically biased towards vascular plants and vertebrates – especially birds – and lack depth for fungi and invertebrates. Available data are also geographically biased, with significant gaps in global coverage (Figure 3). Apps on smart phones are allowing data collection in some poorly studied parts of the world to rapidly accelerate, but there are still regions with almost no data, and validation of data, especially for poorly-known taxa, is a problem.

The increasing numbers of satellites in orbit and the diversity of products they deliver, means there is a rapidly expanding array of metrics being produced using remote sensed data (see Annex 1 for lists). However, very few products fit the needs of specific end-users in the biodiversity community, and biodiversity scientists are often required to adapt existing products to their needs (172). Despite the hopes of the biodiversity metrics community, this situation has not improved much over the last two decades. But the new generation of landcover products (e.g., 173–176), with AI-enabled learning and rapid update, may – if linked to ecological and biodiversity expertise – provide ways forward in coming years. However, this cannot replace the need for metrics derived from in situ monitoring.

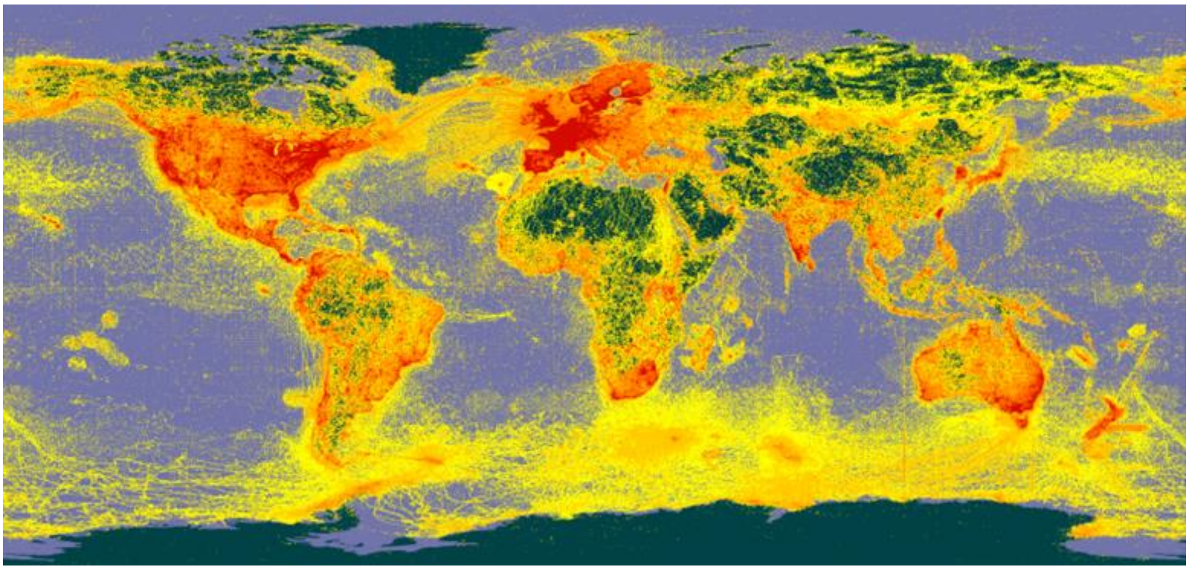


Figure 3: Biodiversity data records per one degree grid globally (Data provided by GBIF.org)

6.2 The role of civil society

Civil society has an important role to play in contributing data to create biodiversity metrics and indicators (177, 178). For example, civil society is particularly active in the use of citizen science smart-phone and web-based data collection tools such as iNaturalist, eBird and the Lost Ladybug Project. Occurrence data generated through these tools, as well as camera traps, bird feeders, smart listening devices, e-DNA surveys and Environmental Impact Assessments are typically integrated with museums and herbaria through platforms such as GBIF (179).

Although spatial coverage of these tools is variable, and quality may vary depending on how data are ground-truthed/validated, they are starting to deliver the best available data on many species, and this trend seems likely to continue. Statistical methods are advancing to deal with some of the data limitations of these approaches (180). Civil society can also be involved in evaluating ecosystem services (e.g., 181) using tools like i-Tree developed by the USDA Forest Service. Substantial attention is also now being devoted to advancing application of indigenous and local knowledge in support of biodiversity metrics, for example in the IUCN Red List (182).

6.3 The need for sustainable financing

For the main metrics in use, and new ones that will be developed, there is a crucial need for *ongoing* investment in maintaining the flows of data and aggregation capacity to continue to deliver the metric (183). There is also a need to ensure that core metrics are backed by institutional commitments to deliver them to agreed user communities and that work continues to make their production easier, faster, and cheaper – especially through the use of new technologies. These are key factors in sustainability and utility for government or business decision-making.

