GEO BON INDICATORS FOR THE POST-2020 GLOBAL BIODIVERSITY FRAMEWORK

Contents

GEO BON

1.0 Background

1.1 The Group on Earth Observations Biological Observation Network (GEO BON)

GEO BON is a global biodiversity observation network, a flagship of the Group on Earth Observations (GEO) that contributes to effective management policies for the world's biodiversity and ecosystem services with a mission to improve the acquisition, coordination, and delivery of biodiversity observations and related services to users including decision-makers and the scientific community[1].

GEO BON consists of over 2,100 researchers and experts from 129 countries working in collaboration with government agencies to support their ability to produce and reproduce national data products. By integrating primary biodiversity observations, remote sensing data, genetic data (genomic and environmental DNA), and models, GEO BON can provide the standardized and evidence-based indicators required for understanding biodiversity trends and assessing progress towards the goals of the Convention on Biological Diversity (CBD).

1.2 Essential Biodiversity Variables (EBVs)

Inspired by the Essential Climate Variables (ECVs) that guide Parties in the implementation of the United Nations Framework Convention on Climate Change (UNFCCC), Essential Biodiversity Variables (EBVs) and derivation framework developed by GEO BON, has been endorsed by the Convention on Biological Diversity (Decision XI/3)[2].

Essential Biodiversity Variables serve to harmonize biodiversity observation data and define a minimum set of essential measurements to capture the multiple dimensions of biodiversity change. By integrating and standardizing data collected on several spatial and temporal scales, EBVs can be considered the first abstraction of complex biodiversity information, and act as an intermediary between primary observations and biodiversity indicators (Pereira *et al.* 2013). Since they are derived from raw biodiversity data and measurements, EBVs can be used to report on biodiversity status and trends and have an important role in biodiversity monitoring initiatives and informing conservation decisions and policies (Figure 1.1)[3].

---

[1] https://geobon.org/

[2] Monitoring progress in implementation of the Strategic Plan for Biodiversity 2011-2020 and the Aichi Biodiversity Targets

[3] Scalable data, observation systems and indicators to support effective monitoring of goals and targets for the post-2020 global biodiversity framework: GEO BON support for implementation

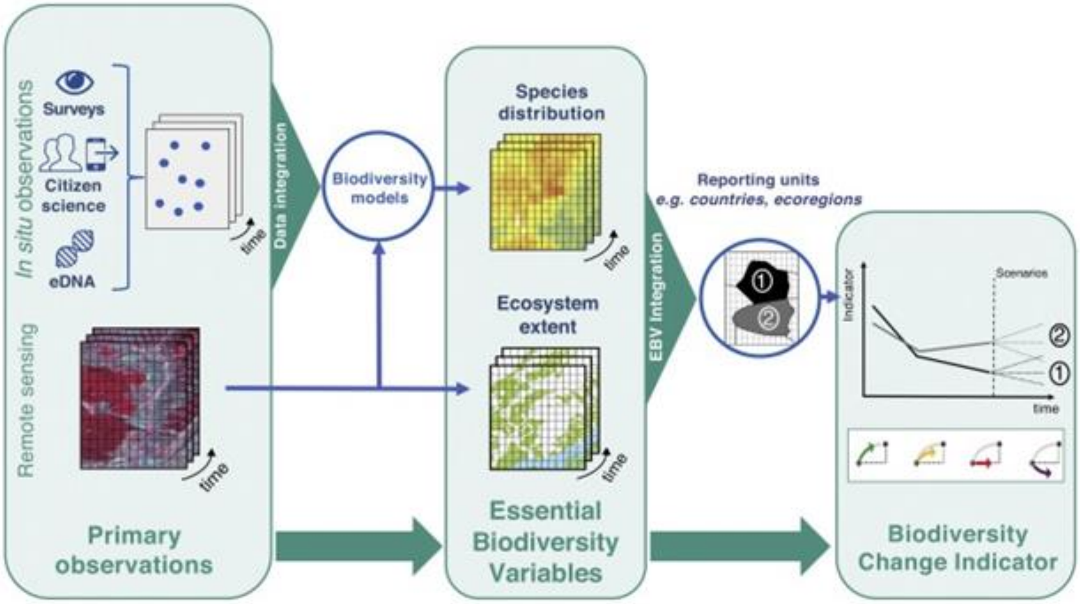

Figure 1.1 *Essential Biodiversity Variables (EBVs) are derived from primary observations made at local, national, regional and global scales using different methodologies (e.g.,* in-situ *or remote sensing). By harmonizing data across scales and sources, EBVs can report on biodiversity trends. The EBVs developed can be used directly as biodiversity indicators, or work in complementarity to support several indicators capable of reporting on biodiversity status and trends (Source: Navarro* et al. *2017).*

A number of variables can serve to measure, report and contribute to biodiversity management. GEO BON has tested numerous variables and screened them to meet the requirement of scalability, temporal sensitivity, feasibility, and relevance. The resulting EBVs are sufficiently general to apply across taxonomic groups, terrestrial, freshwater, and marine systems[4].

2.0 EBV-based indicators of the monitoring framework for the post-2020 global biodiversity framework

Traceability and methodological transparency are at the core of EBV-based indicators. The hierarchical derivation from primary observation to EBV, then to the indicators is done under an open access process, transparently documented and accessible, including original data and methodologies (Kissling *et al.* 2015). Continuous engagement with scientists, policy-makers, stakeholders and other communities is an essential part of the process.

[4] Scalable data, observation systems and indicators to support effective monitoring of goals and targets for the post-2020 global biodiversity framework: GEO BON support for implementation

In order to operationalize the indicators of the framework, the data, tools and services for the calculation of indicators must be available. The following sections describe the GEO BON indicators for the proposed headline (Sections 3-5 below) and complementary (Sections 6-8) indicators of the monitoring framework for the post-2020 global biodiversity framework[5] (Figure 2.1). Lastly, we further detail a candidate indicator for measuring forest ecosystem integrity (Section 9).

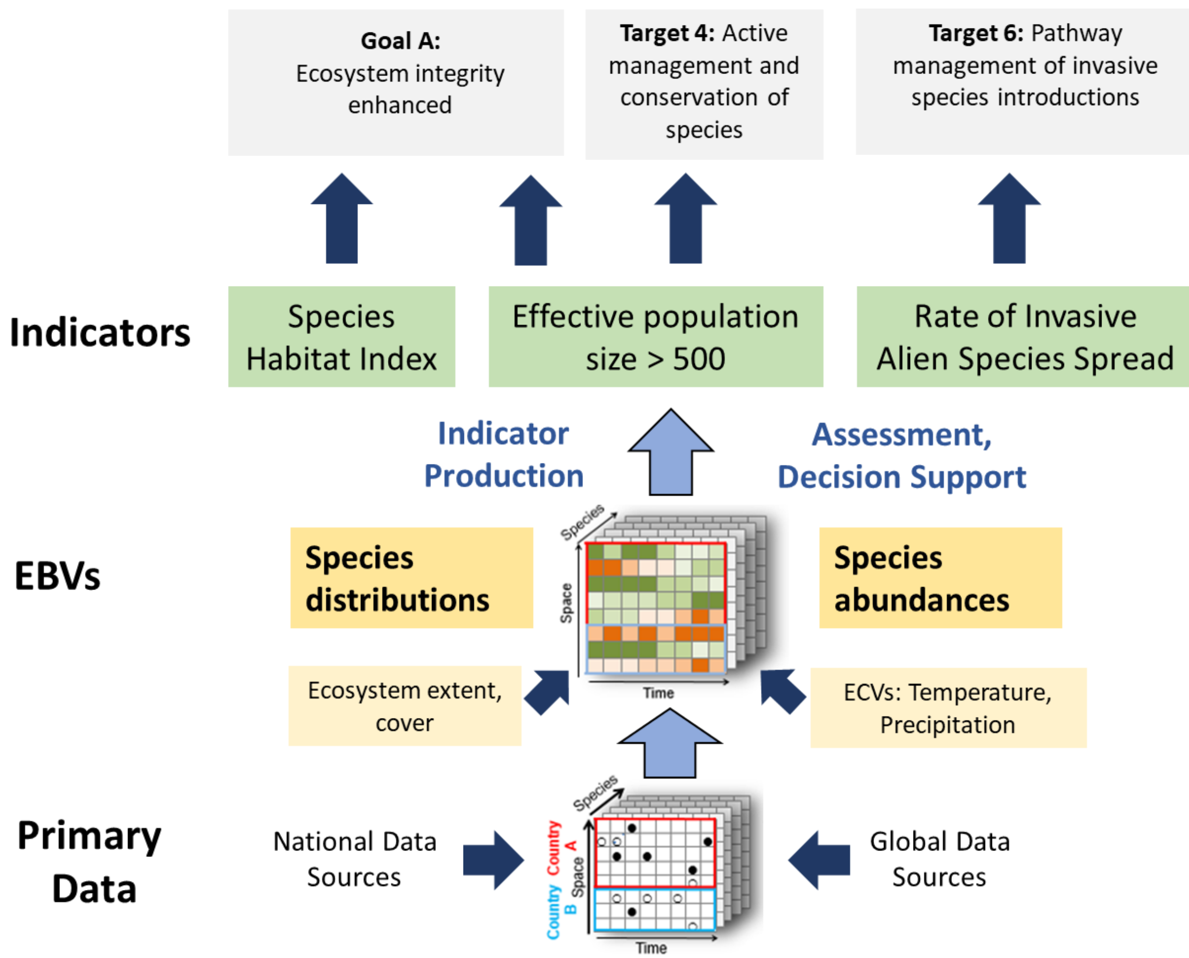

Figure 2.1 *GEO BON's proposed headline indicators of the proposed monitoring framework (the Species Habitat Index, the proportion of populations within species with a genetically effective population size > 500, and the rate of invasive alien species spread) were developed based on the EBV framework. These indicators support Goal A, Target 4 and Target 6 of the first draft of the post-2020 global biodiversity framework.*

[5] CBD/WG2020/3/3/Add.1

3.0 Species Habitat Index (SHI)

The Species Habitat Index (SHI) measures changes in the estimated connectivity, size, and quality of species habitats. The SHI uses species as core units of analysis, thereby capturing the individual ecological processes species represent that are central to ecosystem integrity. The index is also spatially explicit at a resolution of single pixels, e.g. 1 km^2, and their species assemblages. When aggregated across species in a defined geographic unit (landscapes, seascapes, mountains, regions, and country) it measures changes in the area's ecological integrity and, specifically, connectivity. Evaluated over species' geographic ranges, it measures trends in species population size, distribution, health, and, as proxy, genetic diversity (Jetz *et al.* 2019).

