Towards monitoring ecosystem integrity within the Post-2020 Global Biodiversity Framework

Andrew J. Hansen[1,*], Benjamin P. Noble[1], Jaris Veneros[1], Alyson East[1], Scott J. Goetz[2], Christina Supples[3], James E.M. Watson[4], Patrick A. Jantz[3], Rajeev Pillay[5], Walter Jetz[6], Simon Ferrier[7], Hedley S. Grantham[8], Thomas D. Evans[8], Jamison Ervin[3], Oscar Venter[5], Anne L.S.Virnig[3]

[1]Ecology Department, Montana State University, USA hansen@montana.edu
[2]School of Informatics, Computing and Cyber Systems, Northern Arizona University, Flagstaff, AZ, USA
[3]United Nations Development Programme, New York, NY, USA
[4]Centre for Biodiversity and Conservation Science, The University of Queensland, Brisbane, Queensland, Australia; School of Earth and Environmental Sciences, The University of Queensland, Brisbane, Queensland, Australia; Global Conservation Program, Wildlife Conservation Society, New York, NY, USA
[5]Natural Resources and Environmental Studies Institute, University of Northern British Columbia, Prince George, British Columbia, Canada
[6]Ecology and Evolutionary Biology, Yale University, New Haven, CT, USA
[7]CSIRO Land and Water, Canberra, New South Wales, Australia
[8]Wildlife Conservation Society, Global Conservation Program, Bronx, New York 10460, USA

Correspondence
*Andrew J. Hansen, Ecology Department, Montana State University, USA. Email: hansen@montana.edu

Abstract

Signatory countries to the Convention on Biological Diversity (CBD) are formulating indicators through 2030 under the post-2020 Global Biodiversity Framework (GBF). These goals include increasing the integrity of natural ecosystems. However, the definition of integrity and methods for measuring it remain unspecified. Moreover, nations did not achieve their 2011-2020 CBD targets, partly due to inability to monitor and report progress on these targets. Here, we define ecological integrity (EI) and suggest a framework to measure and evaluate trends in terrestrial EI. Our approach builds on three topics: the concept of ecological integrity, satellite-based Earth observation, and “Essential Biodiversity Variables”. Within this framework, EI is a measure of the structure, function and composition of an ecosystem relative to the pre-industrial range of variation of these characteristics. We recommend 13 indicators of EI to facilitate the efforts of nations to monitor, evaluate, and report during implementation of the post-2020 GBF. These indicators can help assess the condition of ecosystems relative to benchmark states, and track the degradation or improvement of ecosystem condition due to human impacts or restoration strategies. If operationalized, this framework can help Parties to the CBD systematically evaluate and report progress on achieving ecosystem commitments in the post-2020 GBF.

1 INTRODUCTION

Although 150 countries committed to protect biodiversity and ensure the sustainable use of nature in the early 1990s, a framework to consistently support nations in monitoring their progress towards reaching these goals is yet to be developed. In 2010, Parties to the Convention on Biological Diversity (CBD 2010) agreed to targets to reduce biodiversity loss by the end of that decade. Yet, 2020 closed and none of the Aichi Biodiversity Targets were fully achieved (CBD 2020a). Nations lacked common mechanisms for monitoring, reporting, and adaptively managing their progress towards these targets during the past decade, resulting in the partial achievement of goals (Maxwell et al. 2020). The CBD is now formulating global targets for 2030 and 2050 in the context of the post-2020 Global Biodiversity Framework (GBF) (CBD 2020b). The current draft of the post-2020 GBF specifies the goal of increasing the integrity of ecosystems, without defining the term or recommending methods to measure it.

Since the inception of the CBD, our ability to observe the Earth and draw inference on the status of biodiversity has continuously progressed through an increase in the number and capacity of satellite sensors and large data networks(Turner 2014; Watson & Venter 2019; Runting et al. 2020). Moreover, the Earth observing community has united to produce a set of "Essential Biodiversity Variables" (EBVs) that represent the minimal set of metrics to monitor the status of species and ecosystems(Pereira et al. 2013). Consequently, opportunities exist to harness satellite and other big data to build on the EBV approach to monitor and evaluate the integrity of ecosystems.

Here, we explore how Earth observations (EO) can be used to monitor and evaluate global terrestrial ecosystem integrity to help countries evaluate their progress towards achieving the post-2020 GBF targets related to ecosystems. We first define ecological integrity (EI) and explore its utility for evaluating spatiotemporal trends in ecosystem condition. We then summarize current and emergent technologies to monitor ecological change with Earth observing satellite data. Third, we explore progress on developing EBVs and their relevance as indicators of EI. We suggest that synthesis of the EI concept, progress in EO, and the EBV approach lays the foundation for tracking indicators of EI in the context of the post-2020 GBF. We recommend a framework for selecting indicators, defining reference states, evaluating change over time, and operationalizing our approach globally. While we focus on EI in this paper, it is important to recognize that it is only one element of the ecosystem goals recommended for safeguarding biodiversity (Díaz et al. 2020). Operationalizing this EI framework and monitoring indicators EI, such as some or all of the 13 recommended here, can enable Parties to the CBD better evaluate, report and adaptively manage their progress towards reaching the 2030 and 2050 ecosystem-related targets in the post-2020 GBF.

2 WHAT IS ECOLOGICAL INTEGRITY?

EI is defined as a measure of ecosystem structure, function and composition relative to the pre-industrial range of variation of these characteristics (Parrish et al. 2003; Wurtzebach & Schultz 2016). It is rooted in the concept of an ecosystem consisting of communities of organisms and the physical elements with which they interact (Tansley 1935).

The state of an ecosystem is characterized in terms of its structure, function, and composition (Chapin III et al. 2011) (Figure 1A). Structure describes the three-dimensional architecture of biotic and abiotic components, and common metrics relate to vegetation and landform structure such as canopy height and variation in elevation. Function encompasses ecological processes including disturbance, energy flow, nutrient cycling, and succession, which are regulated by physical, chemical and biological processes. Composition characterizes biotic attributes of an ecosystem, such as genetic variation, species richness or evenness, as well as the functional roles or niches inhabited by these species. Ecosystem structure, function and composition vary geographically due, in part, to variation in “state” factors (Chapin III et al. 2011). State factors are larger in scale than ecosystems and set the context in which ecosystems operate. They include climate, geological parent material, topography, regional species pool, successional time, and human activities. To the extent state factors vary geographically, the bounds of ecosystem structure, function, and composition also vary. For this reason, our success in achieving global targets is strongly related to the natural state and integrity of ecosystems in a given location (Díaz et al. 2020).

The concept of EI builds on this definition of ecosystems by recognizing that pre-industrial ecosystems typically varied within bounds set by regional state factors and that variation outside of these bounds may indicate ecosystem degradation (Figure 1B). These levels of variation are referred to as “characteristic of the ecoregion” or “within the natural or historic range of variation” (Parrish et al. 2003; Wurtzebach & Schultz 2016). While human activities in pre-industrial times are often considered within these natural or historic bounds, post-industrial human impacts may not be. Consequently, the EI approach allows for assessment of the current condition of ecosystems relative to their pre-industrial states. In this regard, the EI concept is highly relevant to tracking degradation or improvement in ecosystem condition under the influence of human impacts or restoration strategies and is the heart of the CBD post-2020 GBF.

To date, applications of EI have been carried out only at local to regional scales, largely based on in-situ measurements and expert opinion (Box 1). Because consistent, fine grained, global datasets of ecological structure, function, or composition have only recently started to become available, a comprehensive global analysis of ecological integrity is yet to be done.

BOX 1. Previous applications of EI

Previous applications of the EI concept at local to regional scales demonstrated the approach’s utility (Table 1). EI was initially used to monitor the health of ecosystems via population and community level measures of species composition. Indices of Biotic Integrity (IBIs) (Karr & Dudley 1981), for example, describe the condition of an ecosystem using indicator organisms, or taxa selected due to known responses with important drivers of environmental change (Kwak & Freedman 2010). IBIs have been applied in both aquatic and terrestrial systems using invertebrate populations, where an abundance of non-sensitive taxa are compared to that of sensitive taxa as a proxy for ecosystem health (Diffendorfer et al. 2007. An index of biodiversity intactness was also developed for plant and animal populations across South Africa (Scholes & Biggs 2005). The most comprehensive applications of EI have monitored directly ecosystem structure, function, and composition. Most widely cited of these in the literature are the EI efforts within Canadian National Parks (Parks Canada Agency 2011) and national forests in the northeast portion of the U.S. (Tierney et al. 2009).