6.4 Factors driving the uptake of metrics by governments

Governments require metrics and indicators that can help them to deliver national, and regional policy commitments (such as the EU, African Continental Free Trade Area (AfCFTA), East African Community etc), or globally agreed commitments such as those defined by Multilateral Environment Agreements (MEAs) such as the Sustainable Development Goals, GBF, UNFCCC, CITES, UNCCD and the Ramsar Convention on Wetlands.

Biodiversity metrics are much more likely to be taken up by governments if they are part of a global or regional framework and are possible for the country to collect and report against. Globally generated metrics, often housed and created by UN agencies, NGOs or universities, have the advantage that they have standardised methods and are often comparable across space and time. However, there are often challenges with using these global metrics at national scales. For example, definitions (such as land use/cover classifications) often do not align between global and national users, or with definitions used by business laws and frameworks. For example, the definition of natural habitat/ecosystem within the International Finance

Corporation's (IFC) Performance Standard 6 (184) and the EU Habitats Directive (Council Directive 92/43/EEC) differ and are sometimes conflicting. Academic or NGO-generated metrics may lack political legitimacy at the national level as they are not created or endorsed by governments and may have no institutional mandate for maintenance into the future. These kinds of challenges risk inconsistency between global and national metrics, preventing meaningful comparisons and hence hindering overall assessments of the status and trends in biodiversity. In turn, this may limit the reliability of communications to decision-makers and the public on the situation facing biodiversity around the world.

A political balancing act is therefore required to create systems where nationally generated metrics (by government, citizen scientists or indigenous peoples and local communities) can be used alongside globally or regionally generated metrics. This is illustrated in the periodic Global Biodiversity Outlooks, Global Environmental Outlooks, and Global Forest Resource Assessments. It is also seen in the implementation of deforestation-free supply chain laws, which although developed for good reasons of climate and nature loss, can cause concern and political controversy in countries of commodity origin.

6.5 Factors driving the uptake of metrics by businesses and trade systems

There is interaction between national/regional/international policy and the responses of business and trade systems (185). First, businesses need to reduce current or possible future transition risks, such as loss of competitiveness and earnings due to a failure to align with the requirement of policies and laws (186). These could arise not only from regulatory changes, but also from societal and investor pressures to transform approaches to reduce impacts on biodiversity. Second, businesses also increasingly recognise the scale of nature-related physical risks and the opportunities relating to their own operations and the wider economy (5, 187). This includes the financial risk to businesses from the loss of biodiversity that many companies are already experiencing. Third, if not addressed, loss of biodiversity may lead to systemic risks that prevent businesses from operating at all in the future as biodiversity-based life support systems collapse (188, 189).

Businesses have responded to these emerging issues by participating much more actively in the negotiations around the biodiversity COPs (190, 191). To align with the GBF targets and indicators, businesses are now considering how their impacts and dependencies on biodiversity may be accounted for, how their contributions to these goals and targets can be recognised, and how to select metrics to measure these contributions. Challenges remain, for example, in relation to the required scale of analysis, with operational decisions at company scale often requiring bespoke, context-specific approaches that are intractable using global data and most web-based platforms.

Consensus is emerging across many of the recent assessment and disclosure standards on the need to include both metrics of company's pressures on biodiversity, as well as metrics of the state of biodiversity based on both species and ecosystems. Metrics of the state of biodiversity include those used to screen and prioritise risks to biodiversity, as well as those used to understand impacts (31).

Business is also heavily involved in the global commodity trading system, which is highly interconnected. This means that consumption in one country can have impacts on multiple others (185, 192). Metrics used to measure the impacts of supply chains need to be comparable between producing and consuming governments. Overall, there is a connection between 'standards' that might be applied by either producing or consuming countries and the fact that one needs to support these standards with comparable measures (193). An example system being tested by the UK government is the Commodity Footprints tool that uses the PDF metric and the species persistence score to assess impacts of commodity trading between nations (66). Additional similar systems are in development and seeking to use relevant biodiversity metrics within their system.

7 Summary Points

Following this review of biodiversity metrics, we make four summary points:

1. **Clarifying uses for many metrics**. Many biodiversity metrics are available to inform decisions regarding screening, planning, and resource allocation for countries and business. However, the large number of potential metrics confuses some users and hinders effective decision-making. Capacity to use

existing metrics and take appropriate decisions is often low and needs to increase.