3.1 Key information

Alignment to GBF	Goal A Milestones A.1, A.2, A.3
Relevant headline, component, and complementary indicators	A.0.1 Extent of selected natural and modified ecosystems (i.e. forest, savannahs and grasslands, wetlands, mangroves, saltmarshes, coral reef, seagrass, macroalgae and intertidal habitats) A.0.3 Red list index A.0.4 The proportion of populations within species with a genetically effective population size > 500 t2.8. Species Protection Index
Spatial data coverage	National, regional and global scales. Uses environmental and species data, addressing all terrestrial areas at 1 km spatial resolution
Taxonomic data coverage	Terrestrial vertebrates (~32,000 species) and select vascular plants
Temporal data coverage	Annual land cover data from 2001 onwards
Development status	Developed for terrestrial systems Under development for marine systems
Supporting information	Map of Life web interface: https://mol.org/indicators GEO BON EBV portal: https://portal.geobon.org/ WCMC Post-2020 Indicators Tracker: https://www.post-2020indicators.org/
Contact(s)	Walter Jetz (walter.jetz@yale.edu) GEO BON Secretariat (info@geobon.org)

3.2 Alignment to the global biodiversity framework

The SHI contributes directly to Goal A of the post-2020 global biodiversity framework. SHI has direct relevance to the connectivity and integrity of natural systems, as well as the extinction rate, population abundance (size) and population distribution of species populations, and genetic diversity of species.

SHI and Milestone A.1: *Net gain in the area, connectivity and integrity of natural systems of at least 5 per cent.*

SHI addresses all elements of Milestone A.1, and in particular measures connectivity. It measures changes to the many units, i.e. species, that define ecosystems and drive their ecological processes and integrity. For any defined area, the SHI assesses temporal change in hundreds or thousands of species and provides a compound signal of change in ecosystem integrity.

Indicator “A.0.1 Extent of selected natural and modified ecosystems” is poised to deliver a basic but important capture of the area element of this milestone. Remote sensing enables a high-resolution delineation and tracking of ecosystem modification and areal change. Expert-based quality metrics could add further relevance to indicator A.0.1. But necessarily based on single geographic layers of abutting ecosystems (and thus a single dimension), the A.0.1 extent measure is naturally limited in the capture of ecological connectivity and integrity.

SHI and Milestone A.2: *The increase in the extinction rate is halted or reversed, and the extinction risk is reduced by at least 10%, with a decrease in the proportion of species that are threatened, and the abundance and distribution of populations of species is enhanced or at least maintained.*

The SHI, specifically through the Area component, uniquely and primarily addresses the second portion of Milestone A.2 by capturing trends in species population abundance and distribution.

For the first milestone part, Indicator ‘A.0.3 Red list index’, and in particular national red-listing efforts, the SHI provides a periodic assessment of ‘Extinction risk’ and ‘Threat status’ and, as possible, through expert networks carefully assess “Extinct” status. Species-level SHI values and maps can offer vital information, supporting expert threat assessments by providing temporal immediacy, regional/national specificity, and geographic specificity.

SHI and Milestone A.3: *Genetic diversity of wild and domesticated species is safeguarded, with an increase in the proportion of species that have at least 90 per cent of their genetic diversity maintained.*

In the absence of comprehensive genetic sampling to characterize separate populations and their genetically effective sizes, SHI offers a scalable alternative method to monitor loss of genetic diversity. SHI directly measures the “Proportion of populations, or geographic range, maintained within species", one of two main indicators for measuring genetic diversity recommended by the GEO BON Genetic Composition Working Group, with support from the IUCN Conservation Genetics Specialist Group and others.

The indicator 'A.0.4 The proportion of populations within species with a genetically effective population size > 500' can offer a more direct quantification of genetic diversity when sufficient, range-wide genetic sampling allows. Where sufficient genetic data are lacking, the SHI area and connectivity components are recommended as alternatives to estimate changes in the minimum population sizes. Where range-wide genetic sampling remains limited to a subset of species, the SHI can be a proxy for trends in genetic diversity for a larger and more representative portion of biodiversity.

3.3 Methodology

The SHI is calculated and validated using species occurrence data combined with environmental change data informed by remote sensing. Calculations use best-possible predictions of species geographic distributions (Species Populations EBVs), based on a variety of sources combined with species habitat information. The SHI can be calculated by Parties with national data, such as national biodiversity monitoring data or land-cover classifications. A full suite of annual country-level indicator values and extensive species-level data and metadata supporting it are made available through GEO BON, and Parties can readily use these directly for their reporting or use it to augment their own calculations.

3.4 Calculating indicator values

Parties can directly calculate country-level SHI by leveraging national data, expertise and biodiversity change assessment capacity. GEO BON, through its working groups, and national and thematic Biodiversity Observation Networks, is able to provide capacity support. The calculation follows these specific steps:

Step 1: Determine baseline species distributions. At the most basic level, this can include expert range maps, acknowledging their high false presence rate. Preferably, predictions are based on species distribution models (SDMs) that follow best-possible data integration practices and leverage raw occurrence data and remote-sensing supported environmental layers. Parties can develop these national distribution predictions entirely independently or use existing predictions (e.g. https://mol.org/species/range/Cephalophus_zebra), further modified or as provided.

Step 2: Calculate core metrics and SHI for the baseline period. The species distribution data are combined with remote-sensing supported layers of environmental conditions, such as land-cover, and the data-driven associations species associations have with them. This delivers continuous or binary pixel-level species habitat suitability for the reference period. Via standard GIS processing, this supports for each species estimates of country-wide i) total suitable habitat area (summed pixel suitability) and ii) habitat isolation (average distance to edge of suitable habitat area). These values are combined for all evaluated species in a country as simple average

(National SHI) or as average weighted by the proportion of global population the country is estimated to hold (Steward's SHI). The same species values can also be averaged for each pixel and its composition of species as informed by the species distribution maps.

Step 3: Calculate change in core metrics and SHI. Through standard GIS processing, changes to the baseline levels of suitability of each species-pixel combination are assessed for different time steps using the same or different environmental layers used in Step 2. These layers currently include standard global land-cover and marine change products, but can also comprise national change products or a combination of remotely sensed environmental change signals with high spatial and spectral resolution. Distribution gains beyond the baseline (e.g. through extensive restoration or climatic shifts) are addressed through a rerun of Step 1. For each point in time Step 2 calculations are repeated. SHI is given as the average change in area and connectivity, expressed as percent difference to the reference period, set at SHI = 100.

3.5 Availability of indicator values and resources

Through GEO BON partner Map of Life and associated data, technology and science partners, the SHI has currently (2021) been calculated annually 2001-2019 for all countries, addressing terrestrial vertebrates and select vascular plant groups (https://mol.org/indicators). Inclusion of select marine/coastal, invertebrate, and additional plant groups is in progress. The metrics are informed by a rapidly increasing number of occurrence records from the Global Biodiversity Information Facility (GBIF) and other sources, currently > 500 million records. For mountain regions, partner Global Mountain Biodiversity Assessment (GMBA, https://www.gmba.unibe.ch) supports mountain-specific species assessments. For marine systems, the current source is change in abatable human modification and under further development.

4.0 The proportion of populations within species with a genetically effective population size (N_e) > 500

The "N_e indicator" measures recent, ongoing and near-term losses of genetic diversity. It can track progress in genetic diversity conservation and inform management decisions to slow the loss of genetic diversity. This indicator (which could be renamed the "genetic health of populations indicator") uses populations and their "effective sizes" as core units of analysis. This indicator quantifies the ability of individual populations to maintain their genetic diversity and to evolve in response to environmental change. It is based on a well-regarded principle of conservation biology- small populations lose genetic diversity rapidly and are less able to adapt to environmental change. Specifically, populations with an "effective size" less than approximately 500 lose genetic diversity especially rapidly (with the loss of genetic diversity exponentially increasing with smaller effective size).

This affordable, accessible indicator can leverage data on population sizes from local, national, and global sources. The "effective size" of a population will most often be calculated by using a simple transformation of the "census size"—a count of individual adults—when genetic data is unavailable (Figure 4.1). It can also be directly calculated from genetic or detailed demographic data when it is available. The following paragraphs will mostly focus on use of census size for calculation but will mention where other data can be used. It is important to note that in either case, the indicator *does not* involve reporting Digital Sequence Information (DSI). Even in cases when genetic data is used to calculate N_e, the reporting only involves a count of populations meeting N_e criteria and does not involve accessing species sequence information. The indicator can be aggregated by taking the average (or weighted average) indicator value across all the species or populations within a geographic unit (landscapes, seascapes, mountains, regions, and country). It can be expressed and has meaning as a single time-point state indicator or calculated as a trend.

4.1 Key information

Alignment to GBF	Goal A Milestones A.3 Target 4 (*inter alia*)
Relevant headline, component, and complementary indicators	A.0.2 Species Habitat Index A.8.1 Proportion of populations maintained within species 4.0.1 Proportion of species populations that are affected by human wildlife conflict 4.0.2 Number of plant genetic resources for food and agriculture secured in medium or long-term conservation facilities a.41. Number of threatened species by species group a.48. Genetic scorecard for wild species a.52. Number of plant and animal genetic resources for food and agriculture secured in either medium- or long-term conservation facilities (SDG 2.5.1) t3.3. Changing status of evolutionary distinct and globally endangered species (EDGE Index) t3.4. Percentage of threatened species that are improving in status.
Spatial data coverage	The indicator can be calculated at national, regional, or global scales
Taxonomic data coverage	The indicator can be calculated at the population level or

	species level in any species, and (weighted) averages can be calculated across populations or species.
Temporal data coverage	Dependent on data quality at the national scale
Development status	Under development, in testing phase in 2022 by several countries
Supporting information	Hoban *et al*. (2020) provides an introduction to genetic indicators and context. Further discussion of appropriate use, see Hoban *et al*. (2021). Policy brief outlining indicators at a high level in numerous languages (https://geobon.org/ebvs/working-groups/genetic-composition/see under Documents & Publications). WCMC Post-2020 Indicators Tracker: https://www.post-2020indicators.org/
Contact(s)	Sean Hoban (shoban@mortonarb.org) Linda Laikre (linda.laikre@popgen.su.se) GEO BON Secretariat (info@geobon.org)

4.2 Alignment to the global biodiversity framework

This indicator contributes directly to Goal A of the post-2020 global biodiversity framework. It focuses explicitly on tracking the change in genetic diversity and genetic resilience within species.

Relation to Milestone A.3: *Genetic diversity of wild and domesticated species is safeguarded, with an increase in the proportion of species that have at least 90 per cent of their genetic diversity maintained.*
Relation to Target 4: *Ensure active management actions to enable the recovery and conservation of species and the genetic diversity of wild and domesticated species, including through ex situ conservation...*

This indicator allows a feasible, scalable way to assess whether genetic diversity is being maintained through an accessible proxy that can be collected for at least dozens and likely hundreds or even thousands of species per country. The proxy of effective population size is known to relate to genetic diversity loss and is the best evidence available when DNA sequencing is not available (the case for most species globally). Maintaining effective sizes above 500 will ensure maintaining at least 90 percent (in fact, over 95%) of within population genetic diversity for many generations.

