Towards monitoring forest ecosystem integrity within the post-2020 Global Biodiversity Framework

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Abstract

Signatory countries to the Convention on Biological Diversity (CBD) are formulating goals and indicators through 2050 under the post-2020 Global Biodiversity Framework (GBF). Among the goals is increasing the integrity of ecosystems. The CBD is now seeking input towards a quantifiable definition of integrity and methods to track it globally. Here we offer a schema for using Earth observations to monitor and evaluate global forest ecosystem integrity (EI). Our approach builds on three topics: the concept of ecosystem integrity, the use of satellite-based Earth observations and the use of "Essential Biodiversity Variables" to monitor and report on it. Within this schema, EI is a measure of the structure, function and composition of an ecosystem relative to the range of variation determined by climatic-geophysical environment. We use evaluation criteria to recommend eight potential indicators of EI that can be monitored around the globe using Earth Observations to support the efforts of nations to monitor and report progress to implement the post-2020 GBF. If operationalized, this schema should help Parties to the CBD take action and report progress on achieving ecosystem commitments during this decade.

1 INTRODUCTION

Although 150 countries committed to protect biodiversity and ensure the sustainable use of nature in the early 1990s, these nations have yet to implement a global monitoring framework that systematically measures progress towards reaching these goals. 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, by the end of 2020, 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, and these limitations contributed to their partial achievement (Maxwell et al. 2020). The Parties to the CBD are now formulating global targets for 2030 and 2050 in the context of the proposed post-2020 Global Biodiversity Framework (GBF) (CBD 2020b)

The current version of the draft post-2020 GBF specifies the goal of increasing the area, connectivity and integrity of natural ecosystems (CBD/SBSTTA/24/3 2020) as a measurement of progress towards the Convention's 2030 goals and 2050 vision. The proposed definition of integrity is "the compositional functional, structural and spatial components of ecosystems" (CBD/SBSTTA/24/3/Add.2. 2021). Several potential indicators of ecosystem area, integrity, and connectivity are also suggested (CBD/SBSTTA/24/3Add.1. 2020). A related synthesis of the scientific evidence to inform the development of the post-2020 GBF emphasizes that, "A clear and quantifiable definition of ecosystem integrity is necessary to ensure inclusion of all critical components required to achieve the envisioned outcome" and that "Ecosystem integrity needs to be clearly understood so that the implications for implementation, monitoring and reporting for this goal are well defined" (CBD/SBSTTA/24/INF/9. 2020). Thus, finalizing a post-2020 GBF requires a working definition of ecosystem integrity; indicators of ecosystem structure, function, and composition; and also the means by which countries globally can measure, monitor, and evaluate trends in condition of these indicators; and a system to report improvements or degradation in ecosystem integrity.

Various challenges remain, however, to operationalizing ecosystem integrity (EI) as a central component of the post-2020 GBF. The scientific literature defines the term in alternative ways (Section 2.1). Measurement and monitoring of components of EI has been somewhat successfully done at local to regional spatial scales largely with ground-based methods, but not at global scales. Multiple global metrics of biodiversity have been developed in recent years and there is now considerable confusion among scientists and policy makers as to the utility and reliability of these metrics (Watermeyer et al. 2020). Also yet to be established are the baseline conditions by which success in increasing EI will be judged.

Recent conceptual and technological developments offer the promise of overcoming challenges to operationalizing EI for national biodiversity assessment globally. 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 and to monitor and evaluate the integrity of ecosystems.

