ANNUAL REVIEWS

Annual Review of Environment and Resources

Global Metrics for Terrestrial Biodiversity

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Annu. Rev. Environ. Resour. 2024. 49:673–709

The *Annual Review of Environment and Resources* is online at environ.annualreviews.org

https://doi.org/10.1146/annurev-environ-121522-045106

Keywords

state, pressure, response, benefits, biodiversity, metrics

Abstract

Biodiversity metrics are increasingly in demand for informing government, business, and civil society decisions. However, it is not always clear to end users how these metrics differ or for what purpose they are best suited. We seek to answer these questions using a database of 573 biodiversity-related metrics, indicators, indices, and layers, which address aspects of genetic diversity, species, and ecosystems. We provide examples of indicators and their uses within the state–pressure–response–benefits framework that is widely used in conservation science. Considering complementarity across this framework, 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 on a minimum set of metrics for government and business use, automating 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 were made at the Fifteenth Meeting of the Conference of the Parties (COP15) to the Convention on Biological Diversity (CBD), the UN Framework Convention on Climate Change, and 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.

THE KUNMING–MONTREAL GLOBAL BIODIVERSITY FRAMEWORK AND ASSOCIATED PACKAGE OF DECISIONS

The GBF was adopted during COP15. This historic framework builds on previous strategic plans under the CBD and sets out a 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 COP15. They include a monitoring framework; an enhanced multidimensional approach for planning, monitoring, reporting, and reviewing implementation of the GBF; and decisions relating to the means of implementation that will be necessary to enable effective implementation of the framework (resource mobilization, capacity building and development as well as technical and scientific cooperation, and finally an agreement regarding the fair and equitable sharing of benefits from the use of digital sequence information on genetic resources).

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. A global analysis of progress toward national targets will be completed for review at COP16, based on information submitted by the parties in 2026. COP17, in 2028, will include a global review of collective progress toward implementation of the framework. In this context, monitoring of implementation by governments and other stakeholders will be essential for understanding the progress made toward the 2030 targets. Robust metrics used by both parties and nonstate actors will be key input to the global review of collective progress.

At COP15 in 2022, the parties adopted a package of decisions including the Kunming–Montreal Global Biodiversity Framework (GBF), which contains four goals, 23 targets, and an associated monitoring framework comprising a suite of headline indicators, components, and complementary indicators (see the sidebar titled The Kunming–Montreal Global Biodiversity Framework and Associated Package of Decisions). The GBF complements mechanisms under other biodiversity-related conventions and adds specificity to SDG 14 (life below water), 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 toward 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., how to reduce threats to biodiversity, how biodiversity can be sustainably used to provide equitable benefits for people, and how to ensure sufficient finance and capacity to deliver the adopted decisions) (1). To guide implementation and measure progress toward the goals and targets, robust biodiversity metrics are required for the GBF monitoring framework (2) and the SDG indicators framework (3), both of which aim to measure progress toward global sustainability goals.

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 are committed to implementing the agreements made at climate and biodiversity COPs. More than 5,800 businesses set climate targets aligned with the Paris Agreement, and more than 1,400 called for action on biodiversity at COP15. Several voluntary and mandatory frameworks and standards are emerging to support nature-related assessments, disclosures, and target setting by businesses. Examples include the Taskforce on Nature-Related Financial Disclosures (TNFD), which focuses on nature in general; the Science Based Targets Network (SBTN), which focuses on freshwater and land; the International Union for Conservation of Nature (IUCN) Nature-Positive Initiative, which focuses on biodiversity; and the Global Reporting Initiative (GRI)

Indicators: measures based on verifiable data that convey information; can be (*a*) presented in the context of progress toward a target or (*b*) used to assess the effectiveness of an intervention

Metric: a system or standard of measurement; for example, biodiversity observations collected over space and/or time can be used to create a metric on biodiversity either directly (e.g., number of species observed) or indirectly (e.g., habitat extent or condition) standards, which focus on sustainability, including dedicated standards for selected environmental issues.

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

Mandatory regulatory requirements, which apply to businesses and the trade system between governments, are also emerging. Examples include the European Union's Due Diligence Directive, Deforestation Regulation, and Corporate Sustainability Reporting Directive as well as France's Article 29. The International Finance Corporation's Performance Standard 6 on Biodiversity (6), widely adopted by regional development banks and Equator Principles financial institutions, adds momentum by making access to capital dependent on biodiversity metrics and reporting. The International Sustainability Standards Board's general sustainability disclosure and climate disclosure standards are expected to be mandated in jurisdictions around the globe. Additionally, the International Standards Organisation has established Technical Committee 331 on Biodiversity.

As political and business commitments have been established, and as scientists have increasingly engaged in these processes, numerous metrics (i.e., systems or standards of measurement) for biodiversity have been proposed and conceptualized. Many of them have been developed into readily available tools and data layers for application by users. This proliferation of metrics (and of tools delivering them) makes it difficult for end users to know which are the most reliable, scientifically robust, and appropriate for different use cases (7). This problem is exacerbated by the complexity of many metrics and the inaccessibility of their methodologies and/or underlying data.

Supplemental Material >

In this review, we present an assessment of biodiversity metrics, indicators, and indices (collectively referred to as metrics below) that have been developed for use in decision-making by governments, businesses, financial institutions, and civil society (**Supplemental Table 1**). We distinguish these metrics from scientific discussions on the different ways of quantifying biodiversity change (e.g., 8). We reviewed all metrics against the causal-chain state–pressure–response–benefit (SPRB) framework, widely used for identification of and reporting against indicators (9–11) (**Figure 1**; see also the sidebar titled State–Pressure–Response–Benefit Framework).

In this review, we adopt the CBD's definition of biodiversity, which encompasses three different components: genes, species, and ecosystems (**Table 1**). Each of these components contains a variety of features that require different metrics to measure. For an overview of how biodiversity

STATE–PRESSURE–RESPONSE–BENEFIT FRAMEWORK

The SPRB framework was adapted from the Organisation for Economic Co-operation and Development (OECD) pressure–state–response model (12, 13) and was adopted by the CBD to guide indicator development (14). 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 utilization). Society then attempts to reduce or mitigate these pressures by implementing environmental and economic policies or actions, thereby recovering 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 the benefits category is important in the context of biodiversity policy and practice and justifies our use of the SPRB framework rather than considering only state, pressure, and response. However, we do not use the expanded drivers–pressures–state–impact–response model because drivers and pressures are hard to separate. We also classify metrics of the state of biodiversity derived from bottom-up relative to top-down approaches, as well as metrics measuring significance relative to those measuring intactness (15).

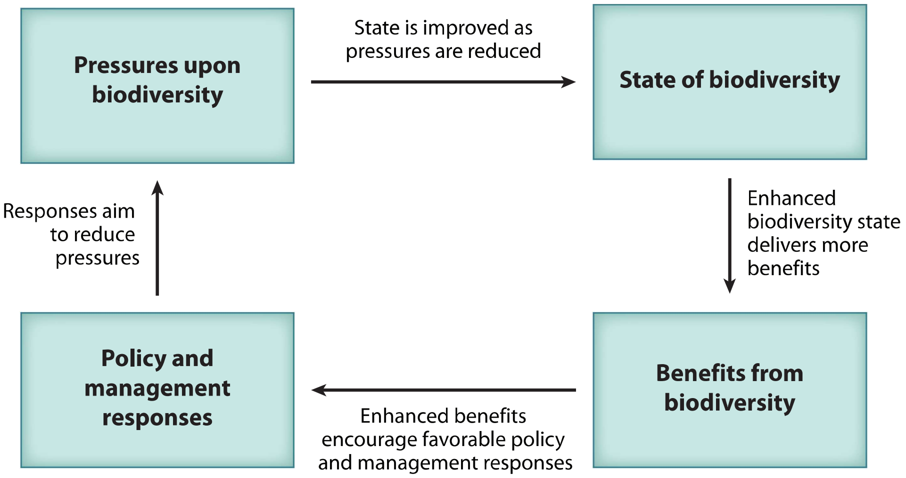


Figure 1

Graphical representation of the state–pressure–response–benefits model often used in biodiversity measurement. In this schema, state refers to the current condition of biodiversity (for example, the level of genetic diversity within and between species, species distribution and abundance, and ecosystem extent and condition), generally within a geographically defined area and often monitored over time. Pressures refer to the threats, mainly caused by humans, that negatively affect biodiversity state (genes, species, and ecosystems). Responses refer to the actions taken by people (individually or via government or other actors) seeking to reduce the pressures on biodiversity or enhance biodiversity state. Benefits are the ecosystem services that biodiversity provides to people and include tangible aspects like food or building materials, as well as less tangible aspects like sense of place or various forms of cultural benefits. Figure adapted with permission from Reference 9.

is defined across disciplines, as well as a review of the values, patterns, and trends of biodiversity, see Díaz & Malhi (16).

This review focuses on terrestrial biodiversity metrics, partly because there are smaller bodies of research on metrics for freshwater (17–21) and marine systems (11, 22–24). 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

Supplemental Material >

We have compiled a database of biodiversity metrics (**Supplemental Table 1**). We did not use a formal literature search protocol; instead, we built our database from several existing lists. These include compilations of possible indicators to support the development of the monitoring framework for the GBF (25–28) based on information provided by the Biodiversity Indicators Partnership, an inventory of spatial data sets developed to support governments and business with spatial planning for biodiversity (29), an assessment of the role of remote sensing in spatial

Table 1 The three components of biodiversity and example features[a]

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

[a] As defined in Article 2 of the text of the Convention on Biological Diversity (**https://www.cbd.int/convention/text/default.shtml**): "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."

Table 2 Numbers of metrics under the GBF and SDGs that are included in our analysis[a]

	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

[a] The sum of headline, component, and complementary indicators does not add up to the total GBF indicators because some indicators are classed as more than one if they are under different targets.

Abbreviations: GBF, Kunming–Montreal Global Biodiversity Framework; SDG, Sustainable Development Goal.

Supplemental Material >

Top-down: refers to metrics that are measured by extrapolating or modeling biodiversity features from samples across a given ecological unit (ecosystem, habitat); often, the modeling includes the impacts caused by threats

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

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

Significance: refers to metrics that compare the relative importance of losses or gains in biodiversity across space and time

planning for biodiversity (30), and a review of top-down intactness compared with bottom-up significance metrics (15). We combined and standardized these lists, 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 **Supplemental Table 2**).

Two authors of this article (N.D.B. and M.H.) assessed each metric in terms of its relevance to spatial or temporal aspects of biodiversity state, pressure, response, or benefits (**Figure 1**), as well as the biodiversity elements of genes, species, or ecosystems. These comparisons yielded greater than 70% agreement, with the remainder harmonized through discussion. Similarly, for biodiversity state metrics, two other authors (F.H. and T.M.B.) assessed the bottom-up/top-down and significance/intactness classifications, yielding 96% agreement; mismatches were harmonized 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 about measurement of pressures. We found that some also contain information relevant to responses. Others that we assessed as measuring benefits to people also created pressures on biodiversity where the use was unsustainable. **Supplemental Table 1** documents these non–mutually exclusive classifications. Ultimately, we identified 573 metrics that aim to measure different elements and features of biodiversity (**Supplemental Table 1**) within the frameworks of SPRB (**Figure 2*a***; **Supplemental Table 3**), genes–species–ecosystems (**Figure 2*b***; **Supplemental Table 4**), and top-down/bottom-up and significance/intactness (**Figure 2*c***; **Supplemental Table 5**).

3. ALIGNING METRICS WITH USERS

Different user communities require biodiversity metrics. The main user groups are governments (including policymakers 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 organizations, intergovernmental trade agreements), technical agencies [international organizations, nongovernmental organizations (NGOs), universities], and civil society encompassing local communities and citizens (Indigenous peoples, general public, resource users). We use the information in **Supplemental Table 1** to highlight metrics, indicators, and indices proposed for use by governments (**Table 2**) and provide examples of their use below.