More recently elements of EI have been mapped using remotely sensed data. For example, vegetation structure of tropical forests was quantified by the Forest Structural Condition Index (FSCI), which is a measure of canopy complexity (stand height, canopy cover, time since disturbance) relative to the biophysical potential of a region to support canopy complexity (Hansen et al. 2019). Similarly, the Loss Forest Configuration Index of Grantham et al. (2020) is a measure of the current patchiness of forest areas derived from satellite imagery relative to the potential in forests without extensive human modification.

In the absence of direct measurement of ecosystem structure, function, and composition, previous work has used human pressure as a full proxy for EI (Beyer et al 2020), or as a proxy for one of its three components (Hansen et al. 2020). While there is evidence to support the use of pressures as a proxy for ecosystem condition (e.g., Di Marco et al. 2018; Grantham et al. 2020), the relationships between human drivers and ecosystem components are often non-linear, ecosystem-specific, and not well understood (Nicholson et al. In Review). Ultimately, monitoring both human pressure and direct ecosystem properties is required for achieving biodiversity goals (Díaz et al. 2020). Given that nations will need to start to measure progress against the new GBF almost immediately, human pressure as a proxy for EI will remain important. As EI monitoring is operationalized, these proxy methods could be replaced with more coherent ways of assessing ecosystem structure, function, and composition relative to reference states.

3 HOW CAN ECOLOGICAL INTEGRITY BE MONITORED GLOBALLY?

To address the underlying causes of biodiversity loss by 2030, nations will need access to monitoring, reporting, and adaptive management frameworks that develop high-quality, inclusive and freely available remote-sensed products that can track changes in conservation outcomes (van Rees et al. 2020). Fortunately, advances in satellite remote sensing have allowed globally consistent monitoring of some key ecological metrics for the past two decades or more, and exciting new capabilities have recently become available (Box 2).

BOX 2. Advances in observation of Earth's ecosystems from space-borne remote sensing

Earth observations of land cover, productivity, fire, and forest extent have been consistently collected since 2000 or earlier, are freely available, and commonly used to make ecological measurements. For example, the Landsat, SPOT, and Sentinel missions map land-cover at fine resolutions (10-30m) across the globe and allow for annual assessments of land-cover change (Phiri et al. 2020). Data from these programs are also used to create indices of human pressure (Watson & Venter 2019) and to assess rates of annual deforestation (Hansen et al. 2013). Primary production of vegetation, carbon budgets, drought effects, and ecosystem degradation and restoration (Ojima 2020) can be quantified using data from the MODIS mission (Running et al. 2004). Temporal patterns of plant growth within ecoregions in the form of onset, end, and length of growing season and total annual productivity are also measured with MODIS products (Cavender-Bares et al. 2020). The MODIS products are validated against field and flux tower gas exchange and are known to be accurate (Pan et al. 2006). MODIS-based sensors also generate accurate active fire imaging daily at less than one km spatial resolution (Schroeder et al. 2014) and are widely used to monitor global fire occurrences, burn severity and associated emissions from combustion (Justice et al. 2002).

New satellite sensors are producing well-defined and documented data products that measure vegetation structure, plant water stress, and functional and species composition around the globe (Johnson 2019). The ECOsystem Spaceborne Thermal Radiometer Experiment quantifies evapotranspiration at a 70-m resolution and is used to map canopy water balance and drought stress. The Orbiting Carbon Observatory-3 measures chlorophyll fluorescence related to gross primary production and atmospheric CO^2 at a 150-m resolution. The Global Ecosystem Dynamics Investigation (GEDI) lidar mission measures three-dimensional canopy structure (Dubayah et al. 2020). Lastly, the hyperspectral sensor Hyperion are being used to determine the richness of plant species with the spectral indices derived from image data for various types of habitats (Somers & Asner 2014). These newer missions are in calibration and initial test phases and have considerable potential to contributing consistent data for ecological monitoring globally during the post-2020 GBF implementation period.

While Earth-observing sensors are dramatically improving our ability to detect change in specific ecological factors, the resulting data are often not used by countries to monitor conservation outcomes. This problem can be overcome by consistently combining data from individual satellite sensors into higher-order metrics that are designed to inform science and policy applications at regular intervals (Anderson et al. 2017). This 'information pyramid' approach (Figure 2) combines several types of raw scientific data into indices relevant to biodiversity and ecosystem monitoring (Fancy et al. 2009).

This need to add value to remotely sensed data to enhance use by policy makers has been recognized by a coalition of national space agencies that are collaborating to generate Essential Biodiversity Variables (Navarro et al. 2017; Vihervaara et al. 2017). EBVs are defined as the derived measurements required to study, report, and manage biodiversity change, focusing on status and trend in elements of biodiversity. Currently still under development, ideal EBVs will be (i) able to capture metrics of ecosystem structure, function, and composition, (ii) global in extent and informed by remotely sensed data and (iii) technically feasible, economically viable, and sustainable over time (https://geobon.org/ebvs/what-are-ebvs/). To date, the Global Earth Observations Biodiversity Observation Network (GEO BON) has specified 20 EBVs relating to ecosystem structure, function, and composition and is now facilitating working groups to develop satellite-based products for EBVs where feasible (Fernández et al. 2020). GEO BON has also collaborated with the CBD in the Biodiversity Indicators Partnership (https://www.bipindicators.net/), which promotes and coordinates the development of indicators of biodiversity change in support of the CBD and related conventions.

More development of EBVs is needed, however, to contribute to monitoring of EI globally. Many EBVs rely on site-based measurements which are not globally coordinated. Only a subset of the EBVs can be measured by remote sensing and mapped across the biosphere. Moreover, EBVs have largely not been developed in the context of reference states as is required for assessing EI. Lastly, most of the EBVs that have matured into usable products, formulated as Biodiversity Partnership Indicators, do not deal with ecosystem structure, function, or composition and thus are not relevant to EI. Yet, a subset of EBVs have good potential as indicators of EI (Box 3). Going forward, new EBVs developed with the criteria described herein could provide measurements of missing dimensions of EI.

BOX 3. Relevance of Essential Biodiversity Variables for monitoring ecological integrity

The potential for the EBV process to contribute to monitoring EI is evident from the subset of EBVs that have developed biodiversity indicators relating to ecological structure, function, or composition (Table 2). These indicators vary in the extent to which they meet key criteria for global monitoring of EI with regards to spatial coverage, temporal resolution, ecological relevance, accuracy, and reference to benchmark states. An example of an EBV-derived indicator that is highly relevant to monitoring EI is the Species Habitat Index product (Jetz et al. 2019). This metric represents the probability of species presence based on biophysical factors such as landform, soils, vegetation, and land cover and use, drawing on several remotely sensed metrics. The maps for individual species are combined into measures of habitat suitability to support species richness of species groups such as forest dependent species or species at risk.

Because land cover and use are inputs into the statistical model, their effects can be statistically removed to represent the biophysical potential of the region to support species richness in benchmark states to assess the effects of current land-cover and use. Moreover, the maps can be updated annually to allow quantification of trends over time. This EBV illustrates the high level of promise of a potential suite of ecological integrity representing ecosystem structure, composition, and function.

4 HOW CAN TEMPORAL CHANGE IN ECOLOGICAL INTEGRITY BE EVALUATED?

Knowledge of reference states is crucial to effective conservation as they give policy makers and managers concrete targets to work towards when managing for and improving ecosystem integrity (Wurtzebach & Schultz 2016). Yet, criteria for defining reference states will need to vary geographically based on the history of human interaction with the ecosystem and knowledge of that interaction.

A recent review (McNellie et al. 2020) provides a conceptual framework for selecting reference states that are both feasible and useful for the biodiversity conservation application at hand (Figure 3). The framework identifies a historical conceptual frame with varying degrees of human presence and land use. It also identifies a contemporary frame that uses best current conditions as the reference state.

The Indigenous Cultural or Pre-Intensification reference states can be reconstructed based on paleo-ecological analyses of tree rings, pollen records, or fire scars (Landres et al. 1999). However, such reconstructions are expensive and often data limited and are thus infeasible in many places. The Hybrid-Historical reference state represents a reconstruction of past states based on current patterns as derived from aerial photographs, land use records, and other types of historical data (e.g. Hessburg et al. 1999). Another approach is to use contemporary areas of low human pressure, such as protected areas, as benchmarks for reference states (Scholes & Biggs 2005).