Here we build on the currently proposed version of the CBD's post-2020 GBF and offer a schema for using Earth observations (EO) to monitor and evaluate forest EI around the Earth to help countries evaluate their progress towards achieving the post-2020 GBF targets related to ecosystems. To provide a scientific context for Parties of the CBD as they consider adopting methods to globally monitor and evaluate EI, we first briefly review historical development of the concept of EI and explore how advances in remote sensing technology can facilitate the systematic collection of necessary data around the globe. We then present a schema for monitoring EI for forest ecosystems in the context of the post-2020 GBF. This includes defining EI in the context of ecosystem theory, recommending an initial set of indicators of EI that can be used to monitor forest ecosystems across the globe at resolutions that allow subnational to global aggregation, specifying reference states for evaluation of trends in EI, and suggesting reporting metrics. A key goal is to identify the indicators of EI that are currently available for use by countries as well as those that could be developed and put to use in the near future. We make recommendations for forest ecosystems because of the rapid progress in remote sensing technology to collect fine scale data for this ecosystem type. Indicators for other ecosystem types will need to be developed as technologies allow.

The schema is a conceptual approach which is meant to provide a starting point for additional development to operationalize the monitoring of EI. Moreover, while we focus on EI in this paper, it is important to recognize that it is only one element of the CBD ecosystem goals recommended for safeguarding biodiversity (Díaz et al. 2020) and other approaches will be needed for the goals relating to ecosystem naturalness, area and connectivity, to species goals, and to genetic goals. Despite these caveats, operationalizing this EI schema and monitoring indicators of EI, such as some or all of those recommended here, can enable Parties to the CBD better evaluate, report and adaptively manage their progress towards reaching the 2030 and 2050 ecosystem-related goals in the post-2020 GBF.

2 HISTORICAL DEVELOPMENT

2.1 The concept of ecosystem integrity

Integrity is defined by the Oxford Dictionary as, “The condition of having no part or element taken away or wanting; undivided or unbroken state; material wholeness, completeness, entirety”. Ecologists have associated the term with naturalness, as in an ecosystem is complete or whole when it is in a natural condition (Karr 1990; Anderson 1991; Noss 2000).

An important branch point is in using human pressure as a proxy measure of integrity versus defining the characteristics of ecosystems that are relatively free from human influence. Several authors have used low degree of human pressure or human modification to identify ecosystems of high integrity (Theobald 2013) or more typically termed high intactness (Beyer et al. 2019). Alternatively, ecosystem integrity has been defined as the ecosystem structure, function, and composition relative to ‘the natural or historic range of variation of these characteristics’ or are ‘characteristic of a region’ (Andreasen et al. 2001; Dale & Beyeler 2001; Parrish et al. 2003; Wurtzebach & Schultz 2016).

The two approaches differ importantly in that the first quantifies human pressure and the later quantifies ecosystem properties (structure, function, and composition) as influenced by human pressure. Moreover, the later approach recognizes that ecosystems exhibit a characteristic range of behavior governed by natural disturbance regimes, climate variation, and geomorphic diversity (Parrish et al. 2003; Wurtzebach & Schultz 2016). This ‘natural range of variation’ has thus been use as a reference state for evaluation of degree of loss of ecosystem integrity (Parks Canada 2008; Tierney et al. 2009).

The approach focused on ecosystem properties has been widely used for ecological assessment (Box 1). To date, applications of EI have been carried out only at local to regional scales, largely based on in-situ measurements and expert opinion. Because consistent, fine grained, global datasets of ecological structure, function, or composition have only recently started to become available, a comprehensive global analysis of ecosystem integrity is yet to be done. The purpose of this paper is to help advance global application.

BOX 1. Some examples of 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; Kwak & Freedman 2010). 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 Lost Forest Configuration Index of Grantham et al. (2020) is a measure of the current anthropogenic-driven patchiness of forest areas derived from satellite imagery relative to the potential in forests without extensive human modification.

2.2 Global ecological observation

To adequately understand and address the underlying causes of biodiversity loss, nations will need access to monitoring, reporting, and adaptive management frameworks that utilize high-quality, inclusive, fine-scale, and freely available remote-sensed products that can track changes in conservation outcomes at regular intervals (van Rees et al. 2020). Fortunately, advances in satellite remote sensing now allow for globally consistent monitoring of some key ecological metrics for two decades or more, and exciting new capabilities have recently become available (Box 2). Challenges remain, however, in converting remotely sensed EO into products that are relevant and available systematically across the globe for this application, and in eliminating overlaps in formulation and nomenclature creating confusion among practitioners. We summarize progress in remote sensing of biodiversity related metrics and overview the global remote sensing community's efforts to develop indicators of biodiversity.