3.1. Governments

Biodiversity metrics for use by governments in relation to international and national policies and laws may be politically agreed upon at various scales (global, regional, national, and subnational). For example, the parties to the CBD adopted a set of 26 headline indicators to track progress toward the goals and targets of the GBF, along with another 58 component and 230

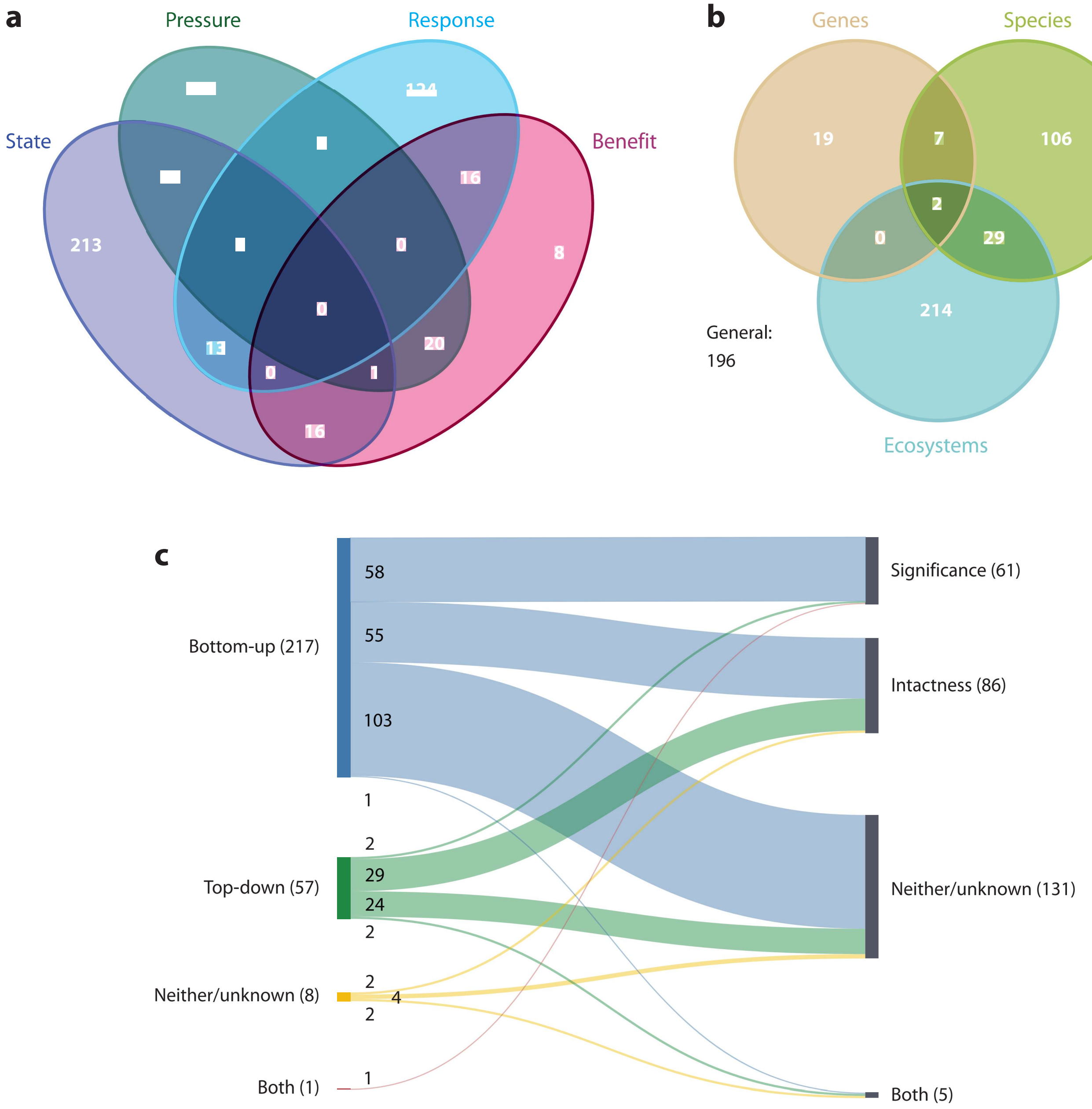


Figure 2

Overview of the 573 metrics we identified (see **Supplemental Table 1**), including remotely sensed measures of ecosystem change; changes in the distribution, abundance, or extinction risk of species (sometimes with the inclusion of the pressures affecting those species); and various measures of genetic diversity within and between species. (*a*) Number of and overlap between metrics classified within the state–pressure–response–benefit framework (see **Figure 1** for an explanation of that framework) showing that there are many metrics for each aspect, but some metrics cover two or more aspects of the framework. (*b*) Number of and overlap between metrics classified within the different components of biodiversity (genes, species, and ecosystems) or classified as general because they relate to all three components (e.g., a global map of natural capital, above- or belowground biomass). (*c*) Number of metrics that are classified as top-down (i.e., compiled through extrapolation, such as the Biodiversity Intactness Index) or bottom-up (i.e., aggregated from individual components, such as protected area extent per country) and that relate to biodiversity significance (i.e., importance) or intactness (i.e., condition). Panel *c* adapted from images created using SankeyMATIC (see also **Supplemental Tables 3–5**).

Supplemental Material >

complementary indicators that governments can use subject to national needs (28). Similarly, national governments have adopted 24 biodiversity-related indicators to track progress toward SDG 15. These metrics are highlighted in **Supplemental Table 1**. **Supplemental Tables 6 and 7** present a shortened list of options for government and civil society use and indicate the online sources of these metrics (other online platforms are listed in **Supplemental Table 2**).

Supplemental Material >

Platforms: systems, typically online, that bring information to users; here we focus on platforms that include a biodiversity metric

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

3.2. Business- and Trade-Related Bodies

There is growing recognition that biodiversity is associated with significant financial risks and opportunities for businesses (4, 5), and regulatory requirements for businesses to report on their climate- and nature-related risks are emerging (31). Target 15 of the GBF, and to some extent Target 16, provides a political impetus for the parties to the CBD 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 already provide or are developing guidance on the use of biodiversity metrics for corporations and finance bodies across value chains, for example, through the TNFD, GRI standards, SBTN, EU Business@Biodiversity Platform, Align Project, Natural Capital Protocol, the IUCN approach to measuring Nature-Positive contributions, and the World Economic Forum Measuring Stakeholder Capitalism initiative. An emerging trend across these initiatives is a growing recognition that businesses need to contextualize 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 species population size and extinction risk (e.g., 15, 31).

Corporate biodiversity footprinting tools often rely on the use of modeled pressure–state relationships (i.e., top-down intactness metrics) to estimate impacts across business value chains. For example, the Global Biodiversity Score (32), Corporate Biodiversity Footprint (33), and Biodiversity Impact Metric (34) use the mean species abundance (MSA) metric. This metric weights MSA by species range rarity, derived from the IUCN Red List of Threatened Species (35). The widely used life cycle impact assessment method ReCiPe (36) applies the potentially disappeared fraction of species (PDF) metric (37) to biodiversity impact assessment. The ReCiPe method is also utilized in business-oriented life cycle assessment 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 species threat abatement and restoration (STAR) (40), not least to ensure their alignment with and track their contributions toward global goals such as the GBF and SDG 15. For a shortened list of options of metrics for business use, including online sources, see **Supplemental Table 7**.

While global metrics are most applicable for screening processes, metrics based on primary data are often needed to calculate the actual, realized footprints on the ground and track the 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 Metrics

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 the positive impacts of responses. However, measurements of changes in the state of biodiversity do 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's definition of the gene component of biodiversity covers within-species aspect of genetic diversity (**Table 1**). Intraspecific genetic variability is critical not only intrinsically but also to ensure that species are resilient to environmental change (46). The importance of genetic diversity and of sharing its benefits is also recognized under Target 13 of the GBF.

Despite the importance of the within-species genetic element, few data sets are available to assess it (**Figure 3**). Metrics of genetic diversity within wild mammal and amphibian species (47) complement research 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 a headline indicator. It acts as a proxy for loss of genetic diversity but is recognized as insufficient (49). Hoban et al. (50) proposed an additional metric, "the proportion of populations maintained within species," which reflects the loss of genetic distinctiveness of a given population. Most of the above examples are bottom-up metrics of biodiversity intactness. Significance metrics for genetic biodiversity have yet to be developed.

The between-species element of genetic diversity (see the sidebar titled State–Pressure–Response–Benefit Framework) can be assessed with phylogenetic diversity metrics, which are bottom-up metrics of biodiversity significance. They measure the shared ancestry of taxonomic groups and the breadth of evolutionary history, and they represent the evolutionary distance between coexisting taxa (52). Several phylogenetic diversity metrics are available for vertebrate groups (53–55) 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, research to date suggests that these metrics 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 the IUCN Red List (17, 35), or data on selected vascular plant groups (57–61). Therefore, vertebrates and vascular plants are often used as surrogates for wider biodiversity applications (e.g., 62). These applications are rather robust (63), even though plants, invertebrates, and fungi sometimes differ in their distribution patterns (e.g., 64). The IUCN Red List contains information about species distribution; population size, structure, and trends; habitat preferences; threats; and actions needed and implemented for more than 150,000 species (35). These data are applied to a set of criteria (65) to classify species' risk of extinction. A total of 42,100 species are classified as threatened with extinction.

Measurements of IUCN Red List species extinction risk can then be aggregated to yield bottom-up metrics of biodiversity significance, such as STAR (40) and LIFE (67). STAR, for example, is a wholly scalable and additive measure of global specific risk reduction opportunity. Furthermore, repeated assessments of species' extinction risk over time enable calculation of the Red List Index (RLI) (10, 68) for complete suites or random samples of species, thereby showing how their aggregate extinction risk has changed over time. The RLI measure of extinction risk has been adopted as a GBF headline indicator and an SDG indicator. These are all bottom-up metrics of biodiversity significance. Meanwhile, the IUCN Green Status of Species (69, 70) aims to measure different dimensions of species recovery. It is meant to be used in tandem with an assessment of extinction risk.

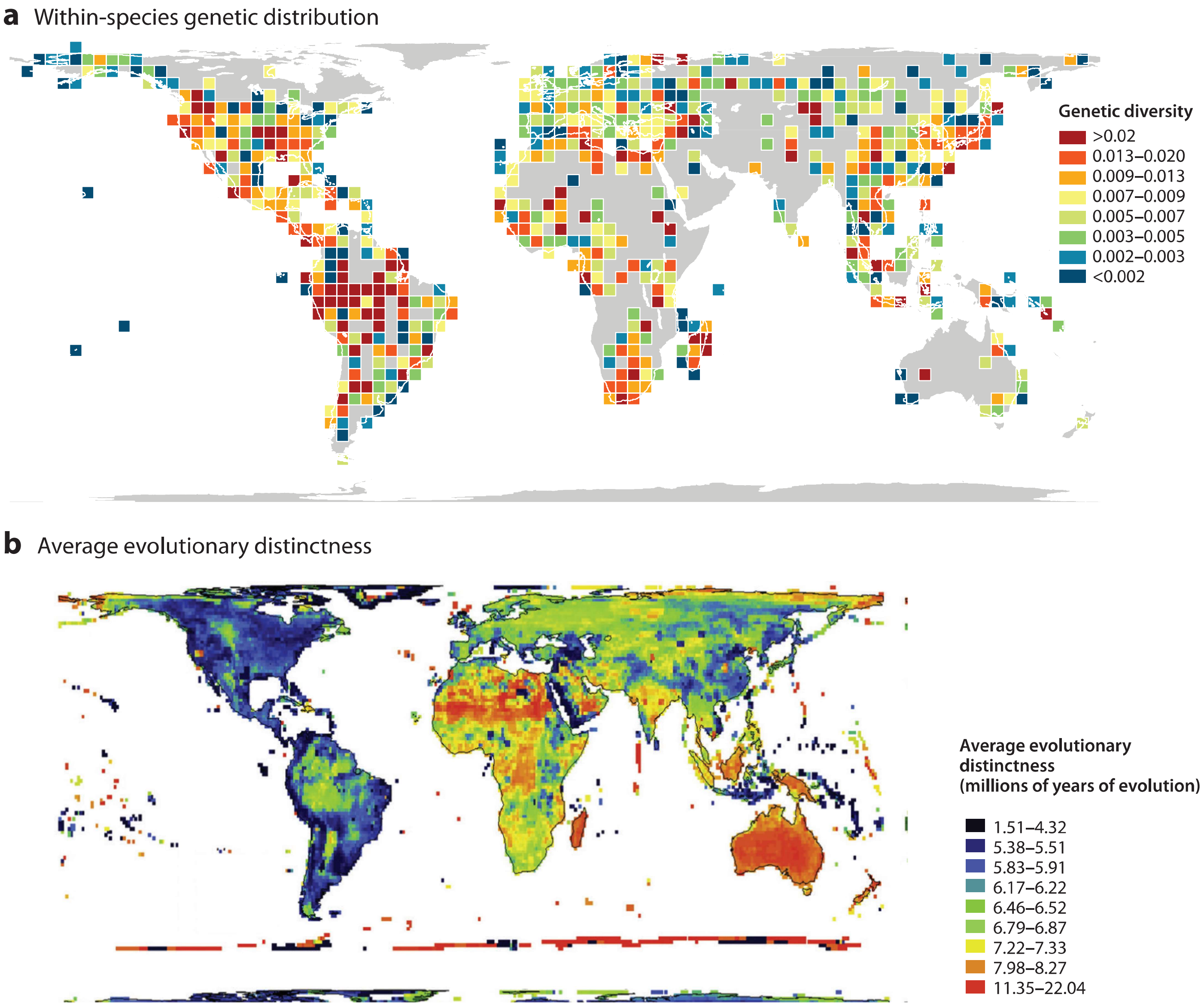


Figure 3

Examples of spatial and temporal genetic metrics. (*a*) Within-species genetic diversity (47) based on 92,801 mitochondrial sequences for >4,500 species of terrestrial mammals and amphibians. Using 86,406 cytochrome b (cytb) sequences, species-specific sequence alignments were performed for 4,675 species, and nucleotide diversity was calculated per site for each species through pairwise comparisons of georeferenced aligned sequences (24,479 cytb sequences from 1,992 species). To map the average number of genetic mutations globally, the metric of genetic diversity was calculated for each equal-area grid cell (~150,000 km^2) by averaging nucleotide diversity per site across all species present and within each grid cell. This study found that within-species genetic diversity is 27% higher in the tropics than in nontropical regions. Geolocated within-species genetic records are patchily distributed globally, and the available data are not sufficient for use in decision-making, the creation of indices, or conservation planning. Panel *a* adapted from Reference 47 with permission from the American Association for the Advancement of Science. (*b*) Geographic patterns of evolutionary distinctness (ED), showing the contribution to the total evolutionary history of each species' clade (expressed in millions of years of evolution averaged across all species occurring in each cell), for 9,993 species of birds. ED is expected to reflect uniquely divergent genomes and functions, and its geographic distribution is clustered, with the world's top 1,000 (i.e., top 10%) species with ED concentrated in the isolated landmasses of Australia, New Zealand, and Madagascar, as well as in Africa and southern parts of South America. Panel *b* adapted from Reference 51 (CC BY 3.0). The boundaries and names shown and the designations used on these maps do not imply official endorsement or acceptance by the United Nations.