2. **Meeting the needs of government users**. For governments, nationally generated metrics can be important to address nationally specific circumstances, as well as to create political buy-in and legitimacy, but globally consistent metrics are essential to ensure global consistency. Nested approaches which allow cross-walking between national and global approaches show promise in resolving this (194) (195).

3. **Meeting the needs of business users.** For businesses, frameworks and standards on biodiversity assessment, disclosure and target setting (e.g. TNFD, GRI, ESRS etc) provide an initial set of biodiversity metrics, but further developments of disclosure requirements and guidance will be needed. Business needs to be able to aggregate results from different locations to facilitate decision making at company or portfolio level (189). Metrics that companies use to support screening and target setting should be complemented with metrics that are responsive and amenable to regular updates that allow the company to deliver outcomes and monitor change as a result of management actions (14).

4. **Downscaling metrics to operational scales.** Many global metrics operate at resolutions of $1x1km^2$ due to the resolution of the underlying data. Biodiversity impacts vary at small geographical scales, so metrics that can facilitate understanding of impacts and results of responses at small scales are needed. Metrics developers need to provide clear information about the level of uncertainty in their metrics and the scales where they can reliably be used.

8 Future Directions

1. **Increasing importance of national metrics**. For international and regional agreements there will be an increasing need for core metrics, currently largely

provided by international organisations, to be calculated using agreed standards and methods by national governments. The accelerating demand from business (including finance, and trade related companies) means that creating finer scaled, more frequently updated, more accurate and more actionable metrics will be required (196).

2. **Agreeing a minimum set of metrics for government and business use**. Agreeing on a core set of biodiversity metrics that can work across scales and meet the needs of multiple user groups is clearly desirable. As this review has shown, this is not easy because biodiversity is made up of three components and is both affected by people, managed by people and delivers value to people. The Essential Biodiversity Variables (197, 198) provides another set of options, but many of these proposals are not yet operational, or available, to support decision making.

3. **Automation of metric calculation through and use of technology.** Considerable effort is put into building new products using the latest technology, but these often fail to represent the world in the ways that are useful for biodiversity conservation. For remote sensing and technology companies, and those using AI and machine learning, the inclusion of ecologists and biogeographers familiar with species and ecosystems would improve the biodiversity metrics being generated.

4. **Generating sustainable funding for metric production.** Most areas of society have created funding systems to provide the flows of data and metrics that are required to take decisions. This is the case for health, economy, education, poverty, children, climate and weather, forestry, agriculture, fisheries, genetics, seeds. Most nature data flows are funded through projects or rely on volunteer efforts. This is clearly not a sustainable system and is one of the reasons for fragmentation and duplication of effort.

9 Acknowledgements

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Supplementary Information

Table S1. Assessment of the 562 metrics in Annex 1 in terms of measurement of biodiversity State (S), Pressure (P), Response (R) and Benefits (B) framework (or combinations of these). No metrics were classified as all four.

Metrics classified as one of SPRB		**Metrics classified as multiple of SPRB**			
State	213	State-Pressure	37	State-Pressure-Response	3
Pressure	118	State-Response	13	State-Pressure-Benefit	1
Response	124	State-Benefit	16	State-Response-Benefit	0
Benefit	8	Pressure-Response	4	Pressure-Response-Benefit	0
		Pressure-Benefit	20		
		Response-Benefit	16		

Table S2. Assessment of the 562 metrics in Annex 1 in terms of the metric covering biodiversity components of genes (G), species (S), and ecosystems (E) - or combinations of these.

Metrics classified as only one biodiversity component		**Metrics classified as two biodiversity components**	
Genes	19	Genes-Ecosystems	0
Species	106	Genes-Species	7
Ecosystems	214	Species-Ecosystems	29
Metrics classified as all three	2	General metrics	196

Table S3. Assessment of the 273 metrics incorporating elements of biodiversity state in Annex 1 in terms of their classification as “top-down” or “bottom-up”, and as measures of “intactness” relative to measures of “significance” (14).