4.3 Methodology

As noted above, in some cases the effective size can be calculated using established genetic methods when genetic data is available (Figure 4.1). However for most species it would be calculated by applying a simple transformation to local populations' census size- the number of adult individuals present in a discrete area- and comparing the result to an accepted threshold for loss of genetic diversity. The default transformation to use is to multiply by 0.1, thus assuming a census-to-effective-size ratio of 1:10, a widely accepted though slightly conservative 'rule of thumb'. This would equate to a census size (number of mature individuals) of 5000 having an effective size of 500. However, for some taxonomic groups and for some species a more refined ratio could be employed (see step 2 below). The census size of local populations of target species can be obtained from a variety of sources, including national biodiversity monitoring databases and programs, endangered species management and recovery plans, detailed population information contained in some Red List assessments, and expert consultation. Detailed guidance on these calculations and a variety of example calculations will be available through GEO BON in 2022.

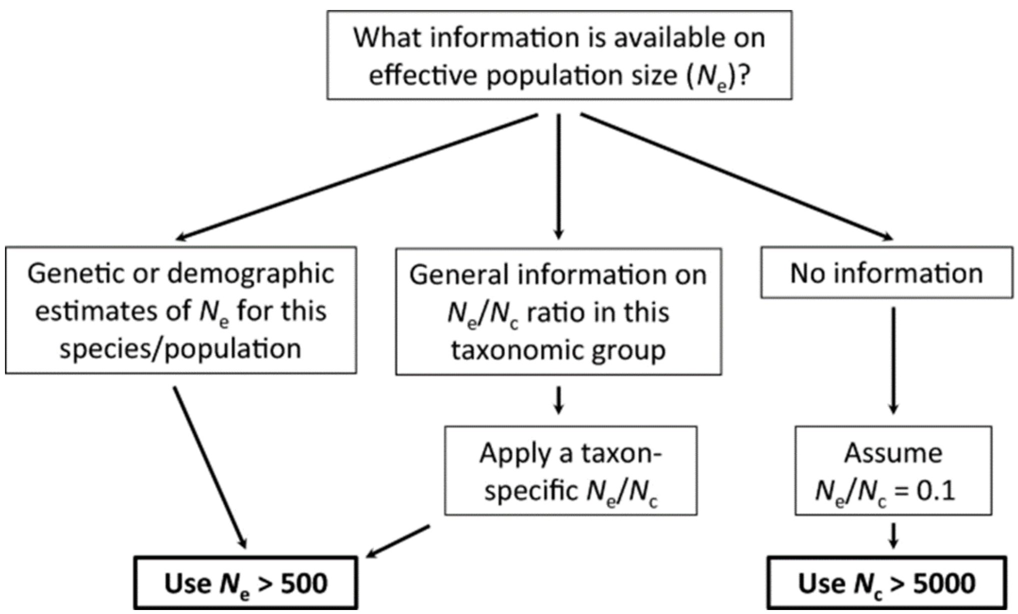

Figure 4.1 *Conceptual diagram for applying the N_e indicator (Hoban et al. 2020). If direct and robust estimates of N_e are available, they should be used. If only general information is available about factors affecting the ratio of N_e to census population size (N_c), then this information should be used to calibrate estimates of N_c from the specific population against the N_e > 500 threshold. If no information is available, the indicator is applied using estimates of N_c with the threshold N_c > 5000, implicitly assuming N_e/N_c = 0.1 (Source: Laikre* et al. *2021).*

4.4 Calculating indicator values

Parties can directly calculate country-level values of this indicator by leveraging national data, expertise and biodiversity assessments by following the guidance manual that is being developed by the GEO BON Genetic Composition Working Group, in collaboration with a broad coalition of conservationists globally, and will be available in 2022. GEO BON, through its working groups, and national and thematic Biodiversity Observation Networks, is able to provide capacity support, training and consultation. Considering that currently the workflow is manual rather than fully automated, the indicator would be calculated for a relatively small number of representative species per country- this might range from dozens on the low end to 1000 or more on the high end but for many countries will be on the scale of 100 species.

The calculation follows these specific steps:

Step 1: Define population boundaries and compile data. For each of the focal species it is first necessary to define 'populations' and to collect data on census population sizes. Many local and national biodiversity monitoring programs (e.g. at species or ecosystem level) may have already defined populations based on geographic isolation, association with a geographic feature like a mountain range or lake, etc. Full guidance on defining populations for a wide variety of organisms will be provided in the guidance manual for this indicator. After defining populations, it is necessary to collect data on census population sizes (or to use genetic data). Again, many biodiversity monitoring programs for priority species will have this data available - in some cases in a centralized national database while in other cases it may be scattered among different national reports and assessments.

Step 2: Calculate each population's effective size. As noted above, for most species, it will entail first choosing a ratio of census to effective size, and then multiplying each population's census size by this ratio, to obtain each population's effective size. As mentioned above, the default ratio that we recommend, which is slightly conservative, is 1:10 or 0.1. Alternatively a taxon specific ratio can be obtained in one of several ways: (a) from recent reviews of the literature which give means for broad groups such as mammals, bony fish, annual plants, trees, etc., (b) from formulas that take into account a species' biological characteristics (especially the male-female sex ratio and the variance in offspring production), or (c) from published literature on the species or even populations that are the focus of study. For instance, the ratio in large-bodied mammals is typically more on the scale of 0.3. These are all valid ways of obtaining the ratio. To incorporate uncertainty in calculations, the calculation can be repeated using multiple thresholds.

Step 3: Calculate the proportion of populations above the 500 N_e threshold. For each species, count the number of populations with an N_e above 500 and the number with N_e below 500; these two added together should equal the total number of populations. The indicator can be reported as a proportion (from 0 to 1) of all populations that are above 500, or as ratio in the form of 'number of populations above 500': 'total number of populations.' (Recently extinct populations would have a size of 0 to avoid an increase in the indicator value when populations are lost).

Step 4: To combine across species in a given country or geographic location, a simple average of the proportion from step 3 for all the relevant species should be performed; alternatively this can be weighted by the proportion of the species' range within the country. This can be disaggregated by type of species. The indicator would range between 0 and 1 (with 1 being the desired state- all populations above an effective size of 500).

Step 5: Change over time. The change in the indicator value can be calculated over time, but we first note that *the current state of the indicator can be directly interpretable and has important meaning for genetic biodiversity*. Any population with an effective size below 500 is likely losing genetic diversity fairly quickly, and is losing its ability to respond via adaptation- the state of the indicator itself signals an ongoing erosion of genetic diversity. In addition, temporal change in the indicator can be calculated using multiple time point values of population size. Temporal change would indicate improvement, worsening, or stable state of the indicator and thus in the rate of genetic erosion and can be calculated using temporal data on population sizes.

4.5 Availability of indicator values and resources

Indicator values are not yet available in a database similar to Map of Life. Testing of the indicator is occurring for several countries in 2022. A guidance manual on calculating the indicator using genetic data or the proxy outlined here will be available in 2022.

5.0 Rate of invasive alien species spread

The rate of invasive alien species spread measures the change in impact risk from invasive alien species (IAS) that are expected to have entered a new region given general observation trends and available impact data. This indicator can be expressed as a trend or a species distribution, and disaggregated by taxonomic group, region, country and type of impact to prioritize impacts and sites to eliminate or reduce these impacts.

The RIASS indicator benefits from country checklists of IAS provided by the Global Register of Introduced and Invasive Species (GRIIS), ongoing collection of data by countries on the presence and distribution of IAS, GBIF occurrence data and a range of other resources. It is designed to measure and report on long-term progress to slowing the rate of IAS introductions, within and across policy reporting cycles.

5.1 Key information

Alignment to GBF	Target 6
Relevant headline, component, and complementary indicators	t5.1. Number of invasive alien species in national lists as per the Global Register of Introduced and Invasive Species t5.2. Proportion of countries adopting relevant national legislation and adequately resourcing the prevention or control of invasive alien species

Spatial data coverage	This indicator can be disaggregated by pathways at the national, regional, and global level, as well as for priority sites and protected areas.
Taxonomic data coverage	Plants and animals across terrestrial, freshwater, brackish, marine, host, and combinations
Temporal data coverage	From 1980
Development status	Near ready
Supporting information	Global Register of Introduced and Invasive Species (GRIIS): https://griis.org/ Invasive Species Specialist Group (ISSG): http://www.issg.org/ Global Biodiversity Information Facility (GBIF) global register of introduced and invasive species datasets by country: https://www.gbif.org/dataset/search?publishing_org=cdef28b1-db4e-4c58-aa71-3c5238c2d0b5 WCMC Post-2020 Indicators Tracker: https://www.post-2020indicators.org/
Contact(s)	Melodie McGeoch (M.McGeoch@latrobe.edu.au) iDiv sTWIST: https://www.idiv.de/en/stwist.html GEO BON Secretariat (info@geobon.org)

5.2 Alignment to the global biodiversity framework

The rate of invasive alien species spread directly supports Target 6 of the framework on managing pathways for the introduction of invasive alien species, and preventing and reducing their rate of introduction and establishment. Because invasive species are a major threat to biodiversity, this indicator indirectly informs management actions on species and ecosystems recovery and conservation.

5.3 Methodology

This indicator links the management success of introduction pathways of IAS to the desired outcome and target of preventing new IAS species country establishments. A time series showing the change in the number of IAS in a country, region or globally, or each of these for a specific pathway of introduction or taxon, is an intuitive way to visualize growth in biological invasions. High or increasing introduction rates suggest that prevention and control measures have been ineffective. Low or declining introduction rates suggest that prevention efforts are succeeding.

However, time series of raw data on IAS discoveries are misleading because observer activities and species occurrence reporting rates differ vastly across regions and taxa. New IAS occurrences in some places and for some species groups will be strongly underestimated compared to those with very abundant data. The number of actual new IAS known to be introduced and established in a country over time is therefore determined by both the actual rates of introduction to the country and the discovery and reporting of these new populations. A robust indicator metrics therefore needs to take this sampling effect into account.

The number of IAS per time step is modelled to account for both the introduction and sampling processes, thus providing an improved estimate of the underlying introduction rates. Once the model has been applied, the indicator is the parameter of the model describing the change in the underlying introduction rate over time (β1)2. Positive values of β1 indicate accelerating introduction rates while negative values indicate decelerating rates (β0 provides the baseline rate, i.e., is the trend increasing or decreasing). Note that β1 is calculated over a time span (e.g., t1= 1970-1990, t2= 2000-2020), and cannot be calculated for a single year.

Currently, the indicator is based on records of established species in countries, i.e., the subset of species that have been introduced to, and successfully established, in that country. The same method can be extended to include post-establishment eradications in the estimate where the data are available.