The contemporary reference state framework focuses on current ecological patterns and identifies areas with higher biodiversity values relative to other locations within the same ecosystem, regardless of the disturbance history (McNellie et al. 2020). Perhaps the most feasible approach within the contemporary landscape is to use change over the monitoring period as a guide to conservation success. One widely used example is tracking deforestation during 2000-present using the forest loss data of Hansen et al. (2013). Whichever approach is used by a country, conservation success can best be evaluated if the approach and its assumptions are clearly described.

Quantification of change from reference state to present can be done using statistical analysis, direction and magnitude of change over time, and expert opinion (Parks Canada Agency 2011; Hansen & Phillips 2018).

5. AN APPROACH FOR MONITORING ECOLOGICAL INTEGRITY IN THE POST-2020 GBF

We suggest that developments in Earth observations, and successful application of EBVs for ecological decision making, provide the basis for tracking trends in EI globally and applying these data to improve biodiversity policy outcomes. To effectively track temporal trends in EI, nations need consistent indicators, evaluation benchmarks, and enabling infrastructure for regular monitoring, evaluation, reporting, and adaptive management. Our recommended approach

(Figure 4) addresses these needs. Satellite remote sensing can provide high-resolution and high-quality data products on ecosystem structure, function, and composition. These products are combined or used as input to models to derive higher-order indicators of EI for the post-2020 GBF. The change from reference states over time is analyzed to evaluate trends in the indicators. These types of results can be reported using formats that can readily interpreted by policy makers.

5.1 Selection of metrics

The post-2020 GBF sets global targets for minimizing loss of natural ecosystem area and integrity and restoring the integrity of managed ecosystems. To more effectively monitor and evaluate the progress that nations are making to meet them, Parties to the CBD need to be supported to access EO data on ecosystem structure, function, or composition. To be meaningful at the national scale, these data should be monitored globally at fine to moderate spatial extents (< 1km) and repeated annually or semi-annually to allow change over time to be assessed. Ideally, Parties also need support to develop spatial data on reference states under low human pressure and/or within the natural or historic range of variation. We suggest data scientists work with Parties to nationally validate these data by establishing accuracy and obtaining permission for use. Governments also need technical support to analyze and interpret them for the purposes of monitoring, evaluation, reporting and adaptive management using technically feasible, repeatable, and cost-effective mechanisms,

Considering these needs, we recommend 13 indicators that can serve as a starting place to develop a low cost, globally consistent EI monitoring program (Table 3). We selected these recommended indicators on the basis of their: (i) relevance to ecosystem structure, function, or composition, (ii) potential to be quantified globally at fine to moderate spatial and temporal resolutions; (iii) known credibility through validation and peer review; and (iv) public (or soon to be) availability. We encourage Parties, EO agencies, scientists, and other stakeholders to use these recommendations a starting place to develop a related globally consistent monitoring framework.

5.2 Benchmarks for evaluation trends over time

We recommend that each country define an approach for establishing reference states based on their history of land use and data availability for the historical period. While any of the reference states in Figure 3 may be relevant within a particular country, it is likely that the Hybrid-historical and the Contemporary reference states will be the most feasible for many countries. The most suitable methods for quantifying these reference states will likely vary among countries and in many cases among ecoregions within countries. As illustrated in Figure 1, we recommend plotting trends in the condition of the indicator during the contemporary monitoring period relative to that in the reference period. This will facilitate assessment of improvement or degradation in the indicator over the monitoring period relative to the reference state.

5.3 Evaluating change over time

With regards to the post-2020 GBF targets, monitoring the recommended indicators will help nations determine how their condition is changing over time, and thus approaching or departing from a target. Monitoring systems that provide annual or semiannual updates on indicator condition are appealing because statistical trend analysis can be used to draw conclusions about the slope and magnitude of change over the period of interest. In these cases, thresholds for magnitude of change and level of statistical confidence can be used to objectively categorize if performance is declining, stable, or improving (Timko & Innes 2009). When data are inadequate for drawing statistical inference, expert opinion can help draw conclusions about trends in indicator condition (e.g., (Mastrandrea et al. 2010). Conclusions about trends in the indicators can be summarized in color-coded report card displays that facilitate communication to diverse stakeholders (e.g., (Hansen & Phillips 2018). These report cards can be done by ecoregion for national reports and by country for international summaries.

5.4 Creating Enabling Infrastructure

Reporting within the CBD agreements is done by each nation but summarized globally. Thus, standard and accessible monitoring methods are needed to allow systematic and comparable monitoring among countries across the globe. The GEO BON EBV effort has provided excellent examples of standardized work flows for some if its initial variables. The Species Populations Working Group of GEO BON, for example, outlined in detail an approach that links key actors, workflows, and informatics infrastructure for the production and use of the Species Populations EBV (Jetz et al. 2019). This approach involves four main steps: (1) data generation, contribution and aggregation, (2) data integration, (3) modeling and production of SP EBVs and (4) delivery and use of the product. This example and similar efforts can be generalized into standardized workflow in the context of the post-2020 GBF and then refined as needed for each indicator. Publicly available software and cloud processing such as Google Earth Engine can facilitate workflow development. This would allow each country to execute the workflows in relatively standardized ways, making refinements as appropriate for their national applications.

6 CONCLUSION

We are in a unique period of history where nearly every nation in the world is collaborating to improve the state of nature. Advances in technology are creating a concurrent opportunity to monitor and evaluate trends in ecological condition in a standardized manner across the Earth. The inability to consistently measure and monitor indicators of biodiversity globally or nationally has previously been a deterrent to evaluating the progress that Parties are making to achieve CBD targets. Fortunately, progress in EO and analyses can now facilitate annual monitoring of the condition of nature and help overcome the gaps that currently limit the capacity for nations to evaluate progress in meeting specific biodiversity targets.

The current draft of the post-2020 GBF includes the global targets for minimizing the loss of natural ecosystem area and integrity and restoring the integrity of managed ecosystems. This commitment recognizes that previous global goals relating to ecosystem extent are insufficient, and that the integrity of ecosystems is central to sustaining biodiversity (Watson et al. 2018). The scientific community is actively recommending a comprehensive set of ecosystem goals and indicators for the post-2020 GBF including consideration of ecosystem naturalness, representativeness, integrity, risk of collapse, and restoration potential (Nicholson et al. In Review; Díaz et al. 2020; Maron et al. 2020; Maxwell et al. 2020; Mokany et al. 2020). We focused in this review on EI and have made the case that to overcome past limitations on CBD success, a pathway to globally defining and measuring EI must be determined.

Our synthesis of the concept of ecological integrity, progress in EO, and development of EBVs provides the foundation for defining, monitoring, and evaluating trends in indicators of EI in terrestrial ecosystems. The resulting approach (Figure 4) could allow for the consistent, fine-scale, nationally relevant, global monitoring of EI that would facilitate success in reaching the

CBD 2030 and 2050 biodiversity targets. We advocate that Parties to the CBD build on our framework and operationalize a comprehensive approach for using EO to monitor indicators of EI to best achieve global and national targets in the post-2020 GBF. Catalyzing this opportunity will help nations to better identify, address, monitor, and overcome critical underlying causes of ecosystem and biodiversity loss by the end of this decade and beyond.

CONFLICT OF INTEREST

We report no conflicts of interest.

ACKNOWLEDGEMENTS

The work was funded by the NASA Biodiversity and Ecological Forecasting Program under the 2016 ECO4CAST solicitation through grant no. NNX17AG51G, the NASA Global Ecosystem Dynamics Investigation grant no. NNL15AA03 to S.J.G. and the NASA GEO solicitation grant no. 80NSSC18K0338 to P.J.

REFERENCES

Anderson, J.R., Hardy, E.E., Roach, J.T. & Witmer, R.E. (1976). *A Land Use And Land Cover Classification System For Use With Remote Sensor Data*.

Anderson, K., Ryan, B., Sonntag, W., Kavvada, A. & Friedl, L. (2017). Earth observation in service of the 2030 Agenda for Sustainable Development. *Geo-Spatial Inf. Sci.*, 20, 77–96.