Metrics relating to distribution and diversity that cover biodiversity patterns of nonvascular plants or invertebrates—for instance, for soil biota such as fungi (71), earthworms (72), and nematodes (73)—are also becoming available. Nevertheless, the lack of data on some of the most speciose groups (72, 74–76) 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 issue has been known for decades and is only slowly being addressed.

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), and indices aim to reduce complexity into individual measure(s)

The Global Biodiversity Information Facility (GBIF; see **https://www.gbif.org**) assembles 2.97 billion (as of July 18, 2024) 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 the availability of biodiversity data, but GBIF data are fed into many other biodiversity state metrics, 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 information, and sometimes distance to water and other factors, to model species' distributions and changes therein 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 (77, 78). With its higher spatial resolution, area of habitat is more useful for spatial analyses of biodiversity values than the underlying range maps (78, 79) and is used to underpin STAR, LIFE, and other metrics (for examples, see **Figure 4**).

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

Connectivity is a multifaceted state measure. 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 (80). Areas where the flow of species movement is concentrated are identified, as they have the potential to disproportionally reduce connectivity.

4.1.3. Ecosystems.

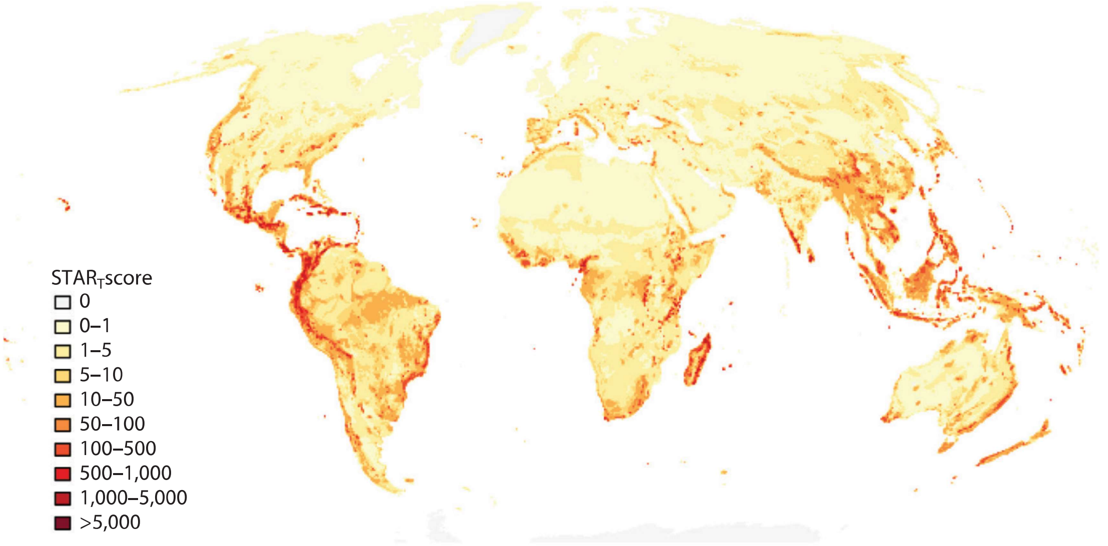
More than 100 years of research aiming to classify ecosystems underpins the creation of ecosystem metrics reflecting area and condition. The most recent advance in ecosystem classification is the development of the IUCN Global Ecosystem Typology (81, 82).

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. Bottom-up intactness metrics that assess the extent of individual ecosystems throughout the world—such as forests (83–85), mangroves (86), seagrasses (87), salt marshes (88), coral reefs (89), peatlands (90), and wetlands and water bodies (91, 92)—are increasingly available (**Figure 5**). Measuring the extent of some ecosystems still poses challenges—for example, in differentiating natural grasslands from pasture or croplands, differentiating natural forest from plantations or tree crops (e.g., rubber, palm oil; 93), 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 standardization in land use and land cover classifications, and the creation of national land cover and land use maps for most countries, facilitates the use of satellite remote-sensing data to measure changes in ecosystem area and condition at local to national scales (30).

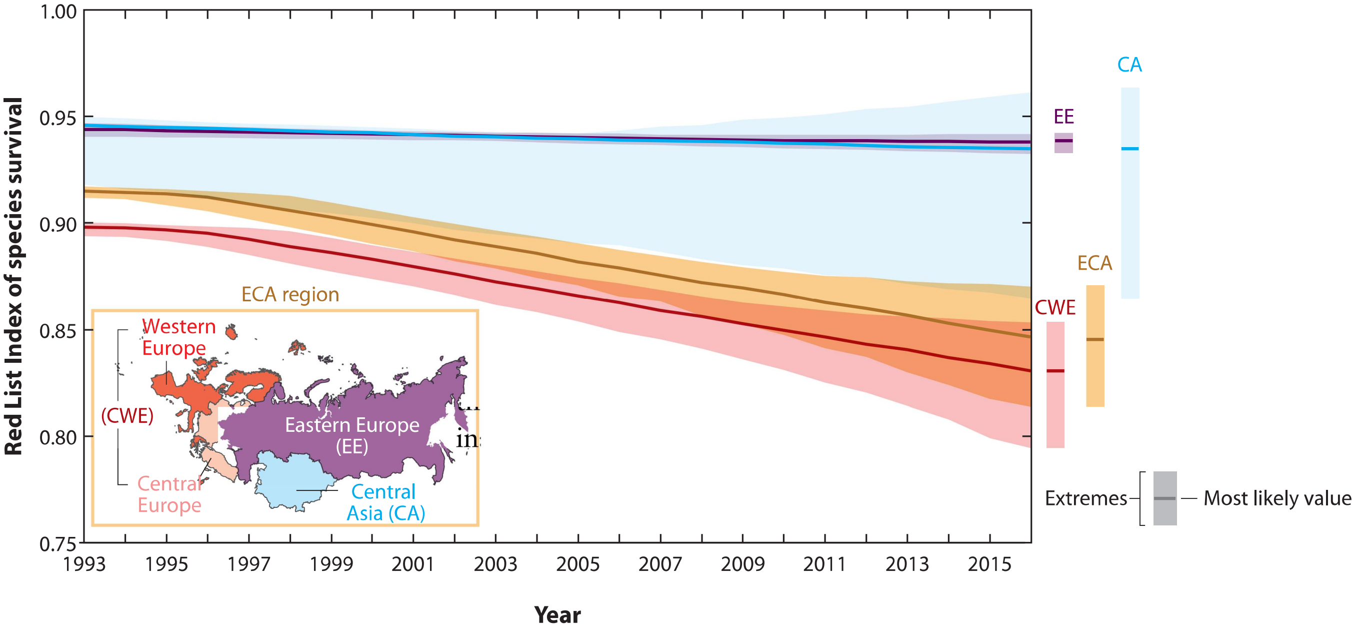
Using remote sensing to directly calculate metrics of ecosystem condition is difficult, so such metrics are often assessed indirectly to generate top-down intact measures through proximity to pressures (e.g., 84). However, measures such as tree canopy height (97) or radar-based forest condition assessments (98) can deliver metrics of condition for forest ecosystems (84, 99). Another way to calculate ecosystem condition uses the intactness of species assemblages. The PREDICTS database, which contains 376,992 records of site-level species assemblages, has been used to create the Biodiversity Intactness Index (100, 101), which provides an estimated percentage of the original number of species and their remaining abundance following changes in land use. The MSA metric is a similarly modeled index of biodiversity assemblage intactness (102, 103) (**Figure 6**).

The IUCN Red List of Ecosystems is a large program that aims to assess ecosystem condition. It uses a nationally driven approach and links to a globally agreed-upon methodology (104–107). It is gradually developing worldwide assessments of the state of ecosystems in terms of their risk of collapse and has been incorporated into the GBF. In turn, these assessments will allow the derivation of bottom-up metrics of biodiversity significance at the ecosystem level (e.g., 108).

a Spatial metrics: species extinction risk reduction opportunity



b Temporal metrics: trends in species extinction risk



(*Caption appears on following page*)

Figure 4 (*Figure appears on preceding page*)

Examples of spatial and temporal species metrics. The IUCN Red List is an inventory of the global extinction risk of species, using data on population size, trends, and distribution, among other factors, to assign species to categories of extinction risk. Assessments include documentation of threats impacting each species and conservation actions in place and needed. Assessments for species are repeated periodically. The Red List allows the creation of different metrics relating to species' state and the impacts of different pressures on extinction risk. (*a*) STAR metric (40) showing the STAR_{T} scores that quantify the contributions of mitigating threats in a location to reducing global extinction risk. The total global STAR_{T} score represents the global threat abatement effort needed for all Near Threatened and threatened (Vulnerable, Endangered, and Critically Endangered) amphibian, bird, and mammal species, according to the IUCN Red List. This score can be disaggregated by threat type based on the known contribution of each threat to species' risk of extinction. Scores range from 0 to >5,000 with the score calculated as follows: Each species has a global STAR_{T} score, weighted relative to their extinction risk. Each STAR_{T} score can be disaggregated spatially on the basis of the AOH currently mapped for each species. The total STAR_{T} score per grid cell is thus the sum of the individual species' STAR_{T} scores. In the map, STAR_{T} scores from white to pale yellow are locations where species face threats that can be addressed with some effort, whereas regions colored orange through dark red contain species where reducing threats will require considerable effort. Panel adapted with permission from Reference 40; copyright 2021 *Nature Ecology & Evolution*. (*b*) The Red List Index shows trends in the overall extinction risk of groups of species (birds, mammals, and amphibians) based on data from the IUCN Red List. It is calculated from the number of species in each Red List category and the number moving between categories when reassessed owing to genuine improvements or deteriorations in their status that are of sufficient magnitude to qualify for higher or lower Red List categories of extinction risk. Changes between categories owing to improved knowledge or revised taxonomy are excluded. Red List Indices for Europe and Central Asia (66) illustrate trends in the rate at which species are moving toward (or away from) extinction in these regions. Red List Index calculations for 1993–2015 show no overall trend toward extinction for species in Eastern Europe or Central Asia but do suggest trends toward extinction in Central and Western Europe. Panel *b* adapted with permission from Reference 66; copyright 2018 IPBES. Abbreviations: AOH, area of habitat; ECA, Europe and Central Asia; IUCN, International Union for Conservation of Nature; STAR, species threat abatement and restoration; STAR_{T}, threat abatement component of STAR. The boundaries and names shown and the designations used on these maps do not imply official endorsement or acceptance by the United Nations.