5.4 Calculating indicator values

I. The indicator is calculated from Country Checklists of Introduced and Invasive Species[6], which are available via the Global Register of Introduced and Invasive Species[7]. The checklists are updatable via the same mechanism and form the backbone of country monitoring frameworks for IAS. The information value of this indicator is dependent on recent data on new IAS established in the country, and ongoing updating of the Country Checklist and Dates of First Record for the country (see next steps). It is also informed by ongoing collation of in-country evidence on which species have started to cause harm (have a negative impact) or continue to do so, and this information being fed back into GRIIS Country Checklists via checklist updates.

II. The indicator can be calculated for different species subsets: (1) Species known to have an impact (i.e., based on the subset of invasive alien species in GRIIS for which there is evidence of impact in at least one country (denoted as ‘Invasive’ in the ‘isInvasive’ field of the country checklists)). (2) All alien species in a country. (3) All alien species introduced via a particular pathway of introduction.

III. For this subset of ‘isInvasive’ species in the country, the dates of introduction, estimated dates of introduction, or dates of ‘first record’ are required. These data can be collated from in-country sources, or from the Alien Species First Records Database15. Date information can be compiled on a taxon-by-taxon basis, starting with those taxa for which the data are most readily available and complete.

[6] Available at: https://www.gbif.org/dataset/search?publishing_org=cdef28b1-db4e-4c58-aa71-3c5238c2d0b5
[7] https://griis.org/

IV. Raw data trends can be compiled showing the known number of new introductions or records per year.

V. To estimate the 'Rate of Spread Indicator', the above information is then modelled to estimate the 'rate parameter ($\beta 1$)' along with an estimate of uncertainty around the parameter and invasion trend (see ref. 2, the formula and scripts for calculation will be made available shortly).

VI. Stable use of this indicator by Parties relies on use of the same baseline data set and a consistent method for estimating the rate parameter. Further tools are currently being prepared by GEOBON – Theory and Workflow for Invasive Species Tracking (sTWIST) sDiv working group to assist countries with this step.

5.5 Availability of indicator values and resources

The GEO BON Species Populations Working Group and sTWIST are currently collaborating to produce indicator values for major taxonomic groups and countries, and to make the calculation and code available in readily usable form.

The methodology for the indicator developed by sTWIST is currently under peer review, and available as a pre-print. Data to populate the indicator globally and by country are available from the sources outlined above. Parties can contribute to these efforts and to their own IAS Spread indicator by updating these data sources where necessary, and over time by ongoing observations of new species introductions and materialization of new evidence of IAS impacts within countries. GEO BON is working to produce additional material and tools to further support Parties in using this indicator and will support a baseline indicator calculation that parties can use or in their reporting replace with their own calculation. Updates on this indicator will be made available at: https://geobon.org/ebvs/indicators/

6.0 Biodiversity Habitat Index (BHI)

The Biodiversity Habitat Index (BHI) estimates the level of species diversity expected to be retained within any given spatial reporting unit (e.g., a country, a broad ecosystem type, or the entire planet) as a function of the unit's area, connectivity and integrity of natural ecosystems across it. Results for the indicator can either be expressed as 1) the 'effective proportion of habitat' remaining within the unit – adjusting for the effects of the condition and functional connectivity of habitat, and of spatial variation in the species composition of ecological communities (beta diversity); or 2) the effective proportion of habitat that can be translated, through standard species-area analysis, into a prediction of the proportion of species expected to persist (i.e. avoid extinction) over the long term.

The BHI is used to monitor and report past-to-present trends in the expected persistence of species diversity by repeatedly recalculating the indicator using best-available mapping of ecosystem condition or integrity observed at multiple points in time, e.g., for different years (Figure

6.1). A wide variety of data sources can be used for this purpose, spanning spatial scales from global to subnational, and including data assembled by countries for deriving ecosystem condition accounts under the UN SEEA Ecosystem Accounting framework. The BHI can also serve as a leading indicator[8] for assessing the contribution that proposed or implemented area-based actions are expected to make towards enhancing the present capacity of ecosystems to retain species diversity, thereby providing a foundation for strategic prioritisation of such actions by countries.

6.1 Key information

Alignment to GBF	Goal A Milestones A.1, A.2 Target 1 Target 2 Target 3
Relevant headline, component, and complementary indicators	A.0.1 Extent of selected natural and modified ecosystems (i.e. forest, savannahs and grasslands, wetlands, mangroves, saltmarshes, coral reef, seagrass, macroalgae and intertidal habitats) A.0.2 Species Habitat Index A.2.1 CMS connectivity indicator (CMS) A.3.1 Ecosystem Integrity Index a.25. Forest Fragmentation Index a.26. Forest Landscape Integrity Index a.32. Ecoregion Intactness Index a.33. Biodiversity Intactness Index 1.2.1 Priority retention of intact / wilderness areas 2.2.1 Maintenance and restoration of connectivity of natural ecosystems t3.9. Protected Area Connectedness Index (PARC-Connectedness)
Spatial data coverage	Existing coverage of the entire land surface of the planet at 30-arcsecond grid resolution (approximately 900 m cells at the equator).

[8] CBD/SBSTTA/24/INF/31

Taxonomic data coverage	Derived from data for ~254,000 species of plants, ~133,000 species of invertebrates, and ~24,000 species of vertebrates.
Temporal data coverage	Existing coverage for years: 2000, 2005, 2010, 2015 and 2020.
Development status	Developed globally at 30-arcsecond grid resolution.
Supporting information	Description on the Biodiversity Indicators Partnership (BIP) website: https://www.bipindicators.net/indicators/biodiversity-habitat-index Country-level results provided on the BIP Indicators Dashboard: https://bipdashboard.natureserve.org/map.html?ind=BiodiversityHabitatIndex
Contact(s)	Simon Ferrier (simon.ferrier@csiro.au) GEO BON Secretariat (info@geobon.org)

6.2 Alignment to the global biodiversity framework

The BHI contributes most directly to Milestones A.1 and A.2 of Goal A, and can make significant contributions to Targets 1, 2 and 3.

Relation to Goal A: *The integrity of all ecosystems is enhanced, with an increase of at least 15 per cent in the area, connectivity and integrity of natural ecosystems, supporting healthy and resilient populations of all species, the rate of extinctions has been reduced at least tenfold, and the risk of species extinctions across all taxonomic and functional groups, is halved, and genetic diversity of wild and domesticated species is safeguarded, with at least 90 per cent of genetic diversity within all species maintained.*

The BHI effectively integrates all three of the ecosystem attributes addressed in Goal A – i.e., area, connectivity, and integrity – and the combined effect that changes in these attributes are expected to have on the persistence of species diversity, the second major level of biodiversity addressed in that goal. Because it performs this integration through a community-level analysis, the BHI also accounts for a much larger proportion of the planet's species-level diversity than is currently possible using species-by-species approaches.

Relation to Target 1: *Ensure that all land and sea areas globally are under integrated biodiversity-inclusive spatial planning addressing land- and sea-use change, retaining existing intact and wilderness areas.*

Relation to Target 2: *Ensure that at least 20% of degraded freshwater, marine and terrestrial ecosystems are under restoration, ensuring connectivity among them and focusing on priority ecosystems.*

Relation to Target 3: *Ensure that at least 30% globally of land areas and of sea areas, especially areas of particular importance for biodiversity and its contributions to people, are conserved through effectively and equitably managed, ecologically representative and well-connected systems of protected areas and other effective area-based conservation measures, and integrated into the wider landscapes and seascapes.*

The BHI can also serve as a leading indicator for assessing the contribution that proposed or implemented area-based actions under Targets 1, 2 and 3 are expected to make to enhancing the capacity of ecosystems to retain species diversity. This would allow actions under these targets to be better linked to outcomes under Goal A.

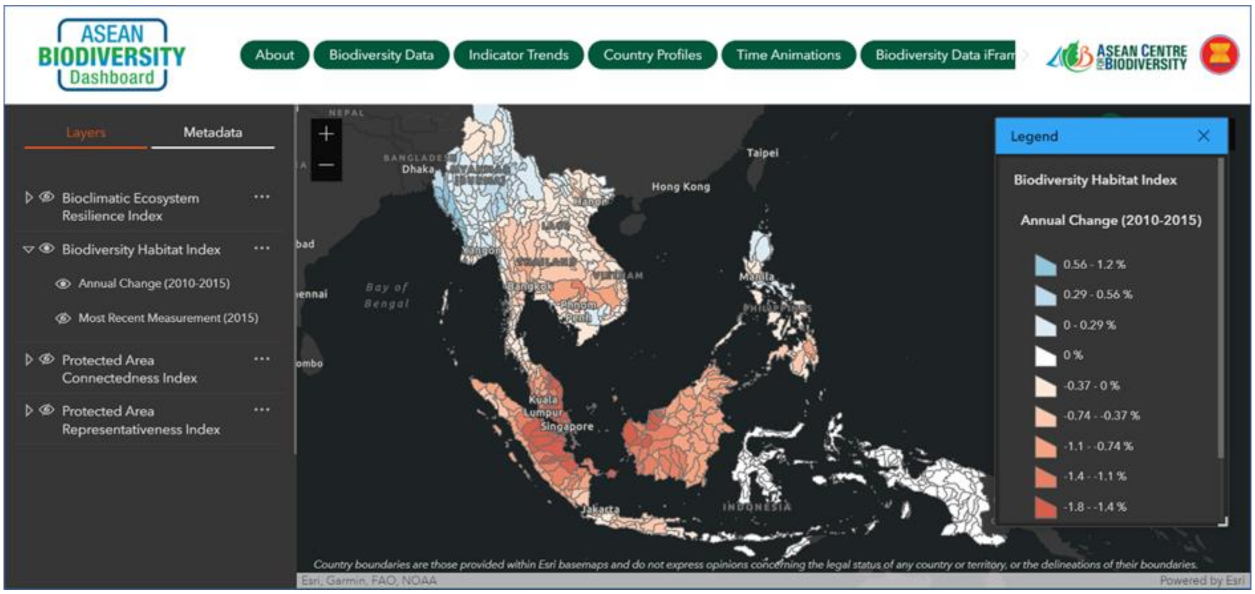

Figure 6.1 *Example mapping of change in the Biodiversity Habitat Index between 2010 and 2015, reported by watershed, and served through the Asean Biodiversity Dashboard*[9].

6.3 Methodology

The BHI is generated from two main inputs: 1) pre-derived modelling of spatial variation in the species composition of ecological communities; and 2) a spatial grid indicating, for each grid-cell, the present condition or integrity of the natural ecosystem associated with that cell[10]. These two inputs are combined to assess the 'effective proportion of habitat' remaining within any spatial reporting unit of interest (e.g. a country, or a broad ecosystem type) – adjusting for the effects of the condition and functional connectivity of habitat, and of spatial variation in the species composition of ecological communities, across that unit. This effective proportion of habitat can optionally be translated, through standard species-area analysis, into a prediction of the

[9] Available at: https://experience.arcgis.com/experience/2ffc8feeafab47c8a6dcf9e88436e37c/page/Indicator-Trends/

[10] See https://www.bipindicators.net/indicators/biodiversity-habitat-index for more details.

proportion of species expected to persist over the long term. The rigour with which functional habitat connectivity is addressed by the BHI has now been enhanced significantly by the recent incorporation of analytical techniques (least-cost-path, and cost-benefit, analysis) previously implemented in the closely related Bioclimatic Ecosystem Resilience Index (BERI, see next section).