Cavender-Bares, J., Gamon, J.A. & Townsend, P.A. (2020). *Remote sensing of plant biodiversity*. *Remote Sens. Plant Biodivers.*

CBD. (2010). *Convention on Biological Diversity*. *COP 11 Decis. X/2. Strateg. Plan Biodivers. 2011-2020.*

CBD. (2020a). *Secretariat of the Convention on Biological Diversity (2020a) Global Biodiversity Outlook 5.* Montreal.

CBD. (2020b). *Convention on Biodiversity*. *Conv. Biodiversity. Rep. OPEN-ENDED Work. Gr. POST-2020 Glob. Biodivers. Fram. ITS Second Meet.*

Chapin III, F.S., Matson, P.A. & Vitousek, P.M. (2011). *Chapter 1: The Ecosystem Concept*. *Princ. Terr. Ecosyst. Ecol.* New York, Dordrecht, Heidelberg, London.

Chuvieco, E., Pettinari, M.L., Lizundia-Loiola, J., Storm, T. & Padilla Parellada, M. (2018). *ESA Fire Climate Change Initiative (Fire_cci): MODIS Fire_cci Burned Area Pixel product, version 5.1.*

Díaz-Delgado, R., Cazacu, C. & Adamescu, M. (2018). Rapid Assessment of Ecological Integrity for LTER Wetland Sites by Using UAV Multispectral Mapping. *Drones*, 3, 3.

Díaz, S., Zafra-Calvo, N., Purvis, A., Verburg, P.H., Obura, D., Leadley, P., Chaplin-Kramer, R., De Meester, L., Dulloo, E., Martín-López, B., Shaw, M.R., Visconti, P., Broadgate, W., Bruford, M.W., Burgess, N.D., Cavender-Bares, J., DeClerck, F., Fernández-Palacios, J.M., Garibaldi, L.A., Hill, S.L.L., Isbell, F., Khoury, C.K., Krug, C.B., Liu, J., Maron, M., McGowan, P.J.K., Pereira, H.M., Reyes-García, V., Rocha, J., Rondinini, C., Shannon, L.R., Shin, Y.J., Snelgrove, P.V.R., Spehn, E.M., Strassburg, B., Subramanian, S.M., Tewksbury, J.J., Watson, J.E.M. & Zanne, A.E. (2020). Set ambitious goals for biodiversity and sustainability. *Science*, 370, 411–413.

Diffendorfer, J.E., Fleming, G.M., Duggan, J.M., Chapman, R.E., Rahn, M.E., Mitrovich, M.J. & Fisher, R.N. (2007). Developing terrestrial, multi-taxon indices of biological integrity: An example from coastal sage scrub. *Biol. Conserv.*, 140, 130–141.

Di Marco, M., Ferrier, S., Harwood, T.D. et al. Wilderness areas halve the extinction risk of terrestrial biodiversity. Nature 573, 582–585 (2019).

Dubayah, R., Blair, J.B., Goetz, S., Fatoyinbo, L., Hansen, M., Healey, S., Hofton, M., Hurtt, G., Kellner, J., Luthcke, S., Armston, J., Tang, H., Duncanson, L., Hancock, S., Jantz, P., Marselis, S., Patterson, P.L., Qi, W. & Silva, C. (2020). The Global Ecosystem Dynamics Investigation: High-resolution laser ranging of the Earth's forests and topography. *Sci. Remote Sens.*, 1, 100002.

Fancy, S.G., Gross, J.E. & Carter, S.L. (2009). Monitoring the condition of natural resources in US national parks. *Environ. Monit. Assess.*, 151, 161–174.

Fernández, N., Ferrier, S., Navarro, L.M. & Pereira, H.M. (2020). Essential biodiversity variables: Integrating in-situ observations and remote sensing through modeling. In: *Remote Sens. Plant Biodivers.*

Fraser, R.H., Olthof, I. & Pouliot, D. (2009). Monitoring land cover change and ecological integrity in Canada's national parks. *Remote Sens. Environ.*, 113, 1397–1409.

Grantham, H.S., Duncan, A., Evans, T.D., Jones, K., Beyer, H., Schuster, R., Waltson, J., Ray, J., Robinson, J., Callor, M., Clements, T., Costa, H.M. & DeGemmis, A. (2020). Modification of forests by people means only 40 % of remaining forests have high ecosystem integrity. *Nat. Commun.*

Haberl, H., Erb, K.-H. & Krausmann, F. (2014). Human Appropriation of Net Primary Production: Patterns, Trends, and Planetary Boundaries. *Annu. Rev. Environ. Resour.*

Hansen, A., Barnett, K., Jantz, P., Phillips, L., Goetz, S.J., Hansen, M., Venter, O., Watson, J.E.M., Burns, P., Atkinson, S., Rodríguez-Buritica, S., Ervin, J., Virnig, A., Supples, C. & De Camargo, R. (2019). Global humid tropics forest structural condition and forest structural integrity maps. *Sci. data*, 6, 232.

Hansen, A.J., Burns, P., Ervin, J., Goetz, S.J., Hansen, M., Venter, O., Watson, J.E.M., Jantz, P.A., Virnig, A.L.S., Barnett, K., Pillay, R., Atkinson, S., Supples, C., Rodríguez-Buritica, S. & Armenteras, D. (2020). A policy-driven framework for conserving the best of Earth's remaining moist tropical forests. *Nat. Ecol. Evol.*, 4, 1377–1384.

Hansen, A.J. & Phillips, L. (2018). Trends in vital signs for Greater Yellowstone: application of a Wildland Health Index. *Ecosphere*, 9.

Hansen, M.C., Potapov, P. V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S. V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O. & Townshend, J.R.G. (2013). High-resolution global maps of 21st-century forest cover change. *Science (80-.).*, 342, 850–853.

Hessburg, P.F., Smith, B.G. & Salter, R.B. (1999). Detecting change in forest spatial patterns from reference conditions. *Ecol. Appl.*, 9, 1232–1252.

Hill, S., Arness, A., Maney, C., Butchart, S., Hilton-Taylor, C., Ciciarelli, C., Davis, C., Dinerstein, E., Purvis, A. & Burgess, N.D. (2019). Measuring Forest Biodiversity Status and Changes Globally. *Front. For. Glob. Chang. | www.frontiersin.org*, 1, 70.

Hoskins, A.J., Harwood, T.D., Ware, C., Williams, K.J., Perry, J.J., Ota, N., Croft, J.R., Yeates, D.K., Jetz, W., Golebiewski, M., Purvis, A., Robertson, T. & Ferrier, S. (2020). BILBI: Supporting global biodiversity assessment through high-resolution macroecological modelling. *Environ. Model. Softw.*, 132.

Jantz, P., Berner, L., Hansen, A., Laporte, N. & Goetz, S. (n.d.). Tropical Deforestation Accelerates Isolation of Intact Forest Landscapes. *Nat. Sustain.*

Jetz, W., McGeoch, M.A., Guralnick, R., Ferrier, S., Beck, J., Costello, M.J., Fernandez, M., Geller, G.N., Keil, P., Merow, C., Meyer, C., Muller-Karger, F.E., Pereira, H.M., Regan, E.C., Schmeller, D.S. & Turak, E. (2019). Essential biodiversity variables for mapping and monitoring species populations. *Nat. Ecol. Evol.*, 3, 539–551.

Johnson, M. (2019). Earth Remote Sensing from the International Space Station [WWW Document]. URL http://www.nasa.gov/mission_pages/station/research/news/b4h-3rd/eo-earth-remote-sensing-iss

Justice, C.O., Giglio, L., Korontzi, S., Owens, J., Morisette, J.T., Roy, D., Descloitres, J., Alleaume, S., Petitcolin, F. & Kaufman, Y. (2002). The MODIS fire products. *Remote Sens. Environ.*, 83, 244–262.

Karr, J.R. & Dudley, D.R. (1981). Ecological perspective on water quality goals. *Environ. Manage.*, 5, 55–68.

Kwak, T. & Freedman, M. (2010). Assessment and Management of Ecological Integrity. In: *Inl. Fish. Manag. North Am. third Ed.* (eds. Hubert, .A. & Quist, M.C.). American Fisheries Society, Bethesda, Maryland, pp. 353–394.

Laestadius, L., Maginnis, S., Minnemeyer, S., Potapov, P., Saint-Laurent, C. & Sizer, N. (2011). Mapping opportunities for forest landscape restoration. *Unasylva*, 62, 47–48.