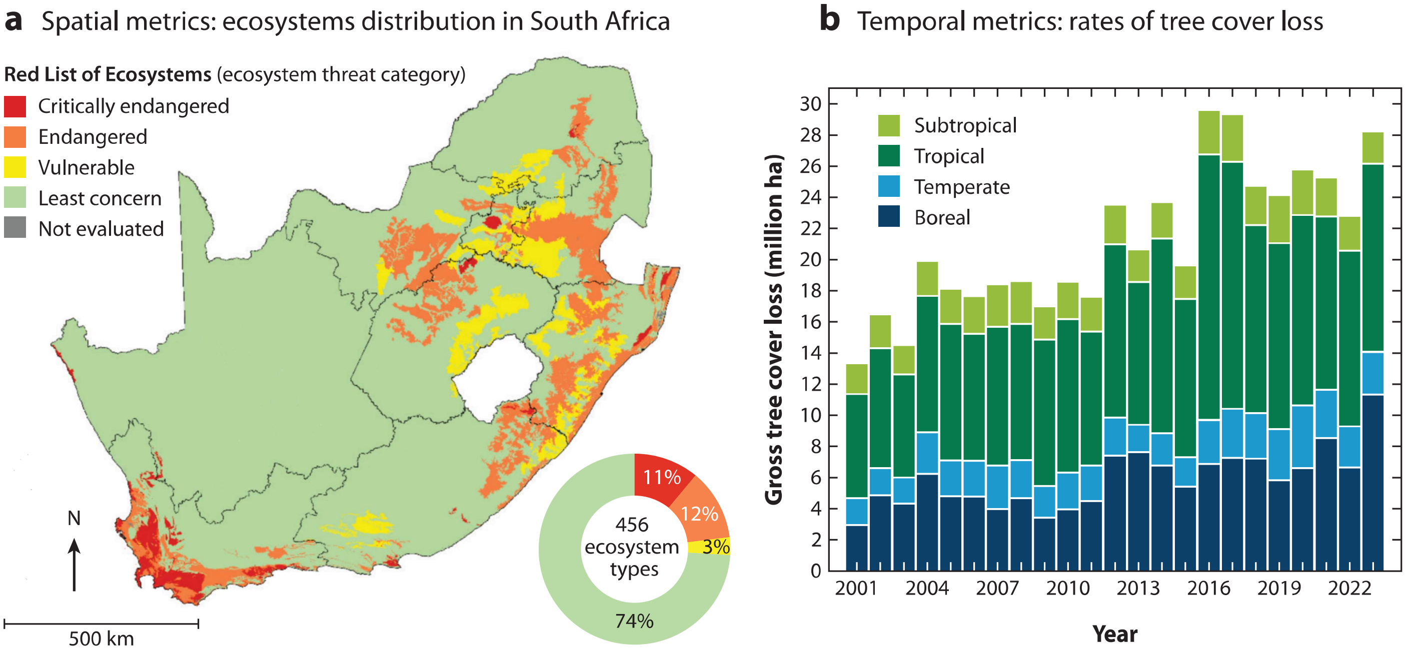


Figure 5

Spatial and temporal metrics of ecosystem extent. (*a*) Distribution of threatened terrestrial ecosystems in South Africa (94) as assessed using the framework of the IUCN Red List of Ecosystems. The inset pie chart shows the percentage of ecosystem types that fall within each threat category. The map shows the historical extent of ecosystems (95), but the assessments of ecosystem threat status were completed between 2017 and 2021. Panel *a* adapted from Reference 94 (CC BY 4.0). (*b*) Global trends in annual gross tree cover loss by ecozone since 2001 (83, 96), illustrating one of the ecosystems that can be monitored from space to illustrate global declines in tree cover in different parts of the world. Panel *b* adapted from Global Forest Review (96) (CC BY 4.0), which includes data from Reference 83 and Global Forest Watch. The boundaries and names shown and the designations used on these maps do not imply official endorsement or acceptance by the United Nations.

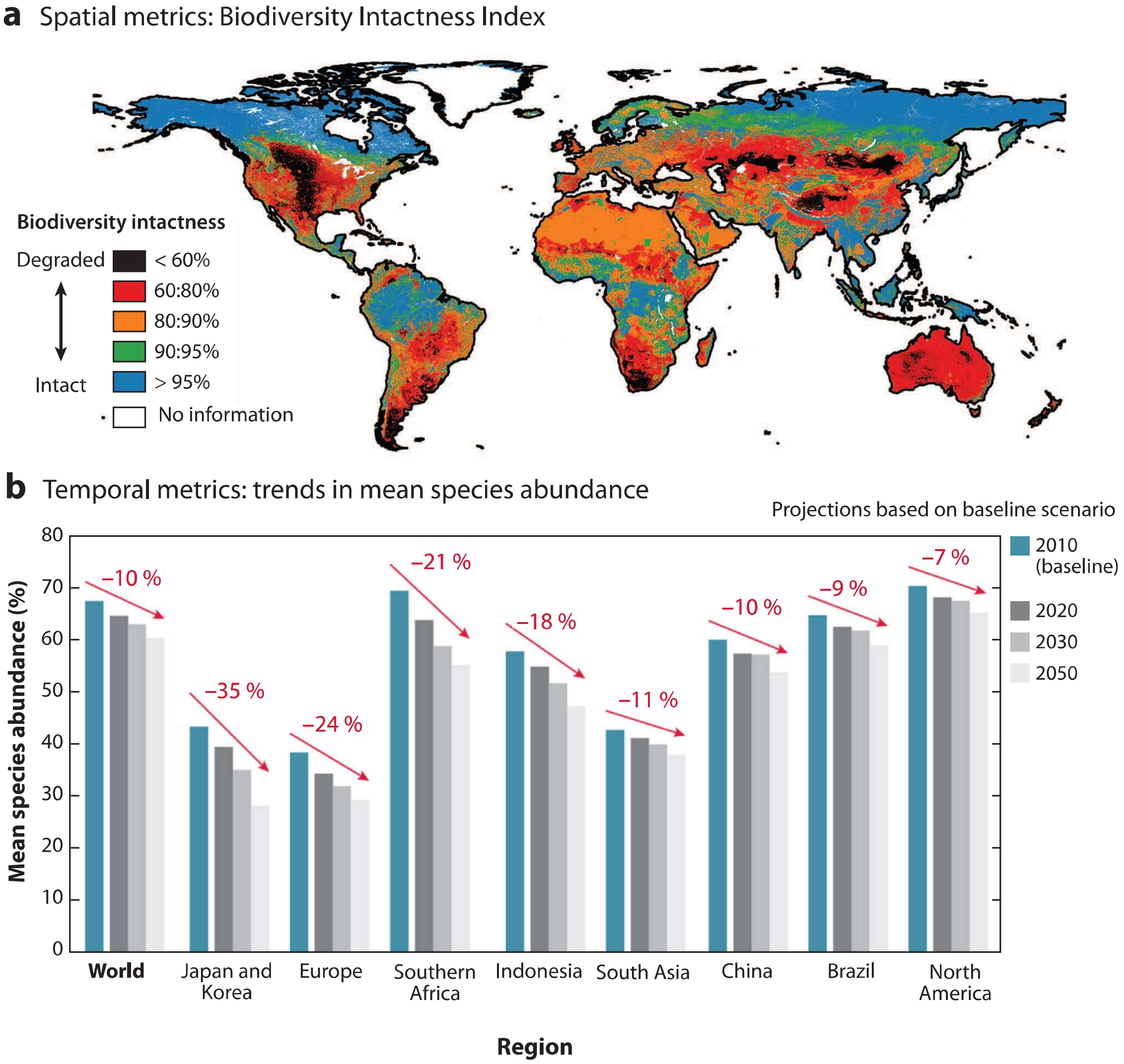


Figure 6

Examples of spatial and temporal ecosystem condition metrics. (*a*) The Biodiversity Intactness Index (BII) (101), which shows how the assemblage of biodiversity has changed from a historical baseline situation. The BII is an estimated percentage of the original number of species and the abundance that remains in any given area despite human impacts. It helps us understand past, current, and future biodiversity changes. The BII uses a database of around 58,000 species, encompassing birds and mammals, as well as plants, fungi, and insects. Published studies allow the creation of a baseline of the number and diversity of species at near-undisturbed sites and allow comparison of this baseline to the biodiversity at sites with medium and high human activity. In combination with satellite imagery of land cover, infrastructure, and human population, a BII can be modeled for terrestrial areas of the world. Panel *a* adapted from Reference 101 with permission from the American Association for the Advancement of Science. (*b*) Projected trends in mean species abundance (MSA) from the baseline year of 2010 to 2050 (109), showing how assemblage composition has changed (negatively) and is projected to change (negatively) in various regions of the world. The MSA metric is an indicator of local biodiversity intactness. MSA ranges from 0 to 1, where 1 means that the species assemblage is fully intact and 0 means that all original species are extirpated (locally extinct). Red arrows and numbers indicate the predicted percentage decline in mean species abundance up to 2050. Panel *b* adapted from Reference 109; copyright OECD. The boundaries and names shown and the designations used on these maps do not imply official endorsement or acceptance by the United Nations.

4.2. Biodiversity Pressure Metrics

Conservation efforts often focus on reducing pressures in order to reduce biodiversity loss and ultimately facilitate improvements in the state of biodiversity (110). The creation of biodiversity pressure metrics facilitates decision-making by assessing both (*a*) the kinds of pressures that need to be addressed to improve the state of biodiversity (i.e. through planning) and (*b*) how effective actions have been in reducing pressures (i.e., using 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. **Supplemental Table 1** presents many examples of pressure metrics that affect all aspects of biodiversity, including metrics of hunting, pollution, greenhouse gas emissions, air pollution, expansion of invasive alien species, logging, and many other human activities.

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

Supplemental Material >

4.2.1. Pressures on genetic diversity.

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

4.2.2. Pressures on species.

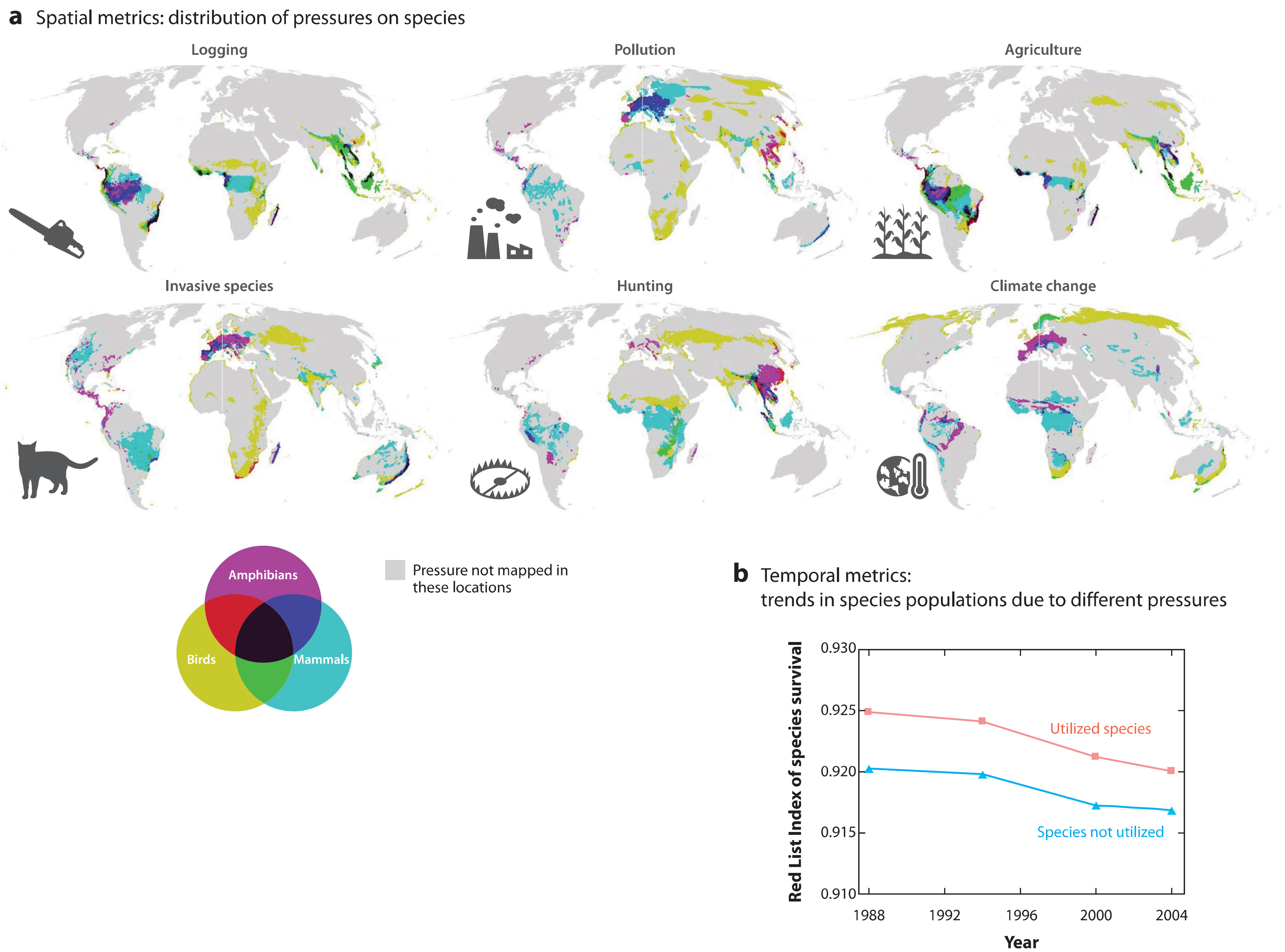
Metrics of pressures on species can be disaggregated from IUCN Red List database–derived metrics (111, 112) (**Figure 7**) such as the STAR metric (40, 113). Threats Classification Scheme (114) documentation is required for all IUCN Red List assessments, so STAR can be disaggregated as a metric of the 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 so-called persistence score, or LIFE metric, developed by Durán et al. (67). This metric uses IUCN Red List data but calculates extinction risk with regard to both the original extent of habitat and the extent of remaining habitat, rather than from the IUCN categories directly, and it includes all species (including those classified as of least concern) (115). The list can be disaggregated to provide a pressure metric for threats contributing to land use change.