BOX 2. Advances in observation of Earth's ecosystems from space-borne remote sensing that provide a foundation for monitoring EI

Since 2000 or earlier, EO of land cover, productivity, fire, and forest extent are being consistently collected using remote sensing, are freely available, and are 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). For example, 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).

Some of these newer missions are technology demonstrations with limited lifespans, thus their potential contributions to ecological monitoring globally during the post-2020 GBF implementation period will depend on future mission decisions by space agencies. One such mission already in development is a new imaging spectroscopy “Surface Biology and Geology” satellite that promises global monitoring of plant functional diversity (Cawse-Nicholson et al. 2021), following powerful earlier demonstrations from aerial sensing (Asner et al. 2017) and exploratory space-borne sensors (Schimel et al. 2020).

While EO sensors are dramatically improving our ability to detect change in specific ecological factors, the resulting data are infrequently used by governments around the world 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 transforms 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 its policy relevancy is recognized by a coalition of national space agencies and scientists that are collaborating to generate Essential Biodiversity Variables (EBV) (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 (Pereira et al. 2013). 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). The GEOBON EBV effort can provide critical data to help develop and monitor globally replicable indicators of biodiversity change in support of the CBD and related conventions, such as those suggested by the Biodiversity Indicators Partnership (https://www.bipindicators.net/) for various post-2020 GBF goals.

More development of EBVs and EBV-derived indicators 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 been extended into usable products, such as those formulated as Biodiversity Partnership Indicators, do not deal with ecosystem structure, function, or composition and thus are not relevant to EI. However, a subset of EBVs have good potential to drive indicators of EI (see δ**3.2**). Going forward, new EBVs developed with the criteria described herein could provide measurements of missing dimensions of EI.

2.3 Establishing reference states

The concept of EI recognizes that natural ecosystems typically varied within bounds set by the climate, geomorphology, and natural disturbance regimes typical of the area. 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.

Feasible methods for establishing the reference states on natural ecosystems vary geographically (Keane et al. 2009; McNellie et al. 2020). In more remote ecoregions, paleo-ecological reconstructions from tree rings, pollen records, fire scars or geomorphic flooding demarcations can be used to quantify natural or historic range of variation in ecosystem condition (Landres et al. 1999; Swetnam et al. 1999). Even so, the period of time most relevant to serve as the reference state for the current period will vary among locations depending on natural climate variation and human land-use history (Wurtzebach & Schultz 2016). Ecosystem process simulation models or statistical models have also been used to approximate natural range of variation based on known relationships between ecosystem components (Shugart 1984; Wimberly et al. 2000; Gallant et al. 2003; Nonaka & Spies 2005). In some ecosystems, historical records such as aerial photographs, land use surveys, harvest records have been used to reconstruct reference states (e.g. (Hessburg et al. 1999)). Another approach is to use contemporary areas of low human pressure, such as long-established and well managed protected areas, as benchmarks for reference states (Scholes & Biggs 2005). Perhaps the most feasible approach within contemporary landscapes 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, 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).

3. A SCHEMA FOR MONITORING ECOSYSTEM INTEGRITY IN THE POST-2020 GBF

We suggest that developments in EO, and successful application of EBVs for ecological decision making, provide a solid 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 a clear definition of ecosystem integrity, effective indicators of EI selected based on consistent criteria, evaluation of trends relative to reference states, and enabling infrastructure for regular monitoring, evaluation, reporting, and adaptive management. Our recommended approach (Figure 1) 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 be readily interpreted by policy makers.