Landres, P.B., Morgan, P. & Swanson, F.J. (1999). Overview of the use of natural variability concepts in managing ecological systems. *Ecol. Appl.*, 9, 1179–1188.

Maron, M., Simmonds, J.S., Watson, J.E.M., Sonter, L.J., Bennun, L., Griffiths, V.F., Quétier, F., von Hase, A., Edwards, S., Rainey, H., Bull, J.W., Savy, C.E., Victurine, R., Kiesecker, J., Puydarrieux, P., Stevens, T., Cozannet, N. & Jones, J.P.G. (2020). Global no net loss of natural ecosystems. *Nat. Ecol. Evol.*, 4, 46–49.

Mastrandrea, M.D., Field, C.B., Stocker, T.F., Edenhofer, O., Ebi, K.L., Frame, D.J., Held, H., Kriegler, E., Mach, K.J., Matschoss, P.R., Plattner, G.-K., Yohe, G.W. & Zwiers, F.W. (2010). *Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties*.

Maxwell, S.L., Cazalis, V., Dudley, N., Hoffmann, M., Ana, S.L., Stolton, S., Visconti, P., Woodley, S., Maron, M., Strassburg, B.B.N., Wenger, A., Jonas, H.D., Venter, O. & Watson, J.E.M. (2020). Area-based conservation in the 21 st century. *Preprints*, 1–42.

McNellie, M.J., Oliver, I., Dorrough, J., Ferrier, S., Newell, G., Gibbons, P. & Megan McNellie, C.J. (2020). Reference state and benchmark concepts for better biodiversity conservation in contemporary ecosystems.

Miraldo, A., Li, S., Borregaard, M.K., Flórez-Rodríguez, A., Gopalakrishnan, S., Rizvanovic, M., Wang, Z., Rahbek, C., Marske, K.A. & Nogués-Bravo, D. (2016). An Anthropocene map of genetic diversity. *Science (80-.).*

Mokany, K., Ferrier, S., Harwood, T.D., Ware, C., Di Marco, M., Grantham, H.S., Venter, O., Hoskins, A.J. & Watson, J.E.M. (2020). Reconciling global priorities for conserving biodiversity habitat. *Proc. Natl. Acad. Sci. U. S. A.*, 117, 9906–9911.

Naimi, B. (2020). Relative Magnitude of Fragmentation [WWW Document]. *GEO BON.*

Navarro, L.M., Fernández, N., Guerra, C., Guralnick, R., Kissling, W.D., Londoño, M.C., Muller-Karger, F., Turak, E., Balvanera, P., Costello, M.J., Delavaud, A., El Serafy, G.Y., Ferrier, S., Geijzendorffer, I., Geller, G.N., Jetz, W., Kim, E.S., Kim, H.J., Martin, C.S., McGeoch, M.A., Mwampamba, T.H., Nel, J.L., Nicholson, E., Pettorelli, N., Schaepman, M.E., Skidmore, A., Sousa Pinto, I., Vergara, S., Vihervaara, P., Xu, H., Yahara, T., Gill, M. & Pereira, H.M. (2017). Monitoring biodiversity change through effective global coordination. *Curr. Opin. Environ. Sustain.*, 29, 158–169.

Newbold, T., Hudson, L.N., Arnell, A.P. & Contu, S. (2016). Dataset: Global map of the Biodiversity Intactness Index Dataset: Global map of the Biodiversity In. *Science (80-.).*

Nicholson, E. & et al. (n.d.). In Scientific foundations for an ecosystem goal, milestones and indicators for the post-2020 Global Biodiversity Framework. *Nat. Ecol. Evol.*

Ojima, D.S. (2020). A climate change indicator framework for rangelands and pastures of the USA Content courtesy of Springer Nature , terms of use apply . Rights reserved . Content courtesy of Springer Nature , terms of use apply . Rights reserved ., 1733–1750.

Pan, Y., Birdsey, R., Hom, J., McCullough, K. & Clark, K. (2006). Improved estimates of net primary productivity from modis satellite data at regional and local scales. *Ecol. Appl.*, 16, 125–132.

Parks Canada Agency. (2011). *Consolidated Guidelines for Ecological Integrity Monitoring in Canada's National Parks. Protected Areas Establishment and Conservation Branch, Parks Canada.*

Parrish, J.D., Braun, D.P. & Unnasch, R.S. (2003). Are we conserving what we say we are? Measuring ecological integrity within protected areas. *Bioscience*, 53, 851–860.

Pereira, H.M., Ferrier, S., Walters, M., Geller, G.N., Jongman, R., Scholes, R., Bruford, M.W., Brummitt, N., Butchart, S.H.M., Cardoso, A.C., Coops, N.C. & Dulloo, E. (2013). Essential Biodiversity Variables. *Science (80-.).*, 339, 277–278.

Phiri, D., Simwanda, M., Salekin, S., Nyirenda, V.R., Murayama, Y. & Ranagalage, M. (2020). Sentinel-2 data for land cover/use mapping: A review. *Remote Sens.*

Purvis, A., Newbold, T., De Palma, A., Contu, S., Hill, S.L.L., Sanchez-Ortiz, K., Phillips, H.R.P., Hudson, L.N., Lysenko, I., Börger, L. & Scharlemann, J.P.W. (2018). Modelling and Projecting the Response of Local Terrestrial Biodiversity Worldwide to Land Use and Related Pressures: The PREDICTS Project. *Adv. Ecol. Res.*, 58, 201–241.

Radeloff, V.C., Dubinin, M., Coops, N.C., Allen, A.M., Brooks, T.M., Clayton, M.K., Costa, G.C., Graham, C.H., Helmers, D.P., Ives, A.R., Kolesov, D., Pidgeon, A.M., Rapacciuolo, G., Razenkova, E., Suttidate, N., Young, B.E., Zhu, L. & Hobi, M.L. (2019). The Dynamic Habitat Indices (DHIs) from MODIS and global biodiversity. *Remote Sens. Environ.*, 222, 204–214.

van Rees, C.B., Waylen, K.A., Schmidt-Kloiber, A., Thackeray, S.J., Kalinkat, G., Martens, K., Domisch, S., Lillebø, A.I., Hermoso, V., Grossart, H.P., Schinegger, R., Decleer, K., Adriaens, T., Denys, L., Jarić, I., Janse, J.H., Monaghan, M.T., De Wever, A., Geijzendorffer, I., Adamescu, M.C. & Jähnig, S.C. (2020). Safeguarding freshwater life beyond 2020: Recommendations for the new global biodiversity framework from the European experience. *Conserv. Lett.*, 1–17.

Running, S.W., Nemani, R.R., Heinsch, F.A., Zhao, M., Reeves, M. & Hashimoto, H. (2004). A continuous satellite-derived measure of global terrestrial primary production. *Bioscience*, 54, 547–560.

Runting, R.K., Phinn, S., Xie, Z., Venter, O. & Watson, J.E.M. (2020). Opportunities for big data in conservation and sustainability. *Nat. Commun.*, 11, 1–4.

Saura, S., Bertzky, B., Bastin, L., Battistella, L., Mandrici, A. & Dubois, G. (2019). Global trends in protected area connectivity from 2010 to 2018. *Biol. Conserv.*, 238, 108183.

Scholes, R.J. & Biggs, R. (2005). A biodiversity intactness index. *Nature*, 434, 45–49.

Schroeder, W., Oliva, P., Giglio, L. & Csiszar, I.A. (2014). The New VIIRS 375m active fire detection data product: Algorithm description and initial assessment. *Remote Sens. Environ.*, 143, 85–96.

Senior, R.A., Hill, J.K. & Edwards, D.P. (2019). Global loss of climate connectivity in tropical forests. *Nat. Clim. Chang.*

Somers, B. and G. P. Asner (2014). "Tree species mapping in tropical forests using multitemporal imaging spectroscopy: Wavelength adaptive spectral mixture analysis." International Journal of Applied Earth Observation and Geoinformation 31: 57-66.

Spawn, S.A., Sullivan, C.C., Lark, T.J. & Gibbs, H.K. (2020). Harmonized global maps of above and belowground biomass carbon density in the year 2010. *Sci. Data*, 7, 1–22.

Tansley, A.G. (1935). The Use and Abuse of Vegitation Concepts and Terms. *Ecology*, 16, 284–307.