Specific pressures, such as sustainable and unsustainable uses of species from hunting, fishing, harvesting, and the wildlife trade, can also be measured using the IUCN Red List (117), while metrics of species in trade can be calculated using UN Trade and Development databases through the Biotrade Initiative (**Supplemental Table 1**). 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 (79, 118) (**Figure 7**). Specific disaggregation of the RLI (68) shows trends in aggregate extinction risk to species driven by particular pressures, such as unsustainable use, 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 (**Figure 7**).

4.2.3. Pressures on ecosystems.

The most common metrics of pressure on ecosystems are those that measure a decline in ecosystem area caused by land use change. Metrics that measure a decline in ecosystem condition due to pressures are also common. Combinations of different remotely sensed data layers on human pressures on biodiversity have enabled the development of indices of pressure, such as the Human Footprint Index (119–122) (**Figure 8**) and the Human Modification Index (123), which can be disaggregated into their component threats.

Other metrics categorize land on the basis of their extent of pressure, such as low-impact areas (125), natural and modified habitat (126), and anthropogenic biomes (127, 128). GLAD alerts (129), which are pressure indicators for deforestation events available on the Global Forest Watch platform, are used by both governments and NGOs to target interventions to address illegal deforestation and forest degradation. Remote sensing is also used to derive specific pressure metrics relating to, for example, the frequency of fires or the loss of forest to agriculture (**Figure 9**).



a Spatial metrics: distribution of pressures on species

b Temporal metrics: trends in species populations due to different pressures

(*Caption appears on following page*)

Figure 7 (*Figure appears on preceding page*)

Examples of spatial and temporal metrics showing pressures on species. (*a*) Global distribution of threats to bird, mammal, and amphibian species using data from the IUCN Red List of Threatened Species (112) showing that there are spatial patterns in how threats to species are distributed globally. This enables conservation interventions to be targeted to reduce these threats. Each map—here logging, pollution, agriculture, invasive species, hunting, and climate change—shows where IUCN Red List assessments have highlighted that threat as affecting species. Colors show where the pressures are mapped to a location that affects birds, mammals, or amphibians individually or affects more than one species group. Panel *a* adapted from Reference 112 (CC BY 4.0). (*b*) Red List indices (see **Figure 4** for further explanation of Red List indices) for bird species that are utilized versus those that are not utilized by humans (e.g., for food, as pets, for feathers) (116). Both utilized and nonutilized species are being driven toward extinction at similar rates, but nonutilized species are more threatened overall. This is unsurprising, given that people tend to use more common species. Panel *b* adapted with permission from Reference 116; copyright 2008 Cambridge University Press. The boundaries and names shown and the designations used on these maps do not imply official endorsement or acceptance by the United Nations.

4.3. Biodiversity Response Metrics

Supplemental Material >

Most of the biodiversity response metrics listed in **Supplemental Table 1** relate to the GBF, and many enumerate 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. In this section, we focus on metrics that facilitate a richer understanding of how responses might affect biodiversity state or reduce pressures.

Metrics of responses targeting the conservation of genetic diversity typically relate to the numbers of species in long-term storage facilities (e.g., seed banks and tissue banks) or in botanical gardens or zoos. They are further elaborated for domesticated species, where the genetic diversity of crops and domesticated animals is carefully monitored. The number of species (and populations) that are monitored through DNA-based methods has also been proposed as a knowledge response metric (50).

The World Database on Protected Areas (132) and other effective area-based conservation measures (OECMs) (133) contain information on 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 (KBAs) protected over time (134) as well as the condition of ecosystems within protected areas (135) (**Figure 10**).

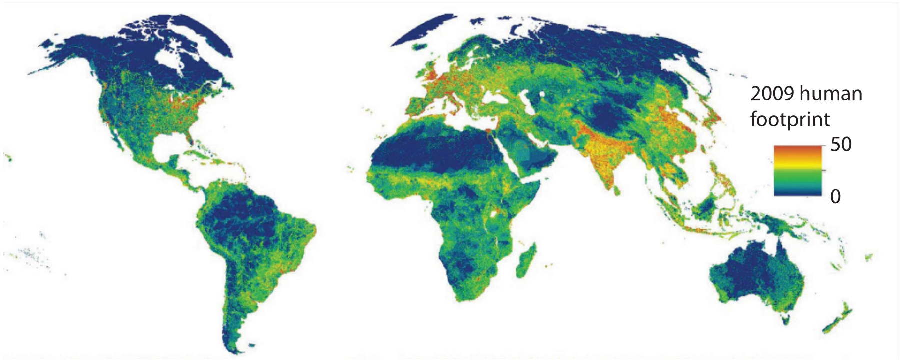
A suite of diverse metrics on protected area connectivity exist (e.g., ProtConn, ProNet, PAI, PARC, ConnIntact) and can inform responses related to enhancing connections between sites to facilitate species movement at landscape scales. Theobald et al. (137) explain some of the differences between these metrics and describe how they can be used. Gaps remain in our understanding of where connectivity conservation is most critical, including in measurements of 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 more than 16,000 sites of significance for the global persistence of biodiversity (138). KBA data underpin metrics on the conservation responses at more than 4,000 sites and on the degree to which KBAs are covered by protected areas and OECMs. These metrics are incorporated into SDG 14—specifically, tracking protected area coverage of KBAs for marine areas, terrestrial and freshwater areas, and mountains—and the CBD and other multilateral environment agreements as a response measure (**Figure 10**).

A variation of the STAR metric, created using data from the IUCN Red List, quantifies reductions in global extinction risk achieved through implementation of responses (40). Similarly, the LIFE metric (67, 115) can be used to measure species responses resulting from restoration. Other metrics relating to ecosystem restoration have also been developed, highlighting areas in need of restoration globally or within a single country (**Figure 11**).

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

a Spatial metrics: distribution of Human Footprint Index



b Temporal metrics: changes in human footprint within ecoregions

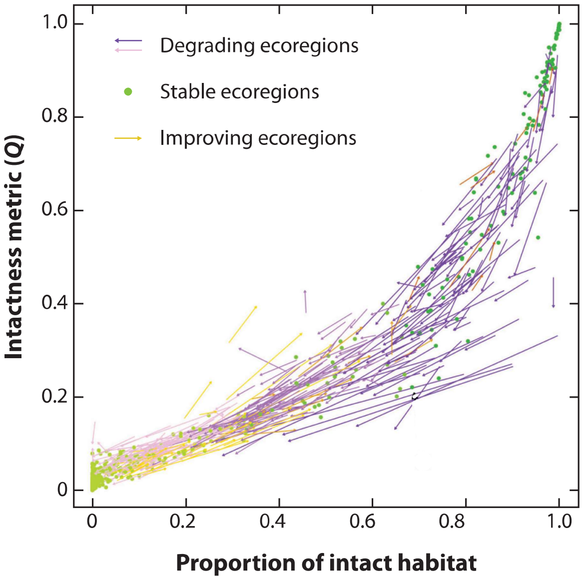


Figure 8

Spatial and temporal examples of pressures on ecosystem condition. (*a*) The Human Footprint Index (119) shows how a series of remotely sensed layers can be combined to yield a spatial metric of the extent of human pressures on nature (note that some pressures, like hunting or climate change, are not included in this metric). Included in the Human Footprint Index are key variables related to human impact, including built-up environments, population density, electric power infrastructure, croplands, pasturelands, roads, railways, and navigable waterways. The data are available at a spatial resolution of approximately 1 km^2. Colors orange through yellow are parts of the world where there are high levels of pressure that can negatively affect biodiversity. Colors blue through green are areas of the world with lower rates of pressure and where biodiversity might be close to its natural condition. Panel *a* adapted from Reference 120 (CC BY 4.0). (*b*) Changes in pressure within ecoregions (124), showing how human footprint change data can be used to measure changes in pressure across more than 800 terrestrial ecoregions. Ecoregions are arranged in terms of the proportion of intact habitat (*y*-axis) and changes in intactness (using the Human Footprint Index) (*x*-axis). In ecoregions with higher, and increasing, pressure over time, we can expect that biodiversity state is declining and benefits to people are reducing. In ecoregions with lower, stable, or declining pressures, we can expect that biodiversity state is stable, or improving, and that there are possibilities for enhanced benefits for people. Panel *b* adapted from Reference 124 (CC BY 4.0). The boundaries and names shown and the designations used on these maps do not imply official endorsement or acceptance by the United Nations.

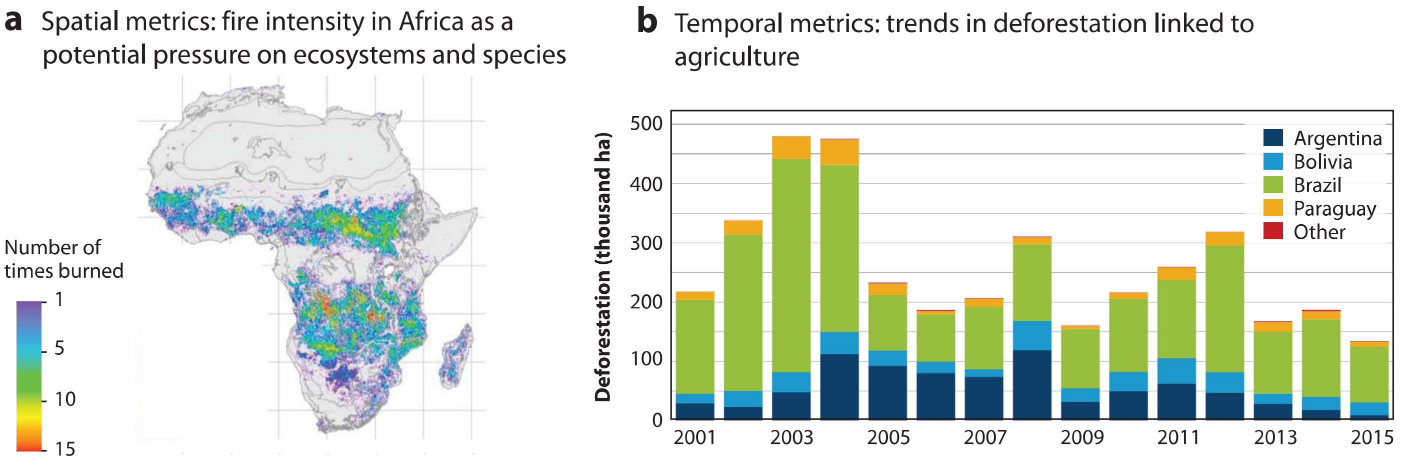


Figure 9

Examples of spatial and temporal measures of specific pressures on ecosystems. (*a*) Number of times areas in Africa burned during the years 2002–2016. The analysis was completed using the Moderate Resolution Imaging Spectroradiometer (MODIS) 500-m^2 resolution remote sensed fires data (130). In some areas of Africa, vegetation is naturally fire prone, but some areas now burn almost every year, at a greater frequency than what would occur without human-set fire. Panel *a* adapted with permission from Reference 130 (CC BY-NC-ND 4.0). (*b*) Trends in the loss of forest cover (deforestation) in 2001–2015 due to the pressure of agriculture in some South American countries (131). There is large annual variation in the amount of forest lost to agriculture in different countries but with an encouraging drop in the amounts of loss in the last years of this time series. Panel *b* adapted from Global Forest Review (131) (CC BY 4.0). The boundaries and names shown and the designations used on these maps do not imply official endorsement or acceptance by the United Nations.

4.4. Biodiversity Benefits Metrics

People benefit from biodiversity through ecosystem services (i.e., nature's contributions to people), such as regulation of water supply, provision of food, pollination of crops, and so forth (136, 141, 142). A potential ecosystem service is a benefit that could be obtained if there were people to use the service, while a realized service is an actual benefit experienced by or delivered to people. These benefits are all underpinned by stocks of natural capital (e.g., 143).

Biodiversity benefits metrics exist to measure both potential and realized ecosystem services as well as to help clarify the consequences for people of biodiversity loss (for examples, see **Supplemental Table 8**). Ecosystem service assessments often use land use and land cover maps that are then linked to attributes of value to people, in order to develop models of realized ecosystem services flows (144–148). This means that many ecosystem service metrics broadly reflect 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 realized 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.