The BHI has already been, and will continue to be, generated at 30-arcsecond grid resolution across the entire land surface of the planet by CSIRO, Australia's national science agency. This global implementation of the indicator makes use of existing compositional-turnover models derived from data for over 400,000 species of plants, invertebrates and vertebrates. These are the same models as those employed in generating the BERI and the Protected Area Representativeness and Connectedness (PARC) indices. The global implementation of the BHI also uses the same time series of change in ecosystem condition as that employed by CSIRO in generating the BERI. This involves translating remotely sensed land-cover attributes (MODIS Vegetation Continuous Fields) and classes (ESA CCI Land Cover) into a continuous measure of change in ecosystem condition through statistical land-use downscaling, and calibration based on meta-analysis of local land-use impacts on biodiversity undertaken by the PREDICTS project (led by the Natural History Museum).

The continuous nature of the ecosystem-condition time series underpinning the global BHI implementation confers an important advantage relative to indicators underpinned by observed changes in the distribution of discrete land-cover classes. The BHI can reflect changes in condition resulting from disturbance or management of an ecosystem represented by a single mapped land-cover type, e.g. "forest", not just changes in the extent of that type. The BHI can also be derived from any other gridded dataset for which ecosystem condition or integrity is estimated on a continuous scale for each cell. For example, a refined version of the indicator has recently been derived across all forests globally, based on 300m grid-resolution mapping of the Forest Landscape Integrity Index. Strong capacity for deriving the BHI from ecosystem condition datasets assembled at national and subnational scale for UN SEEA Ecosystem Accounting has also been demonstrated through recent applications in Australia and Peru.

6.4 Calculating indicator values

Three main options exist, or are anticipated, for Parties to report on changes in the BHI for their country. These options differ both in terms of ease of implementation, and in terms of the extent to which they mobilise national versus global data.

Option 1: In this option Parties would simply extract the raw gridded BHI results (at 30-arcsecond grid resolution) for their country from the relevant globally-generated layers. They could then use standard GIS processing to aggregate and report results by any desired set of spatial units – e.g. provinces, ecosystem types. This is the easiest option to implement, but results would be totally dependent on the quality of the global inputs employed, and would not benefit from incorporation of any better-quality national data.

Option 2: Parties would here make use of the existing global modelling of spatial variation in species composition (the most challenging, and computationally demanding, component of the indicator's workflow) but would replace the globally-generated mapping of change in ecosystem condition with best-available national data – e.g. ecosystem condition mapping generated by a country's implementation of UN SEEA Ecosystem Accounts. This option also opens up potential for Parties to evaluate the contribution that alternative area-based actions might make to improving the present BHI score for their country, thereby providing a foundation for prioritising the implementation of such actions. While Option 2 would allow results for the BHI to reflect a Party's best understanding of changes in the condition of their country's ecosystems, the rigour of these results would still be constrained to some extent by the spatial resolution, and quality, of the global biodiversity modelling employed.

Option 3: In this most demanding option Parties would derive the BHI for their country from scratch, not only employing best-available national data on ecosystem condition, but also making use of best-available biological and environmental data to refine the modelling of spatial variation in species composition – potentially at a finer spatial resolution than that employed in the global implementation.

6.5 Availability of indicator values and resources

Full global results for the BHI will shortly be freely available for download, at raw 30-second grid resolution, via CSIRO's Data Access Portal https://data.csiro.au/. These same data are then also likely to be made available through the UN Biodiversity Lab. This accessibility will allow Parties to report changes in the globally-generated indicator for any desired set of spatial units within their country, as per Option 1 above. Results will initially be available for five time points – 2000, 2005, 2010, 2015 and 2020 – and will be updated incrementally throughout the post-2020 reporting period.

CSIRO is also currently exploring, with partner organisations, potential avenues for giving Parties ready access to the analytical capability needed to implement Option 2 in the near future, and eventually Option 3.

7.0 Bioclimatic Ecosystem Resilience Index (BERI)

The Bioclimatic Ecosystem Resilience Index (BERI) measures the capacity of natural ecosystems to retain species diversity in the face of climate change, as a function of ecosystem area, connectivity and integrity. The indicator assesses the extent to which any given spatial configuration of natural habitat across a landscape will promote or hinder climate-induced shifts in biological distributions. It does this by analyzing the functional connectivity of each grid-cell of natural habitat to areas of habitat in the surrounding landscape which are projected to support a similar assemblage of species under climate change to that currently associated with the cell of interest. The indicator can then be aggregated and reported by any desired spatial unit – e.g. an ecosystem type, a country, or the entire planet.

The BERI can be used to monitor and report past-to-present trends in the capacity of ecosystems to retain species diversity in the face of ongoing climate change by repeatedly recalculating the indicator using best-available mapping of ecosystem condition or integrity observed at multiple points in time, e.g. for different years (Figure 7.1). It can also serve as a leading indicator[11] for assessing the contribution that proposed or implemented area-based actions are expected to make to enhancing the present capacity of ecosystems to retain species diversity, thereby providing a foundation for strategic prioritisation of such actions by countries.

7.1 Key information

Alignment to GBF	Goal A Milestones A.1, A.2 Target 1 Target 2 Target 3 Target 8
Relevant headline, component, and complementary indicators	A.0.1 Extent of selected natural and modified ecosystems (i.e. forest, savannahs and grasslands, wetlands, mangroves, saltmarshes, coral reef, seagrass, macroalgae and intertidal habitats) A.0.2 Species Habitat Index A.2.1 CMS connectivity indicator (CMS) A.3.1 Ecosystem Integrity Index a.25. Forest Fragmentation Index a.26. Forest Landscape Integrity Index a.32. Ecoregion Intactness Index a.33. Biodiversity Intactness Index 1.2.1 Priority retention of intact / wilderness areas 2.2.1 Maintenance and restoration of connectivity of natural ecosystems t3.9. Protected Area Connectedness Index (PARC-Connectedness)
Spatial data coverage	Existing coverage of the entire land surface of the planet at 30-arcsecond grid resolution (approximately 900 m cells at the equator).

[11] CBD/SBSTTA/24/INF/31

Taxonomic data coverage	Derived from data for ~254,000 species of plants, ~133,000 species of invertebrates, and ~24,000 species of vertebrates.
Temporal data coverage	Existing coverage for years: 2000, 2005, 2010, 2015 and 2020.
Development status	Developed globally at 30-arcsecond grid resolution.
Supporting information	Peer-reviewed journal paper describing the indicator (Ferrier *et al.* 2020). Description on the Biodiversity Indicators Partnership (BIP) website: https://www.bipindicators.net/indicators/bioclimatic-ecosystem-resilience-index-beri Country-level results provided on the BIP Indicators Dashboard: https://bipdashboard.natureserve.org/map.html?ind=BERI
Contact(s)	Simon Ferrier (simon.ferrier@csiro.au) GEO BON Secretariat (info@geobon.org)

7.2 Alignment to the global biodiversity framework

The BERI contributes most directly to Target 8, and can make significant contributions to Milestones A.1 and A.2 of Goal A, and to Targets 1, 2 and 3.

Relation to Target 8: *Minimize the impact of climate change on biodiversity, contribute to mitigation and adaptation through ecosystem-based approaches, contributing at least 10 GtCO2e per year to global mitigation efforts, and ensure that all mitigation and adaptation efforts avoid negative impacts on biodiversity.*

The BERI provides a rigorous, yet straightforward, measure of the extent to which cumulative changes in the area, connectivity and integrity of natural ecosystems are helping or hindering efforts to "minimize the impact of climate change on biodiversity" and to "ensure that all mitigation and adaptation efforts avoid negative impacts on biodiversity". It therefore offers an effective means of linking actions under this target to both ecosystem-level and species-level outcomes under Goal A.

Relation to Goal A: *The integrity of all ecosystems is enhanced, with an increase of at least 15 per cent in the area, connectivity and integrity of natural ecosystems, supporting healthy and resilient populations of all species, the rate of extinctions has been reduced at least tenfold, and the risk of species extinctions across all taxonomic and functional groups, is halved, and genetic diversity of wild and domesticated species is safeguarded, with at least 90 per cent of genetic diversity within all species maintained.*

As for the closely related Biodiversity Habitat Index (BHI, see previous section), the BERI effectively integrates all three of the ecosystem attributes addressed in Goal A – i.e. area, connectivity, and integrity – and the combined effect that changes in these attributes are expected to have on the retention of species diversity. However, it differs from the BHI in giving much stronger consideration to the potential impacts of climate change, and particularly to the major role that functional habitat connectivity will play in facilitating climate-induced shifts in the distribution of species and ecological communities.

Relation to Target 1: *Ensure that all land and sea areas globally are under integrated biodiversity-inclusive spatial planning addressing land- and sea-use change, retaining existing intact and wilderness areas.*

Relation to Target 2: *Ensure that at least 20% of degraded freshwater, marine and terrestrial ecosystems are under restoration, ensuring connectivity among them and focusing on priority ecosystems.*

Relation to Target 3: *Ensure that at least 30% globally of land areas and of sea areas, especially areas of particular importance for biodiversity and its contributions to people, are conserved through effectively and equitably managed, ecologically representative and well-connected systems of protected areas and other effective area-based conservation measures, and integrated into the wider landscapes and seascapes.*

Again, as for the BHI (see previous section), the BERI can also serve as a leading indicator for assessing the contribution that proposed or implemented area-based actions under Targets 1, 2 and 3 are expected to make to enhancing the capacity of ecosystems to retain species diversity in the face of climate change. This would allow actions under these targets to be better linked with those under Target 8, and to outcomes under Goal A.