Tierney, G.L., Faber-Langendoen, D., Mitchell, B.R., Shriver, W.G. & Gibbs, J.P. (2009). Monitoring and evaluating the ecological integrity of forest ecosystems. *Front. Ecol. Environ.*, 7, 308–316.

Timko, J.A. & Innes, J.L. (2009). Evaluating ecological integrity in national parks: Case studies from Canada and South Africa. *Biol. Conserv.*, 142, 676–688.

Turner, W. (2014). Sensing biodiversity. *Science (80-.).*, 346, 301–302.

Vihervaara, P., Auvinen, A.P., Mononen, L., Törmä, M., Ahlroth, P., Anttila, S., Böttcher, K., Forsius, M., Heino, J., Heliölä, J., Koskelainen, M., Kuussaari, M., Meissner, K., Ojala, O., Tuominen, S., Viitasalo, M. & Virkkala, R. (2017). How Essential Biodiversity Variables and remote sensing can help national biodiversity monitoring. *Glob. Ecol. Conserv.*, 10, 43–59.

Watson, J.E.M. & Venter, O. (2019). Mapping the Continuum of Humanity's Footprint on Land. *One Earth*, 1, 175–180.

Watson, J.E.M., Venter, O., Lee, J., Jones, K.R., Robinson, J.G., Possingham, H.P. & Allan, J.R. (2018). Protect the last of the wild. *Nature*.

Wurtzebach, Z. & Schultz, C. (2016). Measuring Ecological Integrity: History, Practical Applications, and Research Opportunities. *Bioscience*, 66, 446–457.

Tables.

Table 1. Previous applications of subsets and comprehensive indices of ecological integrity.

Component of ecological integrity	Response variable	Spatial scale	citation
Structure	Forest Structural Condition Index	Pantropical	(Hansen et al. 2019)
	Stand structure	Acadia National Park	(Tierney et al. 2009)
	Habitat fragmentation	Canadian national parks	(Fraser et al. 2009; Parks Canada Agency 2011)
	Aquatic emergent plant cover	Two wetlands	(Díaz-Delgado et al. 2018)
Function	Soil nitrogen saturation	Acadia National Park	(Tierney et al. 2009)
	Fire Intensity and Pattern	South African national parks	(Timko & Innes 2009)
	Succession	Canadian national parks	(Fraser et al. 2009; Parks Canada Agency 2011)
	Primary productivity	Mid-Atlantic US.	(Pan et al. 2006)
Composition	Aquatic Index of Biotic Integrity	Individual streams or rivers	(Karr & Dudley 1981)
	Biodiversity Intactness Index	Populations of plants and animals in South Africa	(Scholes & Biggs 2005)
	Invasive plants	Acadia National Park	(Tierney et al. 2009)
	Species richness	Canadian national parks	(Fraser et al. 2009; Parks Canada Agency 2011)
	Allelic Diversity	Global	(Miraldo et al. 2016)
Structure, Function and Composition	Stand structure, Invasive plants, Soil nitrogen saturation	Acadia National Park	(Tierney et al. 2009)
	Habitat fragmentation, Succession, Species richness	Regional: all Canadian National Parks	(Fraser et al. 2009; Parks Canada Agency 2011)

Table 2. The subset of essential biodiversity variables that have been developed as biodiversity indicators by the Biodiversity Indicator Partnership and potential for serving as indicators of ecological integrity. The EBV classification is from https://geobon.org/ebvs/what-are-ebvs/. Biodiversity Partnership Indicators are from https://www.bipindicators.net/list-of-global-indicators-available-for-review. Potential as an EI indicator is: High-green, Medium-blue, Low-yellow.

Ecosystem component **EBV class**	**EBV name**	**Biodiversity Partnership Indicator (authority or source)**	**Description**	**Potential for EI indicator**
Horizontal structure	Ecosystem extent	Forest Area as a proportion of total land area (Hansen et al. 2013)	Proportion of area with forest cover >30% and >5 m height.	**High**: Global, fine scale, repeated (2000-2020), referenced to 2000.
	Fragmentation / Connectivity	Protected Connected (ProtConn) (European Commission, (Saura et al. 2019))	Percentage of connected lands protected in a given country or ecoregion	**Medium**: Global, intermediate scale, one year (2016), not benchmarked.
Productivity	Primary productivity	Human Appropriation of NPP (Haberl et al. 2014)	NPP measured via NDVI, minus NPP used by humans or for livestock AND NPP lost to land use change	**Low**: Global, fine scale, one year (2018), potential low accuracy, referenced to 'natural' states
Species populations	Species distribution	Red List Index	Risk of population decline and threatened status based on data and expert opinion	**Low**: Global, coarse scale, annual, not directly related to ecological condition, no benchmark
		Species Habitat Index (Yale Univ, (Jetz et al. 2019))	Number of species with suitable habitat modeled from topography, disturbance, climate, and human pressure	**High**: Global, fine scale, repeated (2000-2000), potentially referenced to 'natural' states
	Population abundance	Living Planet Index (IUCN / BirdLife International)	Population size or trends for vertebrate species	**Low**: Global, coarse scale as limited by available data, updated biannually, not bechmarked

		Biodiversity Intactness Index (Natural History Museum London, Newbold et al. 2016)	The average abundance of originally present species relative to abundance in an undisturbed habitat based on land use	**High**: Global, fine scale, change over 2000-2014, referenced to 'natural' states
Community composition	Taxonomic / phylogenetic diversity	Biodiversity Habitat Index (CSIRO, Mokany et al. 2020)	Estimates the effects of habitat loss, degradation, and fragmentation on the expected retention of terrestrial species richness	**Medium**: Global, fine scale, one year (2016), potentially updatable, referenced to 'natural' states

Table 3. Description of recommended ecological indicators and their current status.

Ecosystem Component / Indicator	Description	Citation / Data Source
Ecosystem Structure		
1.Forest Structural Condition Index	Vegetation structure within forest stands. Inputs include canopy cover, canopy height, and time since disturbance. High levels of the index denote tall, multilayered, older forests that are known to support high levels of biodiversity, carbon storage, and ecosystem services. Currently available for pantropical moist forests but can soon be generated for forests globally with new tree height data (Dubayah et al. 2020).	Hansen et al. 2019
2. Lost Forest Configuration (LFC)	Index of the current patchiness of forest areas relative to the natural potential in forests without extensive human modification. Potential configuration was derived based on where forests could potentially grow, if soils and climate were the only limiting factors (Laestadius et al. 2011). LFC is useful as a measure of forest fragmentation and as an input to the Forest Landscape Integrity Index (Grantham et al. 2020).	(Grantham et al. 2020
3. Relative Magnitude of Fragmentation (RMF)	Change in fragmentation of ecosystems over the last 27 years globally at a spatial resolution of 300 m. RMF is calculated using an entropy-based local indicator of spatial association (Naimi 2020).	https://portal.geobon.org
4. Protected Connected Indicator (ProtConn)	The percentage of connected lands protected in a given country or ecoregion and differentiates between unprotected, protected and cross-border categories of connected lands. Available globally every other year from 2010 to 2018.	Saura et al. 2019 https://www.bipindicators.net/
5. Intact Forest Landscapes Connectivity	A measure of potential animal movements between large, minimally disturbed intact forest landscapes (IFLs) across the tropics. Because of their large size and lack of disturbance, IFLs are more likely than other forests to maintain populations of interior forest species. Areas with high connectivity are those with high tree cover between large patches where many corridors overlap. Available for 2000-2018.	Jantz et al. In Review

Table 3. Continued.