Supplemental Material >

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); also known as ecosystem services

Detailed ecosystem service status analyses are available at regional to local scales, for example, for Africa (149), Europe (150), and the United States (151). Numerous publications cover countries or parts of countries, such as Uganda (152), Mozambique (153), and Tanzania (154) (see **Supplemental Table 6**).

Few global ecosystem service metrics are temporal. One exception is the tracking of change over time in biomass carbon, which has been linked to temporal land cover maps that, in turn, allow carbon sequestration and emissions to be calculated (155). Such calculations are relevant

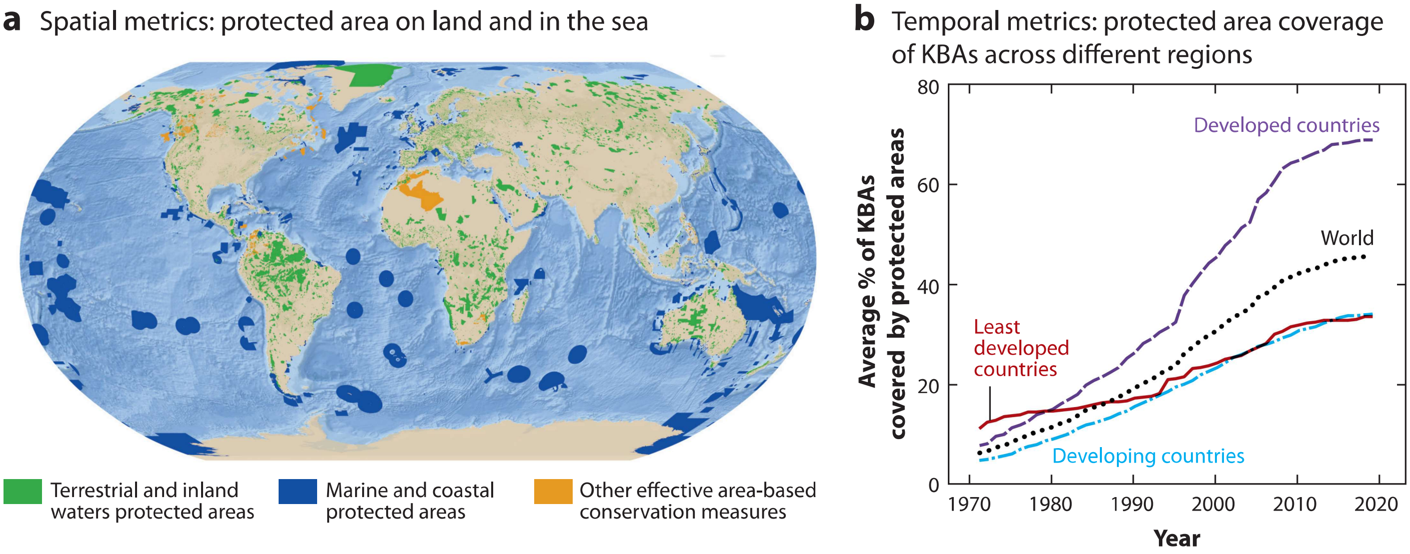


Figure 10

Examples of spatial and temporal response metrics. (*a*) Extent of protected areas globally using data from the World Database on Protected Areas in 2024 (134). Areas of land and sea that have been declared, mainly by governments, for conservation purposes enable calculations of protected areas of land and sea. Panel *a* adapted with permission from Protected Planet (134). (*b*) Changes in mean percentage coverage of Key Biodiversity Areas (KBAs) by protected area for least developed, developing, and developed countries versus globally in 1970–2020 (136). Sites of particular importance for biodiversity are increasingly being conserved within protected areas over time, but coverage is greater in developed than developing countries. KBAs are nationally identified sites that contribute significantly to the global persistence of biodiversity in terrestrial, freshwater, and marine ecosystems. KBAs can either be covered in full or in part by an existing protected area or be wholly unprotected and therefore a candidate for future protection within formal protected areas or other conservation mechanisms. Panel *b* adapted from Reference 136; copyright 2019 Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. The boundaries and names shown and the designations used on these maps do not imply official endorsement or acceptance by the United Nations.

for the ecosystem service of climate regulation and related carbon projects (**Figure 12**). Another example is the modeling of spatial and temporal data on the delivery of water as an ecosystem service, which is often linked to the existence of good-quality natural vegetation (**Figure 13**).

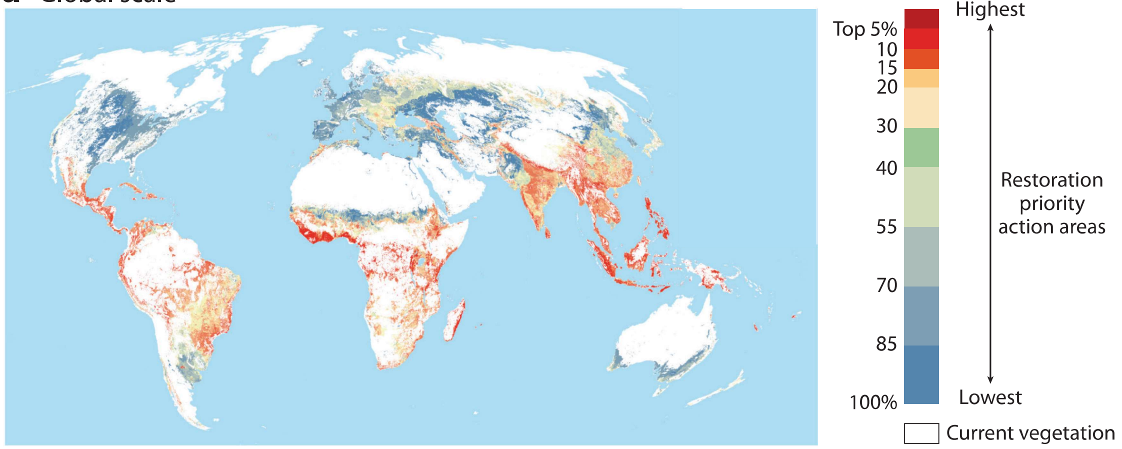
4.5. Multidimensional Indices

Supplemental Material >

Some metrics are multidimensional in that they seek to present information covering biodiversity state and pressures and, occasionally, responses or benefits (**Supplemental Table 1**). For example, the Ecosystem Integrity Index (160) includes measures of ecosystem condition and pressure. The Bioclimatic Ecosystem Resilience Index (161) measures the capacity of ecosystems to retain species under the pressure of climate change. Similar metrics have been developed within the framework of ecoregions both globally (124, 162) and regionally (e.g., 163).

Additional efforts have been devoted to simplifying the problem of multiple metrics, for example, by developing complex indices that represent different dimensions of pressure, state, and response within a single index. An example of a stand-alone index used by governments or businesses is the Local Ecological Footprint Tool (LEFT), which processes seven input data layers into a map of "relative ecological value" (164) (**Figure 14**). Another example is the Multidimensional Biodiversity Index, which aims to combine measures of biodiversity state and its contribution to people in a multidimensional ecological and social approach that considers the specifics of each national context. This metric allows countries to develop policies and take actions that consider the importance of safeguarding biodiversity for sustainable development and well-being (165) (**Figure 14**). This approach is analogous to indices such as the Human Development

a Global scale



b National scale

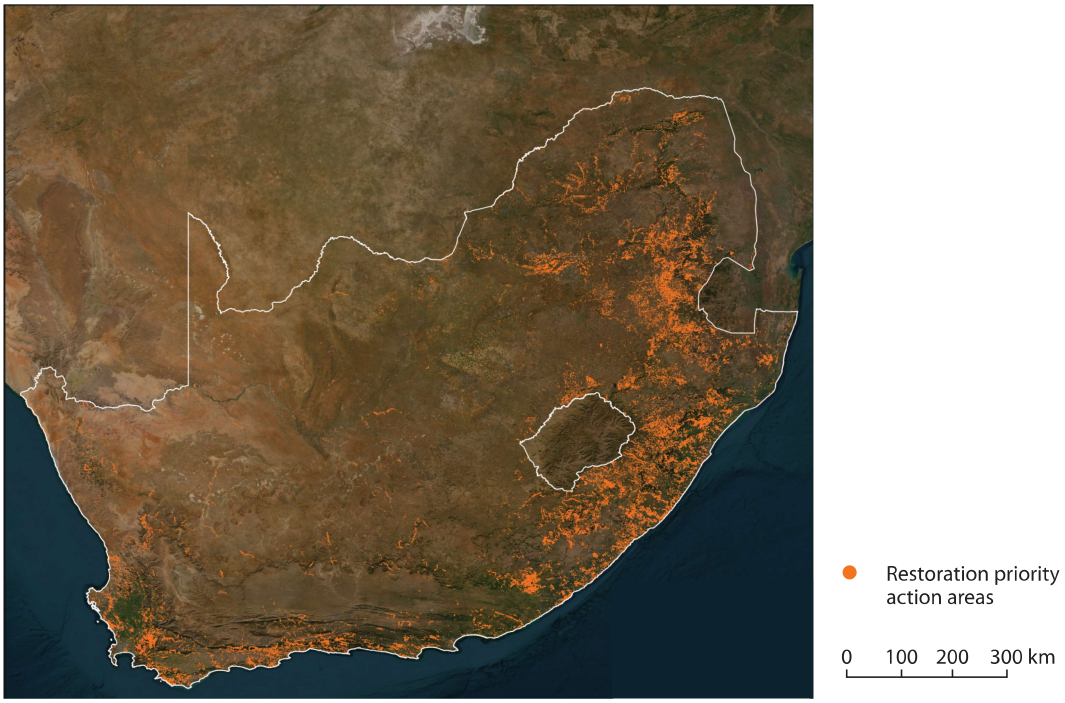


Figure 11

Examples of response metrics at global and national scales. (*a*) Global priorities for restoration that bring together priority areas for restoration focused on biodiversity conservation, the mitigation of climate change, and minimizing costs. All converted lands are ranked from highest priority for restoration (top 5%) (*dark red*) to lowest priority for restoration (85–100%) (*blue*). The spatial patterns for individual criteria varied considerably, and the combined analysis captures synergies (139), showing that there are parts of the world with a much greater priority for restoration to achieve biodiversity conservation and climate-related outcomes at minimum costs. Benefits for biodiversity were quantified as the reduction in potential extinction debt from habitat loss following ecosystem restoration, assessed individually for 20,319 species of mammals, amphibians, and birds. The data were accessed in the period around 2015–2018 but may be derived from information that could be up to a decade older. Panel *a* adapted with permission from Reference 139; copyright Nature Publishing Group. (*b*) Map of priority areas for restoration action in South Africa, derived using the Essential Life Support Areas approach facilitated by United Nations Development Programme (UNDP) but implemented by partners in South Africa. Panel *b* adapted from Reference 140; copyright 2023 UNDP. The boundaries and names shown and the designations used on these maps do not imply official endorsement or acceptance by the United Nations.