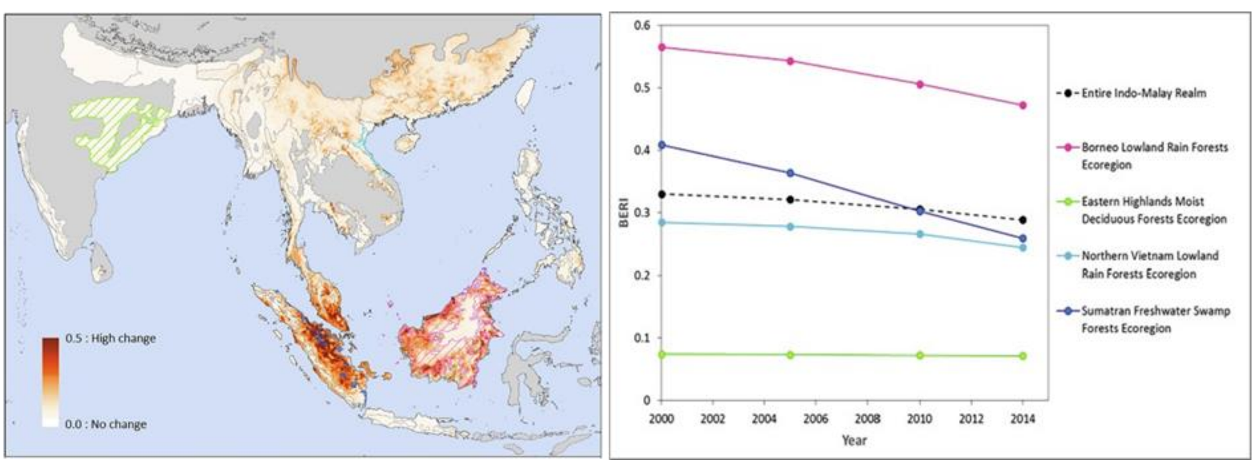

Figure 7.1 *Change in the Bioclimatic Ecosystem Resilience Index (BERI) between 2000 and 2014 mapped for the Moist Tropical Forest biome in the Indo-Malay Realm. The chart displays mean BERI values for the entire bio-realm, and for each of four selected ecoregions (highlighted in corresponding colours on the map;* Source*: Ferrier* et al. *2020).*

7.3 Methodology

The BERI is generated from two main inputs: 1) pre-derived modelling of spatial variation in the species composition of ecological communities, and of potential shifts in species composition over time under a plausible range of climate scenarios; and 2) a spatial grid indicating, for each grid-cell, the present condition or integrity of the natural ecosystem associated with that cell[12] (Ferrier *et al*. 2020). These two inputs are combined to assess the extent to which each cell in the grid is functionally connected (through least-cost-path analysis) to areas of natural habitat in the surrounding landscape which are projected to support a similar assemblage of species under climate change to that currently associated with the cell of interest.

The BERI has already been, and will continue to be, generated at 30-arcsecond grid resolution across the entire land surface of the planet by CSIRO, Australia's national science agency. This global implementation of the indicator makes use of existing compositional-turnover models derived from data for over 400,000 species of plants, invertebrates and vertebrates. These are the same models as those employed in generating the BHI and the Protected Area Representativeness and Connectedness (PARC) indices. The global implementation of BERI also uses the same time series of change in ecosystem condition as that employed by CSIRO in generating the BHI. This involves translating remotely sensed land-cover attributes (MODIS Vegetation Continuous Fields) and classes (ESA CCI Land Cover) into a continuous measure of change in ecosystem condition through statistical land-use downscaling, and calibration based on meta-analysis of local land-use impacts on biodiversity undertaken by the PREDICTS project (led by the Natural History Museum).

7.4 Calculating indicator values

Three main options exist, or are anticipated, for Parties to report on changes in the BERI for their country. These options differ both in terms of ease of implementation, and in terms of the extent to which they mobilise national versus global data.

Option 1: In this option Parties would simply extract the raw gridded BERI results (at 30-arcsecond grid resolution) for their country from the relevant globally-generated layers. They could then use standard GIS processing to aggregate and report results by any desired set of spatial units – e.g. provinces, ecosystem types. This is the easiest option to implement, but results would be totally dependent on the quality of the global inputs employed, and would not benefit from incorporation of any better-quality national data.

Option 2: Parties would here make use of the existing global modelling of spatial variation, and temporal turnover, in species composition (the most challenging, and computationally demanding, component of the indicator's workflow) but would replace the globally-generated mapping of change in ecosystem condition with best-available national data – e.g. ecosystem condition mapping generated by a country's implementation of UN SEEA Ecosystem Accounts. This option also opens up potential for Parties to evaluate the contribution that alternative area-based actions

[12] See https://www.bipindicators.net/indicators/bioclimatic-ecosystem-resilience-index-beri for details.

might make to improving the present BERI score for their country, thereby providing a foundation for prioritising the implementation of such actions. While this option would allow results for the BERI to reflect a Party's best understanding of changes in the condition of their country's ecosystems, the rigour of these results would still be constrained to some extent by the spatial resolution, and quality, of the global biodiversity modelling employed.

Option 3: In this most demanding option Parties would derive the BERI for their country from scratch, not only employing best-available national data on ecosystem condition, but also making use of best-available biological and environmental data to refine the modelling of spatial variation, and temporal turnover, in species composition – potentially at a finer spatial resolution than that employed in the global implementation.

7.5 Availability of indicator values and resources

Full global results for the BERI will shortly be freely available for download, at raw 30-second grid resolution, via CSIRO's Data Access Portal https://data.csiro.au/. These same data are then also likely to be made available through the UN Biodiversity Lab. This accessibility will allow Parties to report changes in the globally-generated indicator for any desired set of spatial units within their country, as per Option 1 above. Results will initially be available for five time points – 2000, 2005, 2010, 2015 and 2020 – and will be updated incrementally throughout the post-2020 reporting period.

CSIRO is also currently exploring, with partner organisations, potential avenues for giving Parties ready access to the analytical capability needed to implement Option 2 in the near future, and eventually Option 3.

8.0 Protected Area Representativeness and Connectedness (PARC) indices

The Protected Area Representativeness and Connectedness (PARC) indices measure the extent to which terrestrial protected areas, and other effective area-based conservation measures (OECMs), are ecologically representative, and well-connected (both to one another, and to other areas of intact natural ecosystems in the surrounding landscape). For the purposes of reporting against the 2010-2020 Aichi Targets, the PARC was originally configured as two separate indicators: the Protected Area Representativeness Index (or 'PARC-representativeness') and the Protected Area Connectedness Index (or 'PARC-connectedness'). However, these two indices were always designed in a manner which would allow them to be logically combined to yield a composite indicator of the extent to which a system of protected areas and OECMs is both ecologically representative and well-connected.

The PARC indices, whether generated separately or as a composite, are used to monitor and report past-to-present trends in representativeness and connectedness by repeated calculation using best-available mapping of protected areas and OECMs at multiple points in time, e.g. for different years. They can also provide a foundation for assessing the contribution that potential additions to the system of protected areas and OECMs might make to improving present PARC scores, thereby providing a foundation for prioritising such actions.

8.1 Key information

Alignment to GBF	Target 3
Relevant headline, component, and complementary indicators	3.0.1 Coverage of Protected areas and OECMS (by effectiveness) 3.4.1 Species Protection Index t3.7. Proportion of terrestrial, freshwater and marine ecological regions which are conserved by protected areas or OECMS
Spatial data coverage	Existing coverage of entire land surface of the planet at 30-arcsecond grid resolution (approximately 900m cells at the equator)
Taxonomic data coverage	Derived from data for ~254,000 species of plants, ~133,000 species of invertebrates, and ~24,000 species of vertebrates.
Temporal data coverage	Existing coverage for years: 1970, 1980, 1990, 2000, 2010, 2012, 2014, 2016, 2018 and 2020.
Development status	Ready globally at 30-arcsecond grid resolution.
Supporting information	Descriptions on the Biodiversity Indicators Partnership (BIP) website: https://www.bipindicators.net/indicators/protected-area-representativeness-index-parc-representativeness and https://www.bipindicators.net/indicators/protected-area-connectedness-index-parc-connectedness Country-level results provided on the BIP Indicators Dashboard: https://bipdashboard.natureserve.org/map.html?ind=PARepresentativeIndex and https://bipdashboard.natureserve.org/map.html?ind=PAConnectednessIndex
Contact(s)	Simon Ferrier (simon.ferrier@csiro.au) GEO BON Secretariat (info@geobon.org)

8.2 Alignment to the global biodiversity framework

Relation to Target 3: *Ensure that at least 30% globally of land areas and of sea areas, especially areas of particular importance for biodiversity and its contributions to people, are conserved through effectively and equitably managed, ecologically representative and well-connected systems of protected areas and other effective area-based conservation measures, and integrated into the wider landscapes and seascapes.*

The PARC-representativeness index provides a rigorous measure of the extent to which a system of terrestrial protected areas and OECMs is ecologically representative of the full range of environmental and biological diversity present within any given spatial reporting unit (e.g. a country). It does so at a much finer, and more ecologically meaningful, resolution than indicators of representativeness based on proportional protection of ecoregions or broad ecosystem types.

The PARC-connectedness index provides a rigorous measure of the extent to which protected areas and OECMs are functionally connected, not only to one another but also to other areas of intact natural ecosystems in the surrounding landscape.

The composite PARC indicator (see Methodology section below) offers a uniquely integrative measure of progress in the expansion of any system of protected areas and OECMs. This indicator is expressed on the familiar scale of proportional (or percent) coverage, but with the position of any given reporting unit (e.g. a country) on this scale rigorously adjusted for the effects of both representativeness and connectedness.

8.3 Methodology

The PARC indices are generated from three main inputs: 1) a spatial grid delineating the coverage of protected areas and OECMs; 2) for the connectedness component of the indicator, a second grid delineating the distribution of intact natural ecosystems across the broader landscape; and 3) for the representativeness component of the indicator, pre-derived modelling of spatial variation in the species composition of ecological communities[13] (Figure 8.1). The functional connectivity of each protected cell to other protected cells, and to cells containing natural ecosystems in the surrounding landscape, is measured using a combination of least-cost-path and cost-benefit analysis, and is expressed as a proportion of the maximum score expected if a cell were surrounded by a continuous expanse of protection. PARC-connectedness is then derived by averaging the connectivity scores of all protected cells in the spatial reporting unit of interest (e.g. a country). PARC-representativeness is derived by using the modelled spatial variation in community composition to estimate the average proportional protection of relatively distinct environments, and therefore species assemblages, across the reporting unit. Alternatively, the contribution that each protected cell makes to this analysis of representativeness can be weighted by the cell's connectivity score, thereby yielding a composite PARC indicator of proportional

[13] See https://www.bipindicators.net/indicators/protected-area-representativeness-index-parc-representativeness and https://www.bipindicators.net/indicators/protected-area-connectedness-index-parc-connectedness for details.

protection (e.g. for a country) adjusted for the effects of both connectivity and ecological representativeness.