Ecosystem Component / Indicator	Description	Citation / Source
Ecosystem Function		
6. MODIS Net Primary Productivity	Amount of new biomass fixed by green plants through photosynthesis. It is important relative to ecosystem energy flow, carbon dynamics, food for consumers and decomposers, disturbance recovery, and nutrient cycling. Available monthly for 2000-present. Can be summarized as annual cumulative, annual monthly minimum, and monthly coefficient of variation, with each of these being relevant to particular ecological response variables (Radeloff et al. 2019).	Running et al. 2004
7. Above and Below Ground Carbon Density	Harmonized global map of terrestrial carbon storage above and below ground in biomass and soil for the reference year 2010. Developed by overlaying satellite-based biomass maps and proportionately allocating their estimates to specific land cover types based on percent tree cover, thematic landcover and a rule-based decision tree. Can be used to account for diverse vegetation carbon stocks in global analyses and greenhouse gas inventories	Spawn et al. 2020
8. MODIS Area Burned	Burning and quality information including date of burning and spatial extent of fires. Available globally monthly at a spatial resolution of 250m. Metrics include the estimated day of first detection, the confidence level, and land cover type burned.	Chuvieco et al. 2018
9. Tree cover loss	Areas of forest loss globally at a 30-m resolution. Loss indicates the removal or mortality of tree cover and can be due to a variety of factors, including mechanical harvesting, fire, disease, or storm damage. Available 2000-2019 and are updated annually.	Hansen et al. 2013 https://www.globalforestwatch.org/
10. Climate connectivity	Potential for tropical species to reach analogous future climates. It is derived as the current temperature of the origin patch minus the future temperature of the destination patch and is related to deforestation and the capacity of the landscape configuration to allow the movement of species in the face of a dynamically changing climate. Available for pantropical humid forests from 2000 to 2012.	Senior et al. 2019

Table 3. Continued.

Ecosystem Component / Indicator	Description	Citation / Source
Ecosystem Composition		
11. Species Habitat Richness	Number of species projected to have suitable habitat based on their modeled responses to climate, landform, vegetation, and land cover. Groups of species such as forest dependent vertebrates can be represented. Available globally for 2000-present.	Jetz et al. 2019 https://www.bipindicators.net
12. Biodiversity Intactness Index (BII)	Average abundance of a large, taxonomically, and ecologically diverse set of naturally-occurring species in a terrestrial area, relative to a baseline with minimal human impacts. Average BII is meaningful at any spatial scale, making it easy to estimate status and trends within any desired region (Purvis et al. 2018). Available for 1900-2010 globally and 2000-2014 for tropical forest.	Newbold et al. 2016 https://www.bipindicators.net/
13. Biodiversity Habitat Index (BHI)	Proportion of gamma diversity retained in any specified spatial reporting unit by combining best-available mapping of ecosystem integrity with beta-diversity modelling. Available for 2016 globally and is being updated for 2000 to 2020.	Hoskins et al 2020; Mokany et al. 2020 https://www.bipindicators.net/

Figures.

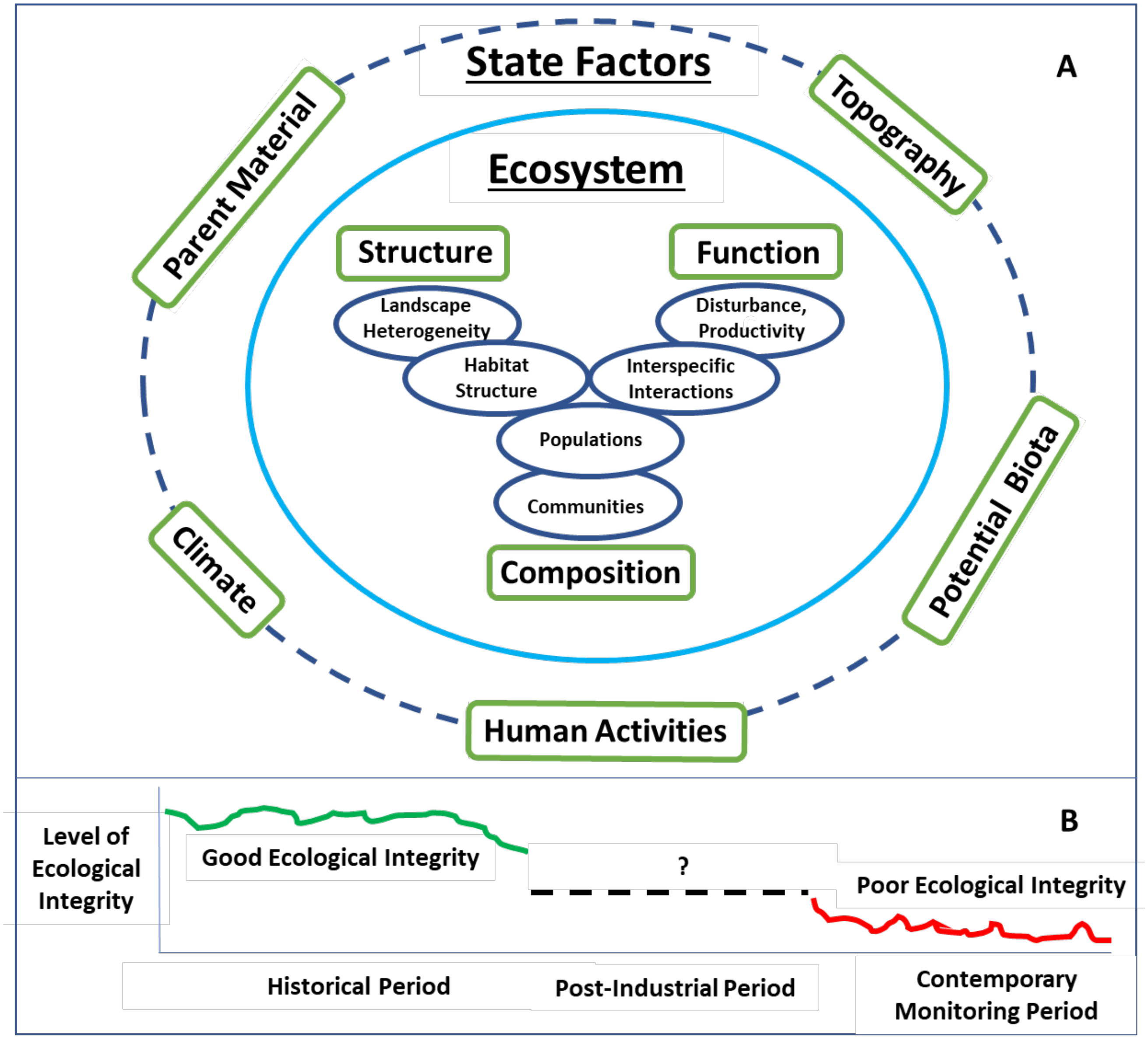


Figure 1. Representation of the concept of ecological integrity in the context of the ecosystem and controlling state factors. (A) An ecosystem is characterized by its structure, function, and composition as influenced by broad-scale state factors such as climate. (B) Ecological integrity represents the condition of elements of ecosystem structure, function, and composition in the current period relative to that characteristic of the ecosystem prior to modern human influence. The trend line depicts declines in ecological integrity during a contemporary monitoring period.