	Intactness	Significance	Neither/unknown	Both	**Total**
Top-down	2	29	24	2	57
Bottom-up	58	55	103	1	217
Neither/unknown	0	2	4	2	8
Both	1	0	0	0	1
Total	61	86	131	5	283

Table S4: Example metrics and their associated online platforms (red highlighted use data from IUCN Red List and green highlighted from GBIF) of relevance for use by countries and civil society

Biodiversity Component	Biodiversity Features	Example metric	Platform / Tool
State and Pressure			
Genes	Between species diversity	Evolutionary Distinct and Globally Endangered species (EDGE)	EDGE of existence
Species	Distribution and Diversity	Range Rarity	IUCN Red List
	Extinction risk	Persistence Score/LIFE (Land-cover change Impacts on Future Extinctions)	
	Extinction risk	STAR	Integrated Biodiversity Assessment Tool
	Extinction risk	Red List Index	Integrated Biodiversity Assessment Tool
	Distribution and Diversity	Condition of KBAs	Key Biodiversity Areas
	Population abundance	Living Planet Index	Living Planet Database
	Knowledge availability	Number of occurrence records over time (GBIF)	Global Biodiversity Information Facility
	Knowledge availability	Species Status Information Index	Map of Life
		Invader relative impact	Environmental Impact Classification for Alien Taxa
		Invasive Alien species records	

	threat status/risk of collapse threat status/risk of collapse		Global Register of Introduced and Invasive Species Global Invasive Species Database
Ecosystem	Extent threat status/risk of collapse threat status/risk of collapse threat status/risk of collapse threat status/risk of collapse Condition/integrity Condition/integrity Condition/integrity Condition/integrity	Tree cover extent Critical habitat Natural and Modified Extent Number of Ecosystems units categorised by risk level Human Footprint Index Ecosystem Integrity Index Biodiversity Intactness Index Mean Species Abundance Human Appropriated Net Primary Productivity	Global Forest Watch None None Red List of Ecosystems database UN Biodiversity Lab None UK Natural History Museum GLOBIO Socio economics and data applications centre
	Ecoregion extent Ecoregion condition/integrity	Spatial extent of Ecoregions in 2017 Ecoregion intactness metric	One Earth Navigator none

Response			
Species Recovery programmes	(reversal of) Extinction risk	Calibrated and Realised Species Threat Abatement and Recovery metric	Integrated Biodiversity Assessment Tool
Protected and Conserved Areas	Extent	Terrestrial and inland waters protected area and OECM coverage	Protected Planet
	Representativeness	Protected area and OECM coverage of Key Biodiversity Areas	Integrated Biodiversity Assessment Tool UN SDG Indicators
	Condition/integrity	Management Effectiveness Tracking Tool	Protected Planet
	Condition/integrity	Percentage of the world covered by Green Listed protected areas	Protected Planet
	Representativeness	Species Protection Index	Map of Life
	Representativeness	Extent of Protection by Ecoregion	Protected Planet
Ecosystem restoration	Opportunities	Metrics of species representation or coverage NatureMap restoration metric International Institute for Sustainability restoration metric	Marxan UN Biodiversity Lab We-Plan Forests PLANGEA
Benefit			
Carbon related	Biomass	Forest Carbon Fluxes	Global Forest Watch

	Soil	Potential Carbon Sequestration Soil Organic Carbon Stock	IUCN Contributions for Nature Platform ISRIC World Soil Information (including: GraphicQL and SoilGrids™)
Water related	Quantity	Water Stress (Aqueduct) Water depletion (Aqueduct) Untreated Connected Wastewater (Aqueduct)	Aqueduct Aqueduct Aqueduct WaterWorld WWF Water Risk Filter Aqueduct
	Quality	Untreated Connected Wastewater (Aqueduct) Human Footprint on Water Quality Index	
Species related	Wildlife trade	Measures (number, weight, volumes etc) of species or parts of species in trade over time, legally (CITES), illegally (TRAFFIC)	CITES Trade Viewer Trade in Wildlife Information Exchange Elephant Trade Information System Wildlife Trade Portal

		Red List Index (Internationally traded species) Red List Index (Species used for food and medicine) Red List Index (Impacts of fisheries)	TRAFFIC Trade mapper IUCN Red List
	Tourism	Visitor number Social media posts	Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) – recreation model Co$tingNature – recreation model
Ecosystem Services		Relative aggregate nature conservation priority index (Co$tingNature) Global Maps of Critical Natural Assets	Co$ting Nature UN Biodiversity Lab

1077 **Table S5:** Example metrics within tools and platforms for business, trade-systems
1078 and financial users