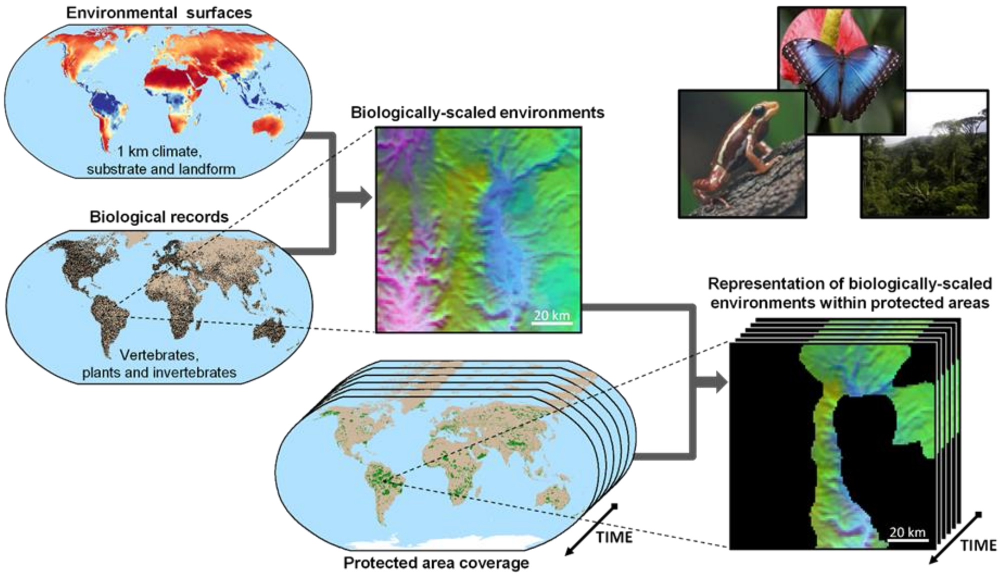

Figure 8.1 *Major steps involved in deriving the PARC-representativeness index from biological, environmental and protected-area data. From: IPBES / GEO BON metadata sheet*[14].

The PARC indices have already been, and will continue to be, generated at 30-arcsecond grid resolution across the entire land surface of the planet by CSIRO, Australia's national science agency. This global implementation makes use of existing compositional-turnover models derived from data for over 400,000 species of plants, invertebrates and vertebrates. These are the same models as those employed in generating the BHI and BERI indices (see previous sections). The global implementation of PARC-connectedness also employs data on the distribution of primary vegetation generated by CSIRO's statistical land-use downscaling.

8.4 Calculating indicator values

Three main options exist, or are anticipated, for Parties to report on changes in the PARC indices for their country. These options differ both in terms of ease of implementation, and in terms of the extent to which they mobilise national versus global data.

Option 1: In this option Parties would simply extract the raw gridded PARC results (at 30-arcsecond grid resolution) for their country from the relevant globally-generated layers. They could then use standard GIS processing to aggregate and report results by any desired set of spatial units – e.g. provinces, ecosystem types. This is the easiest option to implement, but results would be totally dependent on the quality of the global inputs employed, and would not benefit from incorporation of any better-quality national data.

---

[14] Available at:
https://www.ipbes.net/sites/default/files/Metadata_GEO_BON_Protected_Area_Representativeness_Index.pdf

Option 2: Parties would here make use of the existing global modelling of spatial variation in species composition (the most challenging, and computationally demanding, component of the indicator's workflow) but would replace the globally-generated data on protected areas and OECMs, and on the distribution of primary vegetation, with best-available national data. This option also opens up potential for Parties to evaluate the contribution that alternative additions to the system of protected areas and OECMs might make to improving the present PARC score for their country, thereby providing a foundation for prioritising such additions. The rigour of results generated through this option would, however, still be constrained to some extent by the spatial resolution, and quality, of the global biodiversity modelling employed.

Option 3: In this most demanding option Parties would derive the PARC indices for their country from scratch, not only employing best-available national data on ecosystem condition, but also making use of best-available biological and environmental data to refine the modelling of spatial variation in species composition – potentially at a finer spatial resolution than that employed in the global implementation.

8.5 Availability of indicator values and resources

Full global results for the PARC indices will shortly be freely available for download, at raw 30-second grid resolution, via CSIRO's Data Access Portal https://data.csiro.au/. These same data are then also likely to be made available through the UN Biodiversity Lab. This accessibility will allow Parties to report changes in the globally-generated indicators for any desired set of spatial units within their country, as per Option 1 above. Results will initially be available for ten time points – 1970, 1980, 1990, 2000, 2010, 2012, 2014, 2016, 2018 and 2020 – and will be updated incrementally throughout the post-2020 reporting period.

CSIRO is also currently exploring, with partner organisations, potential avenues for giving Parties ready access to the analytical capability needed to implement Option 2 in the near future, and eventually Option 3.

9.0 Forest Structural Integrity Index (FSII)

The Forest Structural Integrity Index (FSII) is a measure of the vertical stature of forests and level of human pressure. It identifies the taller, older, closed-canopy forests with low human pressure that are known to support high levels of native species, carbon storage, water yield, and other ecosystem services. The current version covers the Tropical & Subtropical Moist Broadleaf Biome. FSII is a key component of ecosystem integrity, which denotes levels of ecosystem structure, function, and composition relative to the extant climatic–geophysical environment. When aggregated across forest stands, protected areas, or ecosystems, FSII can be used to map annual change in the ecological quality of forests and the effectiveness of restoration efforts (Figure 9.1). FSII provides a basis for countries to prioritize conservation strategies for protection, restoration of forest structure, or restoration of forest integrity.

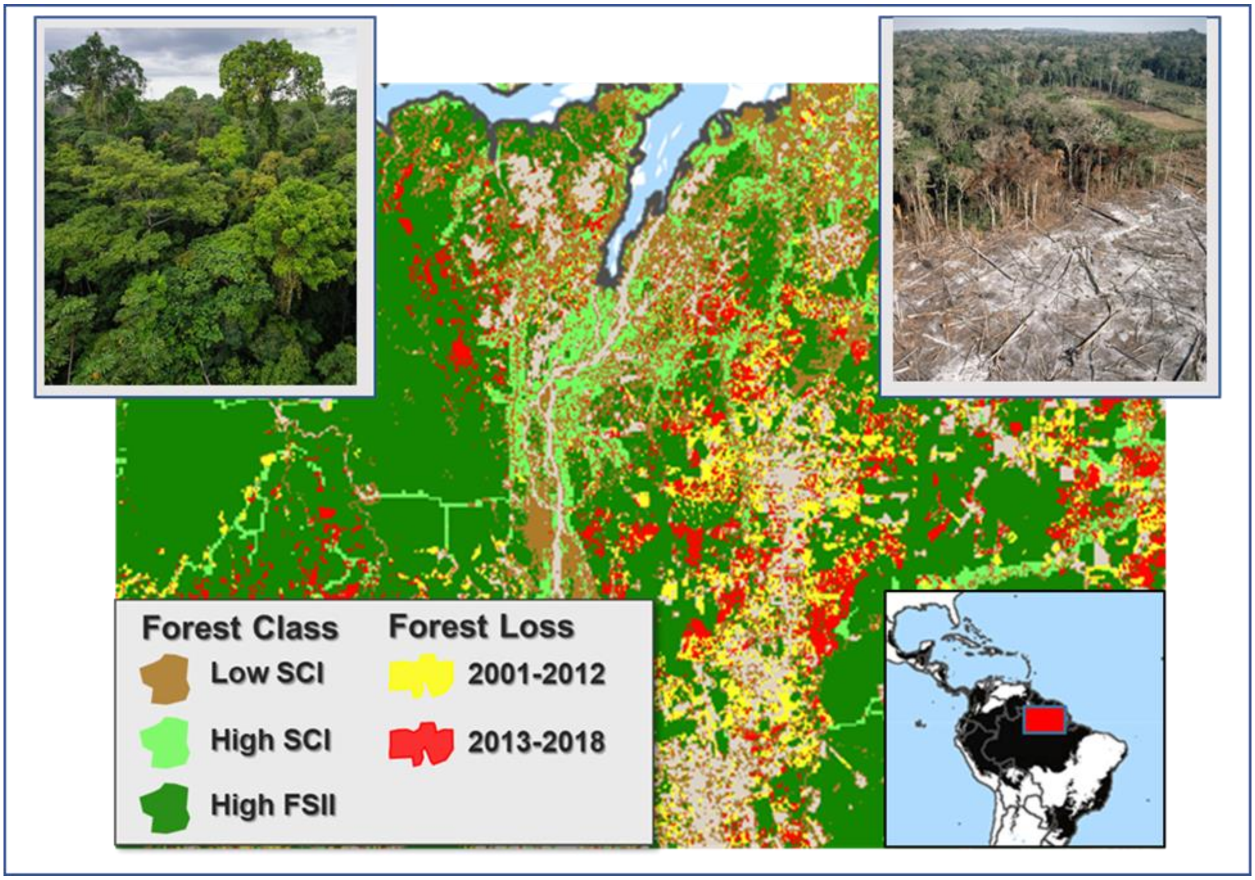

Figure 9.1 *A landscape in the Brazilian Amazon illustrating within forest extents the spatial patterning of Forest Structural Condition (low and high SCI) and Forest Structural Integrity (high FSII). The locations where high FSII forest stands were lost in 2001-2012 (yellow) and 2013-2018 (red) are shown. The photo insets reveal the differences in canopy structure between high FSII stands (top left), and low FSCI stands and stands lost to deforestation (top right). Photo credits: National Geographic.*

FSII is derived from the Forest Structural Condition Index (FSCI), which is based on satellite measures of canopy cover, canopy height, and time since forest loss. The FSCI spans from short, open-canopy, recently disturbed forests to tall, closed canopy stands that have not been disturbed since 2000. The quality of forests of high structural condition can be reduced by human pressure such as over-hunting, illegal logging, uncontrolled burning, and edge effects from roads. Integrating the FSCI with the Human Footprint Index (Venter *et al*. 2016) of human pressure identifies forests of high structural condition and low human pressure which are known to be of the highest ecological value.

Expansion of the FSII from the humid tropics to global forests is being planned as this is now possible due to recent advances in satellite technology. For example, a version under development called FSII-ERP (Ecoregion Potential) is indexed to the natural potential for forest stature within ecoregions. While the current approach is indexed to humid tropical forests in order to identify forests of highest global significance, FSII-ERP will be appropriate to other forest biomes that are naturally lower in forest stature. Moreover, FSII-ERP version may be of particular interest for national reporting because it is benchmarked to local rather than global conditions.

9.1 Key information

Alignment to GBF	Goal A Milestones A.1, A.2
Relevant headline, component, and complementary indicators	A.0.1 Extent of selected natural and modified ecosystems (i.e. forest, savannahs and grasslands, wetlands, mangroves, saltmarshes, coral reef, seagrass, macroalgae and intertidal habitats) A.0.2 Species Habitat Index t.2.0.1 Percentage of degraded or converted ecosystems that are under restoration
Spatial data coverage	This indicator can be aggregated at protected area, ecosystem, regional, national, and global tropical forest levels
Taxonomic data coverage	Tropical & subtropical moist broadleaf biome
Temporal data coverage	2000 onwards
Development status	Developed for humid tropical forests. Under development for forests globally based on ecoregional potential.
Supporting information	UN Biodiversity Lab: https://unbiodiversitylab.org/ GEO BON EBV portal: https://portal.geobon.org/ Figshare: https://figshare.com/projects/Forest_Integrity_Project/72164 Relevant publications: Hansen *et al*. (2019), Hansen *et al.* (2020), and Hansen *et al*. (2021)
Contact(s)	Andrew Hansen (hansen@montana.edu) GEO BON Secretariat (info@geobon.org)

9.2 Alignment to the Global Biodiversity Framework

The FSII contributes directly to Goal A of the post-2020 global biodiversity framework. It is a key component of ecosystem integrity and a driver of species population viability and production of ecosystem services.