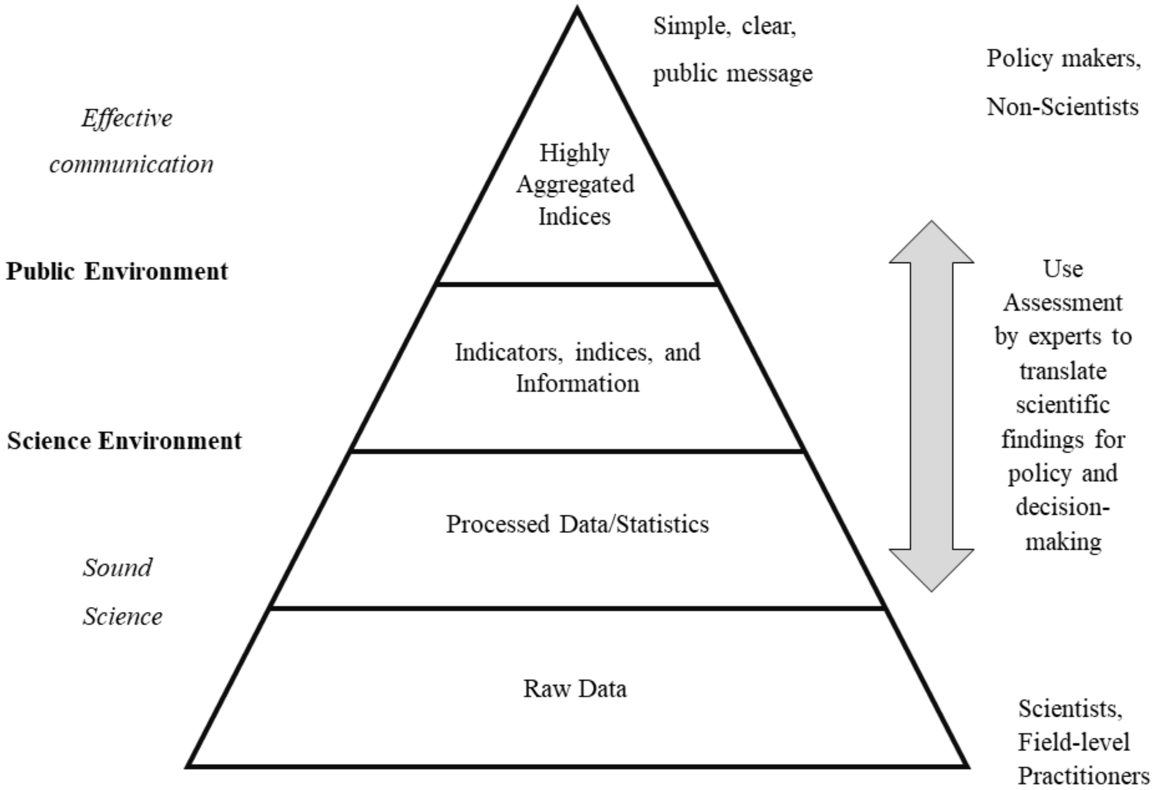


Figure 2. The information pyramid illustrating adding value to raw data by combining data sets into higher order metrics that are relevant to policy makers adapted from (Fancy et al. 2009).

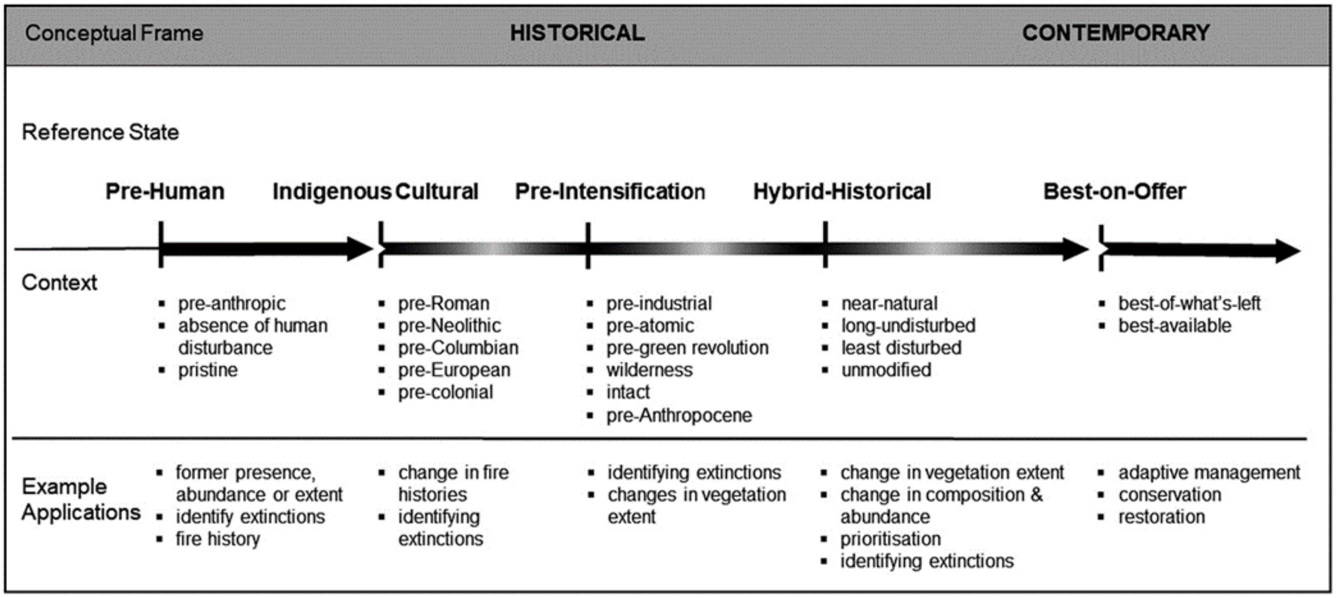
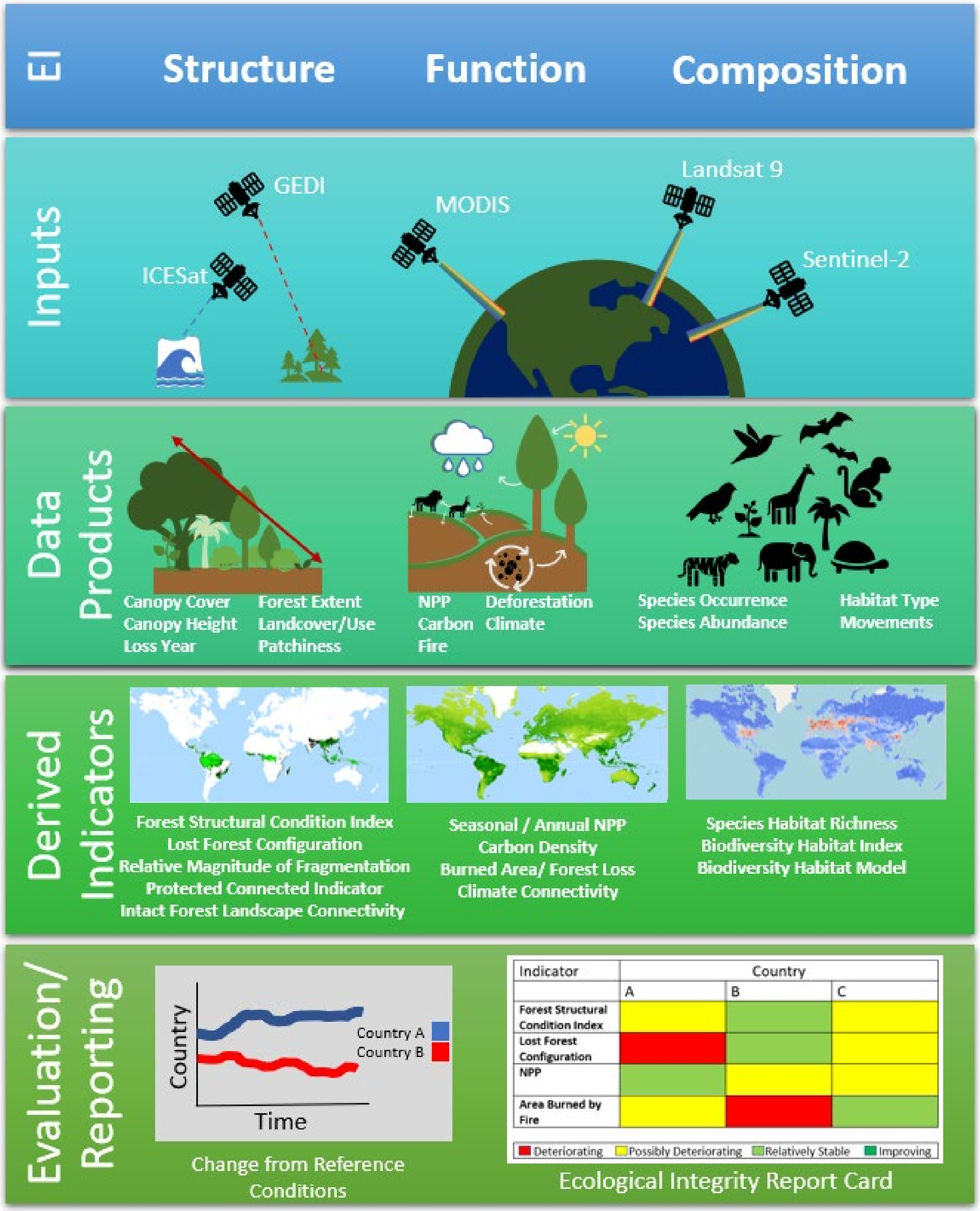


Figure 3 A conceptual framework for synthesizing the historical and contemporary reference states and their context and applications within the context of informing biodiversity conservation and restoration outcomes in existing ecosystems. From McNellie et al. 2020.



Indicator	Country		
	A	B	C
Forest Structural Condition Index	🟨	🟩	🟨
Lost Forest Configuration	🟥	🟩	🟨
NPP	🟩	🟨	🟨
Area Burned by Fire	🟨	🟥	🟩

🟥 Deteriorating 🟨 Possibly Deteriorating 🟩 Relatively Stable 🟩 Improving

Figure 4. Flow diagram of the recommended approach for tracking indicators of ecological integrity.