Business need	Examples of metrics relevant to business need	Examples of tools relevant to the business need
Site, Portfolio, or Corporate level biodiversity footprint	Species Threat Abatement and Recovery (STAR) and · Range Rarity	Integrated Biodiversity Assessment Tool (IBAT) and ENCORE Biodiversity Module
	Potentially Disappeared Fraction (PDF)	Biodiversity Footprint for Financial Institutions (BFFI)
	Mean Species Abundance (MSA)	Biodiversity Impact Analytics (BIA-GBS); Global Biodiversity Score for Financial Institutions (GBSFI); Biodiversity Integrated Assessment and Computation Tool (B-INTACT); Biodiversity Footprint Methodology (BFM); Corporate Biodiversity Footprint (CBF); Global Biodiversity Score® (GBS®); Biodiversity Net Gain Calculator (BNGC)
Life Cycle Assessment / Product level biodiversity footprint	Potentially Disappeared Fraction (PDF)	LC-IMPACT, SCP-HAT, Impact World+
Screening and measuring supply chain	Species Threat Abatement and Recovery (STAR) and	ENCORE

risks and impacts	weighted version of MSA	
	Potentially Disappeared Fraction (PDF)	BioScope
	Forest Landscape Integrity Index (FLII) and Biodiversity Intactness Index (BII)	Land Griffon
	Lists of species of conservation concern and High Conservation Value forests	SPOTT
	Potentially Disappeared Fraction (PDF)	ReCiPe3
	Tree cover change	GFW Pro
	Various water related metrics included	WWF Water Risk Filter
	Uses MSA and other metrics	WWF Biodiversity Risk Filter,
	Uses PDF and Species-ha metrics	Commodity Footprints
Setting targets for nature	Natural Lands Map	The SBTN land targets guidance
	Species Threat Abatement and Recovery (STAR)	
Assessing business	Biodiversity Intactness Index (BII)	Integrated Biodiversity Assessment Tool (IBAT)

dependencies on nature		
	Range rarity	ENCORE
	Aggregated index of water security, timber provision, food provision, habitat intactness, pollination, soil fertility, water quality, regulation of air quality & local climate, erosion control and coastal protection	Biodiversity and Ecosystem Services (BES) Index
Measuring the value of ecosystem services	Spatial and in some cases temporal distribution of ecosystem service layers	Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST)
	Spatial and in some cases temporal distribution of ecosystem service layers	Co$ting Nature
	Static Ecosystem Service maps	Global Modeling of Nature's Contribution to People
	Ecosystem Integrity score (across 7 ecosystem service categories)	Ecosystem Services Identification & Inventory (ESII)

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Table S6: Selected examples of metrics measuring different aspects of natural capital and ecosystem services within the framework of genes, species, ecosystems and multidimensional metrics. Example papers and tools are provided according to the expertise of the authors, supplemented by Des Roches et al. Major categories of natural capital adapted from Leach et al.

Natural Capital type	**Example ecosystem services**	**Example paper**	**Metric presented (Genes=G, Species=S, Ecosystems = E)**
Soils and Sediments	Soil quality	Beillouin et al. (2021) Barrios et al. (2007) Baragaoui et al. (2021)	Soil biota diversity (S) Fungal leaf litter decomposition (G)
Water	Water quality	Duarte et al. (2019) Vaughn (2018) Seena et al. (2023) Thomaz (2023) Waterworld (Mulligan 2009, 2013, 2022)	Water quality metrics (turbidity, pollutant loads, clarity) (E)
	Water availability	Aqueduct (Kuzma et al. 2023) Waterworld	Water stress (E)
Forests	Biodiversity habitats	Zytynska et al. (2011)	Within-species genetic variation (G)
Grasslands	Biodiversity habitats	Sollenberger et al. (2019) Bengtsson et al. (2019)	Pollinator habitat (S)

Genetic resources, and plant, animal, fungal, and algal species	Timber	Felipe-Lucia et al. (2018); Swenk et al. (2012)	Timber volumes in trade (S)
	Nontimber forest products	Chaïr et al. (2011) *Charcoal*: Schaafsma et al. 2014 *Building materials*: Schaafsma et al. 2012	Charcoal and building materials volumes and values in trade (S,E)
	Medicinal plants	*Case studies:* Caballero-Serrano et al. (2019); Perinchery (2020); Sucholas et al. (2017)	Medicinal plants volumes and values in trade (S)
	Wildlife trade / trophy hunting	Traits for hunting selection literature	Volumes, values, numbers of wildlife products in trade (S)
	Wildmeat (Coad et al. 2019; Ingram et al. 2021)	Selection traits literature	Wildmeat species volumes and values in trade (S)
	Domestic species	FAO livestock diversity	Domesticated animal numbers, volumes and values in trade (G)
Multidimen-sional ecosystem bundles	Bundles of services from wild biodiversity	Co$ting Nature; Willcock et al. 2019, 2023; Provost et al. 2022	Ecosystem bundles amounts and values available or delivered to people (S,E)

References

Annex 1. Comprehensive list of Biodiversity Metrics

Annex 2. Example Platforms and Tools that deliver information to governments, civil society and business, but lack associated biodiversity metrics