FSII and Milestone A.1: *Net gain in the area, connectivity and integrity of natural systems of at least 5 per cent.*

FSII addresses the integrity of natural ecosystems. It directly measures the forest structural component of ecosystem integrity and integrates human pressure as a surrogate for direct measurement of ecosystem functional and compositional integrity. For any defined area, FSII assesses temporal change in an index of canopy height, canopy cover, time since forest loss, and human pressure. Thus, it can be used to track change in the integrity of natural and managed ecosystems and the effectiveness of restoration efforts.

FSII complements Indicator "A.0.1 *Extent of selected natural and modified ecosystems by type"* by providing a quantitative measure of the "naturalness" of ecosystems and the ecological quality of both natural and managed forests. This allows selection of the natural forests that rank highest in structure and integrity and the modified ecosystems that have the most potential to be restored.

FSII and Milestone A.2: *The increase in the extinction rate is halted or reversed, and the extinction risk is reduced by at least 10%, with a decrease in the proportion of species that are threatened, and the abundance and distribution of populations of species is enhanced or at least maintained.*

FSII is a quantitative, satellite-based index known to be correlated with vertebrate extinction risk. Thus, it can be used as a basis for selecting areas for protection and for restoration to halt the increase in species extinction rates. A study of 16,396 forest vertebrate species found high FSII forests were associated with significantly lower odds of species extinction risk compared with forest cover alone (Pillay *et al*.; *in review*). The effects of FSII in mitigating extinction risk were stronger when small amounts of high quality forest remained within species geographic ranges, as opposed to when large extents were forested but of low quality. Hence, consideration of both forest extent and quality as measured by FSII can best meet Milestone A.2.

9.3 Methodology

The FSCI and FSII are derived from published, validated, satellite-based global data sets. These input data are updated periodically which allows for estimating change in FSCI and FSII during 2012-2020. The Google Earth Engine code for generating the metrics is open source and freely available allowing countries to derive the metrics using national, rather than global, data sets if desired.

The FSCI is derived from satellite measures of canopy cover, canopy height, and disturbance history. The reference year is 2013, with canopy cover from 2010, forest loss expressed as year of loss before 2020 and canopy height for 2012. These layers are combined to derive an index that ranges from 1 to 18 (Table 9.1). The lowest value is assigned to stands <5 m tall, disturbed since 2012 or with canopy cover less than 25%. The highest value is for stands not undergoing loss since 2000 that are tall in stature and closed canopy. The FSCI validated well (R^2 = 0.93) against airborne lidar data across gradients in forest structure from recently disturbed forests, plantations, older secondary forest, and primary forest (Hansen *et al*. 2019).

Table 9.1. *Forest structural condition index (SCI) classification scheme. Forest height is from 2012, canopy cover is from 2010, and loss year is for 2001 to 2017. Table values are SCI weights which range from 1 (low SCI) to 18 (high SCI).*

Loss year	Forest height (m)										
		0-5	>5-15			>15-20			>20		
	Canopy cover (%)		Canopy cover (%)			Canopy cover (%)			Canopy cover (%)		
	<25		25-75	>75-95	>95	25-75	>75-95	>95	25-75	>75-95	>95
2013-2017	1	1	1	1	1	1	1	1	1	1	1
2001-2012	1	1	2	3	4	5	6	7	8	9	10
<=2000	1	1	10	11	12	13	14	15	16	17	18

The FSII integrates FSCI with the Human Footprint Index (HFI) of human pressure. HFI was derived using remotely-sensed and survey information for built environments, population density, electric infrastructure, crop lands, pasture lands, roads, railways, and navigable waterways. The results were validated against high resolution images in sample plots randomly located across the Earth's non-Antarctic land areas (average error of 13%). For the FSII, HFP was grouped into three classes and assigned weights as follows: Low where HFP <4 and weight is set to 1; Medium where HFP >=4 and <=15 and weight is set to 5; and High where HFP >15 and weight is set to 10. These threshold values of HFP are consistent with those identified as being highly relevant to responses of vertebrate species endangerment trends to human pressure. FSII was calculated as:

$$FSII = FSCI * \frac{1}{Human\ Pressure\ Weight}$$

Resulting values of the FSII range from 0.1 to 18 with the higher values representing forests high in structural complexity and low in human pressure.

The formulation of FSCI and FSII allows for analysis of the metrics to reveal the proportion of forests, protected areas, ecoregions, or countries that are high or low in structural condition and integrity and rates of change during 2000-2020.

To demonstrate the approach, an initial FSII-ERP version was developed for humid and dry tropical forests in Colombia, Ecuador, Peru, and Brazil. Threshold values for canopy cover and height are obtained from "natural forest" cells: those not disturbed since 2000 (lossyear = 0) and low in human pressure (HFP 2013 <4). The maximum potential height and cover for the natural cells is derived from the means of the upper 10% of cells.

The FSCI and FSII can now be expanded to forests globally. The University of Maryland Global Land Analysis & Discovery lab recently produced forest height globally for the years 2000, 2010, and 2020, canopy cover for 2000 and 2010, and loss year annually 2000-2020. Additionally, the Human Footprint Index is now being updated for 2020 at 300 m resolution. These new data products will allow FSCI and FSII to be mapped globally at 30 and 300 m resolution and change analyzed annually 2000-2020.

As satellite technology improves additional refinements could add utility to these metrics. For example, the GEDI sensor measures canopy cover within height classes (Dubayah *et al*. 2020). This allows estimation of the vertical complexity of forests, which is highly relevant to biodiversity and other ecological responses and it would enhance FSII's ability to assess integrity (Valbuena *et al.* 2020).

9.4 Availability of indicator values and resources

FSCI and FSII are completed for humid tropical forests and are freely available at https://figshare.com/projects/Forest_Integrity_Project/72164. These layers can be viewed spatially on the UN Biodiversity Lab (UNBL; https://unbiodiversitylab.org/). The Google Earth Engine code for generating the layers is available at: https://code.earthengine.google.com/625bede18e265d81f6184b27129fecf8. The ecoregional potential versions of FSCI and FSII for humid and dry tropical forests of Colombia, Ecuador, Peru, and Brazil are available upon request.

10.0 References

Dubayah, R., Blair, J.B., Goetz, S., Fatoyinbo, L., Hansen, M., Healey, S., *et al.* (2020). The Global Ecosystem Dynamics Investigation: High-resolution laser ranging of the Earth's forests and topography. *Sci. Remote Sens*., 1, 100002. https://doi.org/10.1016/j.srs.2020.100002

Ferrier, S., Harwood, T.D., Ware, C. & Hoskins, A.J. (2020). A globally applicable indicator of the capacity of terrestrial ecosystems to retain biological diversity under climate change: The bioclimatic ecosystem resilience index. *Ecol. Indic.,* 117, 106554. https://doi.org/10.1016/j.ecolind.2020.106554

Hansen, A., Barnett, K., Jantz, P., Phillips, L., Goetz, S.J., Hansen, M., *et al*. (2019). Global humid tropics forest structural condition and forest structural integrity maps. *Sci. Data*, 6, 232. https://doi.org/10.1038/s41597-019-0214-3

Hansen, A.J., Burns, P., Ervin, J., Goetz, S.J., Hansen, M., Venter, O., *et al*. (2020). A policy-driven framework for conserving the best of Earth's remaining moist tropical forests. *Nat. Ecol. Evol*., 4, 1377–1384. https://doi.org/10.1038/s41559-020-1274-7

Hansen, A.J., Noble, B.P., Veneros, J., East, A., Goetz, S.J., Supples, C., *et al.* (2021). Toward monitoring forest ecosystem integrity within the post-2020 Global Biodiversity Framework. *Conserv. Lett.*, 14, e12822. https://doi.org/10.1111/conl.12822

Hoban, S., Paz-Vinas, I., Aitken, S., Bertola, L.D., Breed, M.F., Bruford, M.W., *et al*. (2021). Effective population size remains a suitable, pragmatic indicator of genetic diversity for all species, including forest trees. *Biol. Conserv*., 253, 108906. https://doi.org/10.1016/j.biocon.2020.108906

Hoban, S., Bruford, M., D'Urban Jackson, J., Lopes-Fernandes, M., Heuertz, M., Hohenlohe, P.A., *et al.* (2020). Genetic diversity targets and indicators in the CBD post-2020 Global Biodiversity Framework must be improved. *Biol. Conserv.*, 248, 108654. https://doi.org/10.1016/j.biocon.2020.108654

Jetz, W., McGeoch, M.A., Guralnick, R., Ferrier, S., Beck, J., Costello, M.J., *et al.* (2019). Essential biodiversity variables for mapping and monitoring species populations. *Nat Ecol Evol*, 3, 539–551. https://doi.org/10.1038/s41559-019-0826-1

Kissling, W.D., Hardisty, A., García, E.A., Santamaria, M., De Leo, F., Pesole, G., *et al.* (2015). Towards global interoperability for supporting biodiversity research on essential biodiversity variables (EBVs). *Biodiversity*, 16, 99–107. https://doi.org/10.1038/s41559-018-0667-3

Laikre, L., Hohenlohe, P.A., Allendorf, F.W., Bertola, L.D., Breed, M.F., Bruford, M.W., *et al.* (2021). Correction to: Authors' Reply to Letter to the Editor: Continued improvement to genetic diversity indicator for CBD. *Conserv. Genet.*, 22, 537–539. https://doi.org/10.1007/s10592-021-01359-w

Navarro, L.M., Fernández, N., Guerra, C., Guralnick, R., Kissling, W.D., Londoño, M.C., *et al.* (2017). Monitoring biodiversity change through effective global coordination. *Curr. Opin. Environ. Sustain.*, 29, 158–169. https://doi.org/10.1016/j.cosust.2018.02.005

Pereira, H.M., Ferrier, S., Walters, M., Geller, G.N., Jongman, R.H.G., Scholes, R.J., *et al.* (2013). Essential biodiversity variables. *Science*, 339, 277–278. https://doi.org/10.1126/science.1229931

Pillay, R., Watson, J., Hansen, A., Armenteras, D., Atkinson, S.C., Burns, P. *et al.* Forest quality matters in mitigating extinction risk in humid tropical vertebrates. *Nat. Ecol. Evol*., In Review.

Valbuena, R., O'Connor, B., Zellweger, F., Simonson, W., Vihervaara, P., Maltamo, M., *et al.* (2020). Standardizing ecosystem morphological traits from 3D information sources. *Trends Ecol. Evol*., 35, 656–667.https://doi.org/10.1016/j.tree.2020.03.006

Venter, O., Sanderson, E.W., Magrach, A., Allan, J.R., Beher, J., Jones, K.R., *et al*. (2016). Global terrestrial Human Footprint maps for 1993 and 2009. *Sci Data*, 3, 160067. https://doi.org/10.1038/sdata.2016.67