3.1 Definition of ecosystem integrity

Consistent with current proposals for the post-2020 GBF (CBD/SBSTTA/24/3Add.1. 2020), we recommend that EI be defined as a measure of ecosystem structure, function and composition relative to the reference state of these components being predominantly determined by the extant climatic-geophysical environment (while acknowledging a backdrop of climate change) (Andreasen et al. 2001; Parrish et al. 2003; Wurtzebach & Schultz 2016; CBD/SBSTTA/24/INF/9. 2020). This definition 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; CBD/SBSTTA/24/INF/9. 2020) (Figure 2A). Structure describes the three-dimensional architecture of biotic and abiotic components, and common metrics related to vegetation and landform structure such as canopy height and variation in elevation, and spatial configuration including fragmentation. Function encompasses ecological and evolutionary 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, phylogenetic diversity, 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, the reference state for evaluating trends in EI should be defined by the ecosystem patterns determined by the predominant climatic-geophysical environment. It is important to recognize and take into account that the reference state may have a backdrop of climate change. It is also important to recognize that the reference state may include human presence and influence, but at levels below being a predominant influence on the ecosystem.

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). In the absence of comprehensive direct measurements of ecosystem structure, function, and composition, previous work has used human pressure as a proxy for overall EI (Beyer et al. 2019), as a proxy for components of an overall EI index in combination with direct measurements of other components (Grantham et al. 2020; Hansen et al. 2020). The schema presented here focuses on direct or modelled measures of specific ecosystem properties and not on human pressure measures or on overall indices of EI. We do so because methods for monitoring human pressure have been widely used, but less attention has been focused on direct measures of ecosystem condition. Thus, we include as a criterion for the selection of indicators that the metric be a measure of a specified ecosystem component. Of course, monitoring both human pressure and direct ecosystem properties is required for achieving biodiversity goals (Díaz et al. 2020).

3.2 Selection of metrics

The proposed post-2020 GBF sets global targets for increasing 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 credible EO data on ecosystem structure, function, or composition at adequate resolutions that can be evaluated relative to natural reference states. Thus, we recommend the following criteria for selecting indicators of EI.

1. A direct measure of a specific aspect of ecosystem structure, function, or composition.
2. Biome to global extent with spatial resolution sufficiently fine to allow for management relevance and subnational assessment (<=1 km).
3. Temporal resolution to allow assessment at annual to five-year periods.
4. Ability of the indicator to be aggregated from subnational to national to global without introducing bias.
5. Known credibility through validation and peer review, data and metadata are publicly available, adheres to open data standards.
6. Potential to be referenced to states characteristic of the climatic, geomorphic, and native community ecosystem.

These evaluation criteria overlap with those proposed by the CBD/SBSTTA/24/3Add.1 2020. As stated earlier, our goal here is to identify the indicators that are currently available and in use by countries as well as those that could be developed and put to use in the near future to more reliably monitor and evaluate trends in EI more systematically around the globe.

We used these criteria to evaluate metrics for the proposed indicators of the post-2020 GBF (CBD/SBSTTA/24/3Add.1. 2020) as well as additional ones from the peer reviewed literature. These proposed indicators are drawn from previous CBD indicators lists, as well as those used for Sustainable Development Goals monitoring and the Biodiversity Indicators Partnership (which included several derived from the EBV effort). We omitted from the CBD list those indicators not directly related to ecosystem structure, function, or composition; quantifying human pressure, quantifying ecosystem extent; not covering terrestrial ecosystems; applicable only to agricultural ecosystems; or for which no published or internet reference could be found.

The potential indicators remaining after these exclusions are listed in Table 2. These potential indicators were rated as either ‘Yes’ or ‘No’ for meeting evaluation criteria 1-6 above.

Those that meet all six criteria are shown in green in Table 2 and we recommend these be used as indicators of EI for the post-2020 GBF. The metrics highlighted with yellow in Table 2 are measures of ecosystem structure, function, or composition but are not currently formulated in the context of a natural reference state. They can, nonetheless, be used in their current form to monitor change over time to evaluate ecosystem improvement or decline during the monitoring period. We recommend these metrics be further developed into indices of EI that indicate current condition relative to the natural reference state or relative to contemporary locations of low human pressure within ecoregions. An example of doing so comes from Haberl et al. 2007 who quantified NPP for actual vegetation relative to that expected for potential vegetation in an ecosystem . The metrics highlighted in red in Table 2 do not meet two or more of the evaluation criteria. These would likely require substantial development to be formulated as suitable indicators of EI and thus are not included in our schema.