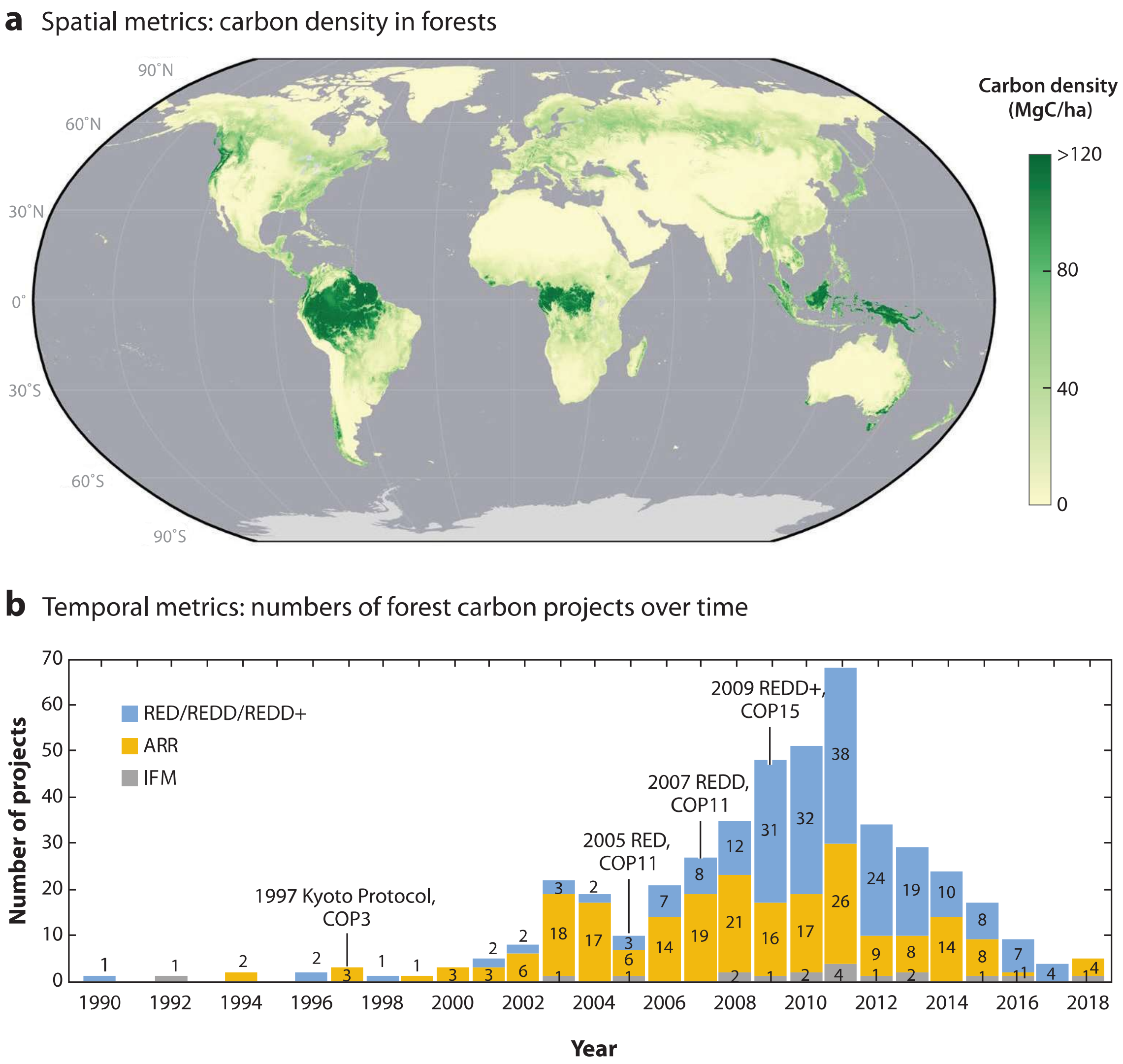


Figure 12

Examples of spatial and temporal carbon metrics. (*a*) Above- and belowground biomass carbon distribution globally in the year 2010 (156), showing a concentration of biomass carbon in the world's forests, especially tropical forests. Panel *a* adapted from Reference 156 (CC BY 4.0). (*b*) Trends in numbers of projects that seek to use the conservation of carbon as a means to generate financial benefits in relation to meetings of the UNFCCC COP (157), showing a peak in new projects focusing on carbon around 2010 with an apparent decline after then. Panel *b* adapted with permission from Reference 157 (CC BY-NC-ND 4.0). Abbreviations: ARR, afforestation, reforestation, and revegetation; IFM, Improved Forest Management Projects; RED, Reducing Emissions from Deforestation; REDD, Reducing Emissions from Deforestation and Degradation; REDD+, Reducing Emissions from Deforestation and Forest Degradation in developing countries, with the plus sign standing for additional forest-related activities that protect the climate, namely sustainable management of forests and the conservation and enhancement of forest carbon stocks; UNFCCC COP, the United Nations Framework Convention on Climate Change Conference of the Parties, with meetings numbered as COP3 (1997), COP11 (2005), and COP15 (2009). The boundaries and names shown and the designations used on these maps do not imply official endorsement or acceptance by the United Nations.

Index, the Multidimensional Poverty Index, and others. Environmental, social, and governance ratings, for use by businesses, are also based on composite metrics constructed from different data inputs.

Multidimensional indices are often controversial because they tend to treat different facets of biodiversity equally, are based on subjective weighting and arbitrary scores, have inconsistent spatial- and timescales of their data sets, or may combine measures. As a result, it is hard to

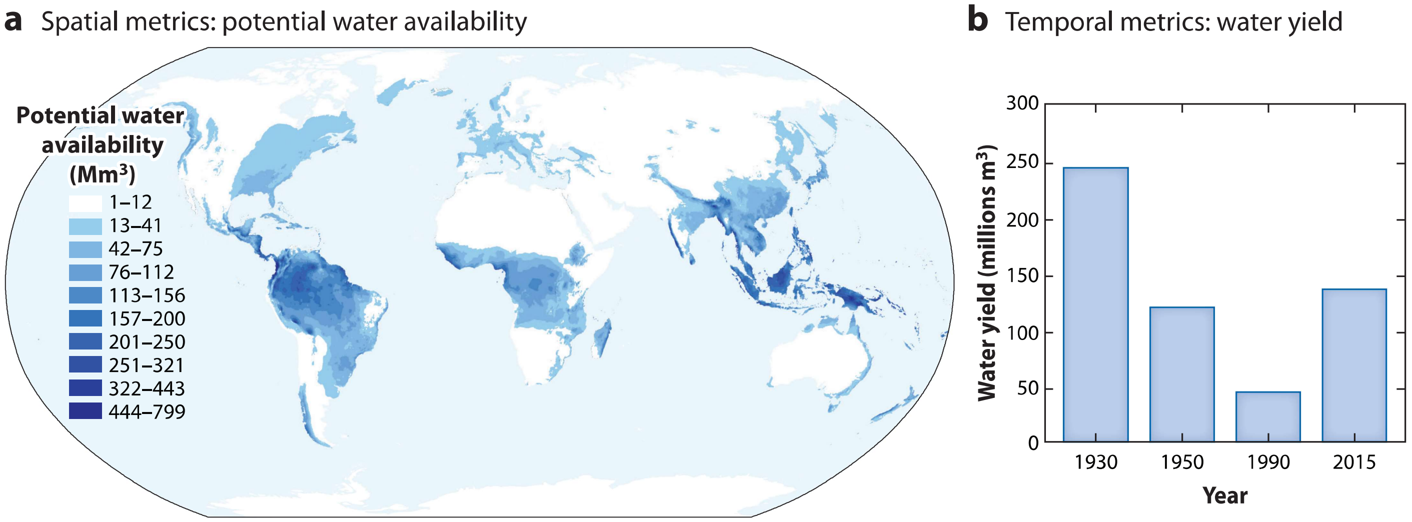


Figure 13

Examples of spatial and temporal water metrics. (*a*) Potential water availability (158), showing areas where there is at least a seasonable abundance of water, especially in some temperate regions and tropical wet areas. The dataset provides the total potential supply of clean water available to users in megameters (Mm^3). Data from Reference 158. (*b*) Changes in realized water for people following agricultural intensification and partial reforestation in Dorset, United Kingdom, 1930–2015 (159). Realized water availability declined until the 1980s as a result of agricultural intensification, followed by recovery since that time, potentially due to efforts to restore natural vegetation. Panel *b* adapted from Reference 159 (CC BY 4.0). The boundaries and names shown and the designations used on these maps do not imply official endorsement or acceptance by the United Nations.

understand what drives trends without breaking the metric down into its constituent parts (166). Nevertheless, both governments and businesses need such indices, and they may play a role in communication and high-level decision-making.

5. TOWARD A MINIMUM SET OF METRICS

Some representatives of governments or businesses have highlighted the complexity of biodiversity metrics and requested that they be simplified. These requests mirror those for climate, where the complexity of the climate system has been reduced to a focus on measuring the three goals of the Paris Agreement: (*a*) reducing emissions of greenhouse gases (especially CO_2) and staying below a 1.5°C temperature rise above preindustrial levels, (*b*) climate change adaptation, and (*c*) climate financing.

For biodiversity, a single metric is often considered scientifically indefensible (168) because (*a*) we can measure biodiversity at different levels (e.g., genes, species, and ecosystems) that are unevenly distributed globally and subject to different temporal trends, (*b*) we can measure biodiversity in terms its benefits (e.g., its direct contributions to people, its role in ecosystems, or its intrinsic value), and (*c*) we can prioritize biodiversity according to various measures of its rarity or extinction risk (or, instead, measure it in absolute terms). There is no right or wrong choice, and the approach depends upon the most suitable approach to measuring biodiversity value in the specific case.

Thus, rather than proposing a single metric, which cannot cover all aspects of biodiversity for all user groups, we have built on earlier publications (169, 170) to identify a small number of metrics that address current needs (**Table 3**). The criteria we used to identify this set of metrics are as follows: (*a*) Each metric is ideally included in SDG 14 and 15 indicators and/or GBF headline indicators (**Table 3**); (*b*) the metric is published, with available methodology and data; (*c*) data flows exist to update the metric; (*d*) one or more responsible institutions have committed to maintaining

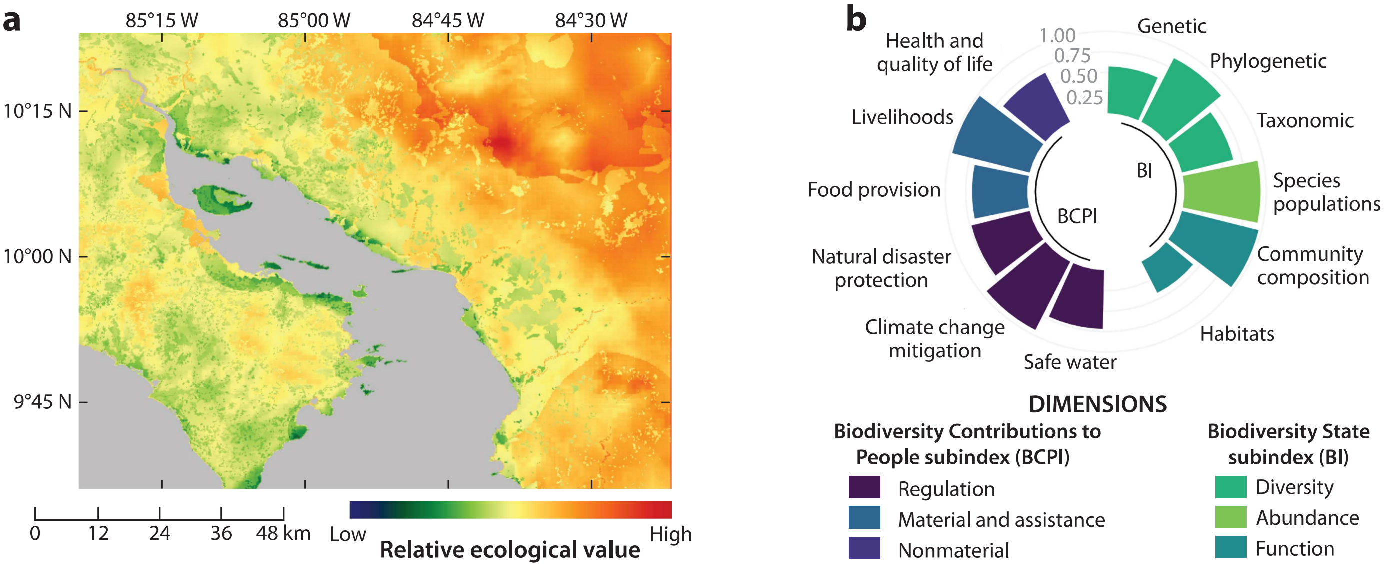


Figure 14

Examples of multidimensional indices. (*a*) An example map of relative ecological value in the region around the city of Puntarenas, Costa Rica (167), created with the Visualization of the Local Ecological Footprint Tool (LEFT) (164). Maps created with LEFT are derived from seven different datasets of species and ecosystem measures that are combined to generate five components of interest (Beta diversity, Vulnerability, Fragmentation, Connectivity, and Resilience) that are themselves then combined into an index that considers each component equally. These maps have been used by some companies for decision-making. Panel *a* adapted with permission from Reference 167. (*b*) A hypothetical example of a Multidimensional Biodiversity Index score (165). Each bar represents a biodiversity objective score ranging from zero to one (where zero corresponds to lower performance and one indicates the highest performance), calculated from a series of indicators. The values can be either considered separately or aggregated to obtain a country's or region's overall score (in this case, 0.76). Green bars represent the Biodiversity State subindex (BI) dimensions and objectives. Blue and purple bars represent the Biodiversity Contributions to People subindex (BCPI) dimensions and objectives. Panel *b* provided by Ana Ramos Rodrigues of the United Nations Environment Programme World Conservation Monitoring Centre. The boundaries and names shown and the designations used on these maps do not imply official endorsement or acceptance by the United Nations.

Table 3 Proposed core set of metrics for measuring state, pressure, response, and benefits aspects of biodiversity

	Genes	Species	Ecosystems
State (significance)	EDGE[a]	STAR RLI[b]	Extent of natural ecosystems[a,c,d] RLE[c]
State (intactness)	None available or recommended	LPI[a]	BII MSA/PDF/cSAR
Pressure	None available or recommended	STAR_T	HFI
Response	None available or recommended	STAR_R STAR_T GSSI[a]	PA coverage[b]
Benefits	None available or recommended	None available or recommended	Biomass carbon flux

[a] These metrics may not meet criterion *e* or *f* as defined in Section 5.

[b] SDG and GBF headline indicators.

[c] GBF headline indicators.

[d] Refers to trends in habitat extent derived from remote sensing.

Abbreviations: BII, Biodiversity Intactness Index; cSAR, countryside species–area relationship; EDGE, Evolutionarily Distinct and Globally Endangered Index; GBF, Kunming–Montreal Global Biodiversity Framework; GSSI, Green Status of Species Index; HFI, Human Footprint Index; LPI, Living Planet Index and associated disaggregations; MSA, mean species abundance; PA coverage, protected area coverage and associated disaggregations; PDF, potentially disappeared fraction; RLE, Red List of Ecosystems Index; RLI, Red List Index and associated disaggregations; SDG, Sustainable Development Goal; STAR, Species Threat Abatement and Restoration metric; STAR_R, restoration component of STAR; STAR_T, threat abatement component of STAR, which can be disaggregated by threats.

and updating the metric for at least 10 years; (*e*) the metric is available for all countries and is freely accessible for government decision-making; and (*f*) there is an established way to use the metric for commercial decision-making.

6. DISCUSSION

We have shown that a diverse array of available biodiversity metrics cover different aspects of biodiversity, including measures of pressure, state, response, and benefit. However, we have also shown that many metrics have been developed for different use cases, and the field remains confusing for many users. Our summary of suggested metrics, drawn from intergovernmental decisions, boils the large number of metrics down to a handful. In this section, we discuss issues that will affect the development and maintenance of metrics for decision-making over the medium term. We conclude with core findings and a way forward.

6.1. Data Availability

In most cases, the limited availability of field-level biodiversity data and data that are regularly updated are significant constraints on a metric's quality. For species data, most available metrics use a handful of data sources that are typically biased toward 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 15**). Smartphone apps have rapidly accelerated data collection in some poorly studied parts of the world, but there are still regions with almost no data, and data validation, especially for poorly known taxa, is a problem.

The increasing number of satellites in orbit and the diversity of the products they deliver mean that a rapidly expanding array of metrics are being produced using remotely sensed data (for a list, see **Supplemental Table 1**). However, very few products fit the needs of specific end users in the biodiversity community, and biodiversity scientists are often required to adapt existing

Supplemental Material >

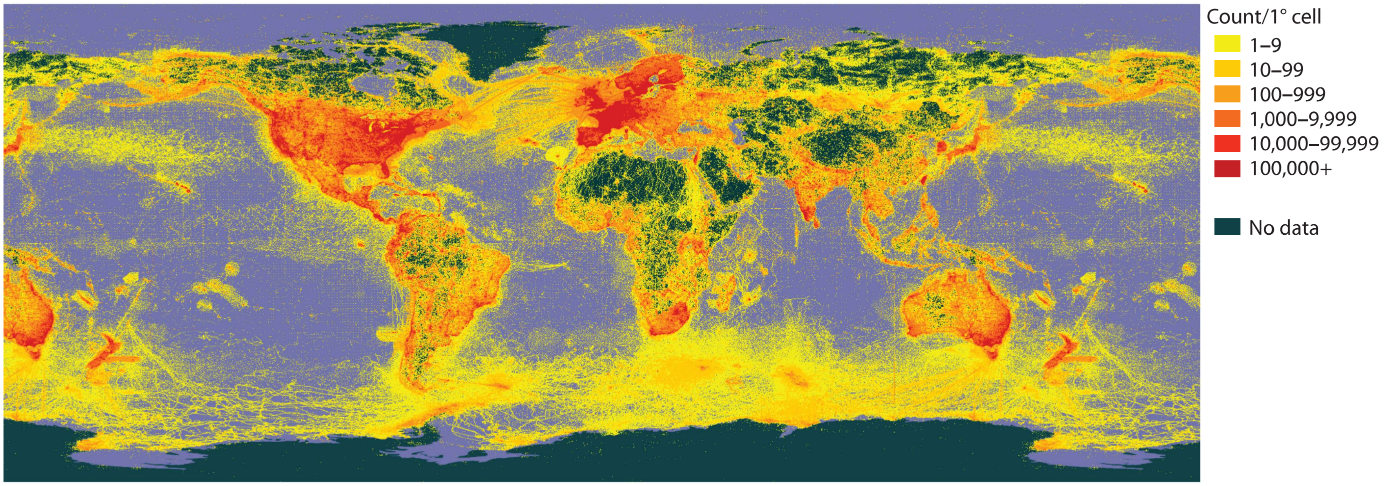


Figure 15

Biodiversity data records per 1° grid cell globally. The image is based on the more than 2 billion records in the Global Biodiversity Information Facility (GBIF) database covering the years 1600 to 2024. It shows that there are considerable numbers of biodiversity records from Europe and North America and in the coastal and mountainous regions of much of the global south. However, large wilderness areas and the interior regions of many parts of the global south have fewer records, especially if they are deserts or dense rainforests where few biological collections or observations have been undertaken. The colors show the number of records in the database within a 1° (approximately 100 × 100 km) grid cell. Dark green means no records for those areas. Image reproduced from **https://www.gbif.org**; the map uses the classic GBIF yellow-red color ramp and classic point style to display the data. The boundaries and names shown and the designations used on these maps do not imply official endorsement or acceptance by the United Nations.

products to their needs (171). For example, the Essential Biodiversity Variables (172, 173) have been suggested as another set of options, but many of them are not yet operational, or available, to support decision-making. Despite the hopes of the biodiversity metrics community, the situation has not improved much over the last two decades. The new generation of land cover products (e.g., 174–177), with learning and rapid updating enabled by artificial intelligence, may—if linked to ecological and biodiversity expertise—provide a way forward in the coming years. However, these products cannot replace the need for metrics derived from in situ monitoring.

6.2. The Role of Civil Society

Civil society has an important role to play in contributing data to the creation of biodiversity metrics and indicators (178, 179). For example, civil society is particularly active in the use of citizen science smartphone- 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, birdfeeders, smart listening devices, eDNA surveys, and Environmental Impact Assessments, are typically integrated with data from museums and herbaria through platforms such as GBIF (180).

Although spatial coverage of these tools is variable and their quality may vary depending on how the data are groundtruthed and 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 (181). Civil society can also be involved in evaluating ecosystem services (e.g., 182) through the use of tools like i-Tree, developed by the US Forest Service of the Department of Agriculture. Substantial attention is also being paid to advancing applications of Indigenous and local knowledge in support of biodiversity metrics, for example, in the IUCN Red List (183).

6.3. The Need for Sustainable Financing

Both current and future metrics will require ongoing investment in maintaining flows of data and aggregation capacity so that the metrics can continue to be used (184). Core metrics must also be backed by institutional commitments to deliver them to agreed-on user communities, and their production must be made 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 deliver national and regional policy commitments (as in the European Union, African Continental Free Trade Area, East African Community, etc.) as well as globally agreed-upon commitments (such as those defined by multilateral environment agreements including the SDGs, GBF, UN Framework Convention on Climate Change, Convention on International Trade in Endangered Species of Wild Fauna and Flora, UN Convention to Combat Desertification, and Ramsar Convention on Wetlands).

A government is much more likely to take up biodiversity metrics if they are part of a global or regional framework and the government can report data against it. Globally generated metrics, often housed and created by UN agencies, NGOs, or universities, have the advantages of standardized methods and the ability to compare across space and time. However, using these global metrics at national scales can be challenging. For example, definitions (e.g., land use and land cover classifications) often do not align between global and national users or with definitions used by business laws and frameworks. For example, the International Finance Corporation's Performance Standard 6 (6) and the EU Habitats Directive use different, sometimes conflicting definitions of natural habitats/ecosystems. Additionally, academic or NGO-generated metrics may lack political legitimacy at the national level because 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. As a result, the reliability of communications to decision-makers and the public on the situation facing biodiversity around the world may be reduced.

A political balancing act is therefore required to create systems in which metrics generated nationally (by governments, citizen scientists, or Indigenous peoples and local communities) can be used alongside those generated globally, as illustrated by the periodically produced Global Biodiversity Outlooks, Global Environmental Outlooks, and Global Forest Resource Assessments.

6.5. Factors Driving the Uptake of Metrics by Business and Trade Systems

National, regional, and international policies interact with responses from 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). Such a loss can arise not only from regulatory changes but also from societal and investor pressure to transform approaches to reduce impacts on biodiversity. Second, businesses increasingly recognize the scale of nature-related physical risks and the opportunities relating to their own operations and the wider economy (5, 187). These include financial risk to businesses arising from the loss of biodiversity that many companies are already experiencing. Third, if not addressed, loss of biodiversity may lead to systemic risks that could prevent businesses from operating at all in the future as biodiversity-based life support systems collapse (188, 189). Another example is the implementation of deforestation-free supply chain laws, which, although developed for good reasons involving climate and nature loss, can cause concern and political controversy in countries of commodity origin.

Businesses have responded to these emerging issues by participating much more actively in negotiations around the biodiversity and climate COPs (190, 191) and in the development of regional and national policies. 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 recognized, and how to select metrics to measure these contributions. Challenges remain, for example, in relation to the required scale of analysis; operational decisions at the company scale often require customized, context-specific approaches that are intractable using global data and existing web-based platforms.

Many recent assessment and disclosure standards have led to consensus on the need to include both metrics of companies' pressures on biodiversity and metrics of the state of biodiversity based on both species and ecosystems. The latter include metrics used to screen and prioritize 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 affect multiple others (185, 192). Metrics used to measure the impacts of supply chains need to be comparable between the 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). The same is true for nationally created metrics where guidance and guidelines for application are also required (194, 195). An example system being tested by the UK government is the Commodity Footprints tool, which uses the PDF metric and the species persistence score to assess the impacts of commodity trading between nations (67). Additional, similar systems are in development and are seeking to use relevant biodiversity metrics, and the accelerating demand from businesses (including finance- and trade-related companies) means that finer-scaled, more frequently updated, more accurate, and more actionable metrics will be required (196).

SUMMARY POINTS

1. Many biodiversity metrics are available to inform decisions regarding screening, planning, and resource allocation for countries and businesses. However, the large number of potential metrics confuses some users and hinders effective decision-making.
2. For governments, nationally generated metrics can be important for addressing nationally specific circumstances, as well as for creating political buy-in and legitimacy, but globally consistent metrics are essential to ensure global consistency.
3. For businesses, frameworks and standards on biodiversity assessment, disclosure, and target setting provide an initial set of biodiversity metrics, but further developments in disclosure requirements and guidance are needed.
4. Many global metrics operate at a resolution of 1 × 1 km^2 due to the resolution of the underlying data. Biodiversity impacts vary at small geographical scales, so metrics that can facilitate our understanding of the impacts and results of responses at small scales are needed.

FUTURE DIRECTIONS

1. Agreeing on a core set of biodiversity metrics that can work across scales and meet the needs of multiple user groups is clearly desirable but not easy, because biodiversity is affected by people, is managed by people, and delivers value to people.
2. For international and regional agreements there will be a greater need for core metrics, which have been developed mainly by international organizations, to be calculated at the national level using standards and methods agreed on by governments.
3. Considerable effort has been devoted to building new products using the latest technology, but they often fail to represent the world in ways that are useful for biodiversity conservation and also lack political legitimacy.
4. Most areas of society have created funding systems to provide the flows of data and metrics that are required to make decisions, but most biodiversity data flows are funded through projects or rely on volunteer efforts. This system is clearly not sustainable and is one reason for the fragmentation and duplication of effort.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

AUTHOR CONTRIBUTIONS

N.D.B., T.M.B., F.H., S.H.M.B., J.M.H.G., C.W., L.V.W., A.v.S., J.H., and M.H. conceived and designed the project; contributed to the acquisition, analysis, and interpretation of data; wrote and revised the article; and reviewed the article critically for important intellectual content. N.K., N.B., M.V., A.P.D., L.M., N.A., S.B., A.R.R., A.C., H.S., and J.B. contributed to the acquisition, analysis, and interpretation of data and reviewed the article critically for important intellectual content. L.S., A.S., C.R., A.H., R.C., and O.M.-L. played key roles in data provision, checking, and manipulation.

ACKNOWLEDGMENTS

We thank all those who have developed biodiversity metrics over the past decades. This research has been funded in part by UK Research and Innovation's Global Challenges Research Fund under the Trade, Development and the Environment Hub project (project number ES/S008160/1). The following people provided editorial input on earlier drafts: Andy Arnell, Samantha Hill, Andrea C. Baquero, Alex Ross, Katherine Despot-Belmonte, Han Meng, Chris McOwen, and Matt Jones (UNEP-WCMC); Amy Molotoks (Stockholm Environment Institute); and Alison Eyres (University of Cambridge).

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