The recommended indicators and the metrics with potential to be developed into indicators of EI are described in more detail in Table 3. Because these metrics are most fully developed for forest ecosystems, we emphasize that our schema is primarily relevant to forest ecosystems. *Lost Forest Configuration* is a measure of forest structure that quantifies current patchiness of forest areas relative to the natural potential in forests without extensive human modification. *Bioclimatic Ecosystem Resilience Index* indicates the extent to which a given spatial configuration of natural habitat will promote or hinder climate-induced shifts in biological distributions. We include it under ecosystem function because it relates to potential dispersal under climate change. *Species Habitat Index* is the modeled reduction in habitat suitability for individual species or groups of species from natural conditions due to human-induced habitat change. *Local Biodiversity Intactness Index* (LBII) and *Biodiversity Habitat Index* (BHI) are related in that both express the proportion of original species diversity remaining at a site. They differ in that LBII’s focus is on average local biotic intactness, which reflects species’ persistence within the landscape and the local ecosystem’s ability to provide many ecosystem services; BHI, by contrast, focuses on how the overall diversity of a larger region is affected by habitat loss and degradation. Users may choose one or the other of these depending on specific interests.

Among the metrics not yet referenced to natural benchmarks (yellow in Tables 2 and 3) is the *Forest Structural Condition Index* (FSCI). This metric integrates remotely sensed canopy cover, canopy height, and time since disturbance into an index of the vertical structure of forests. We are currently developing and validating a version of FSCI that is referenced to the structural conditions of forests with low human pressure thought to be typical of primary or older secondary forests. Termed *FSCI-Ecoregional Potential* (ERP), this metric, once validated and published, can be considered an indicator of forest ecosystem structural integrity. *Net primary productivity* (NPP) is a key measure of vegetation productivity, a critical ecosystem function that is sensitive to land use and climate change. Value can be added to the base NPP product by summarizing various seasonal and interannual metrics (e.g. Radeloff et al. 2019) and these can be used to monitor change over time. It can also be formulated as an index of ecosystem functional integrity through the method described above for FSCI-ERP or through modeling on reference conditions (Haberl et al. 2007). Similarly, the MODIS Burned Area product could be developed as an index of the degree of departure from the natural fire regime (see Barrett et al. 2010).

Thus, we recommend use of the indicators of EI highlighted in green in Table 3 and further development of the potential indicators highlighted in yellow in Table 3. We encourage stakeholders participating in the development of the post-2020 GBF to consider these recommendations as a starting place to develop a globally consistent monitoring framework that countries can choose components of depending on their capacities.

We note that many aspects of structure, composition and function are not directly represented in the list of variables, and whilst it can be expected that these will be correlated to a marked extent with those parameters for which there are metrics, such relationships merit further study and, if necessary, the identification of additional, complementary parameters to ensure a comprehensive representation of the diverse aspects of EI. Moreover, until technology allows more complete global measurement of ecosystem condition, products that blend human pressure with ecosystem components (e.g. Grantham et al. 2020; Hansen et al. 2020) will continue to be highly informative.

While several indicators are ultimately needed to fully monitor EI, the Parties to the CBD are currently deciding on a feasible set of indicators that should be mandatory for Parties to report on. The eight indicators listed in Table 3 would provide a comprehensive representation of forest EI and could be integrated into a single metric to represent a single high-level indicator of ecosystem integrity. However, if a more limited set of indicators is required, we recommend that one measure of each of the three components of ecosystems (structure, function, and composition) are the highest priorities. Using the criteria of relevance to EI, sensitivity to environmental change, tangibility, and global availability, the recommended minimal set for forest EI includes: ecosystem structure - Lost Forest Configuration (LFC); ecosystem function – Mean annual MODIS Net Primary Productivity (NPP); and ecosystem composition – Species Habitat Index by group. We urge the Parties to initiate the monitoring of this minimum set of indicators of forest EI while deriving a more comprehensive set of indicators of EI that should be added to the minimum set.

3.2 Benchmarks for evaluating trends over time

A strength of the EI concept in the context of ecological monitoring is the emphasis of evaluation of current conditions relative to a reference state. This is particularly important in the context of the post-2020 GBF because of the goals specify “increasing” the integrity of ecosystems (CBD/SBSTTA/24/INF/9. 2020).

As described in Section 3.1, some of the recommended indicators (highlighted in green in Table 3) are formulated as relative to the predominant climatic-geophysical environment. For those recommended indicators not currently formulated relative to a reference state (highlighted in yellow in Table 3), 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. For ecosystems that have been altered by human influence, the means of best establishing the ecosystem variation determined by the predominant climatic-geophysical environment may be using paleo reconstructions, process or statistical modeling, or use of historic records (Figure 3). While desirable, these approaches may not be feasible for many ecosystems. In these cases, remaining contemporary areas of low human impact could be drawn upon to establish reference states (as is being done for FSCI-ERP). Perhaps the most feasible approach would be to use the earliest year of monitoring as the reference state and quantify trends up to present. Each country will need to strike balance between degree of representation of the reference state and the feasibility of the method for tracking trends in EI (Figure 3).

3.3 Evaluating change over time

With regards to the post-2020 GBF, monitoring the recommended indicators will help nations determine how ecological 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 trend 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. They could also be done at the level of the individual indicators of EI as well as at the level of an EI index which integrates the results for individual metrics to an overall EI score. In the phraseology of the CBD, the EI Index could be a 'Headline' indicator and the individual metrics 'Component' indicators (CBD/SBSTTA/24/3Add.1. 2020).

3.4 Creating Enabling Infrastructure

Reporting within the CBD 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 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 workflows 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.

4 CONCLUSION

We are in a unique period of history where nearly every nation in the world is collaborating to improve the state of nature in the context of unprecedented human pressure. Advances in technology are creating a concurrent opportunity to monitor and evaluate trends in ecological condition in a standardized manner across the Earth. Limits on the ability to consistently measure and monitor indicators of biodiversity globally or nationally has restricted the evaluation of 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 proposed post-2020 GBF includes the global goal of increasing the area, integrity and connectivity of natural ecosystem area and restoring the integrity of managed ecosystems.

This commitment recognizes 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 (Díaz et al. 2020; Maron et al. 2020; Maxwell et al. 2020; Mokany et al. 2020). Here we have focused on EI and made a case that to overcome past limitations on CBD success, a pathway to globally defining and measuring EI is needed.

Our review of the concept of EI, progress in EO, and development of EBVs provides the foundation for defining, monitoring, and evaluating trends in indicators of EI in forest ecosystems. The resulting schema (Figure 1) could allow for consistent, fine-scale, nationally relevant, global monitoring of the components of EI that would help facilitate measurable success in reaching the CBD 2030 and 2050 biodiversity targets. We advocate that Parties to the CBD build upon this schema and operationalize a comprehensive approach for using EO to monitor indicators of EI to best achieve global and national goals in the post-2020 GBF. Catalyzing this opportunity will help nations to better identify, address, monitor and ultimately overcome critical underlying causes of ecosystem and biodiversity loss by the end of this decade and beyond.

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Tables

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

Component of ecosystem 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. Evaluation of potential indicators of ecosystem integrity. Metrics that meet the criteria are denoted by 'Yes' and those that do not by 'No'. Color codes are: green – meets all criteria; yellow – meets all except 6. Reference State; red – does not meet criteria.

Ecosystem Component (Level I / Level II) Potential Indicator (source)	1. Ecosystem structure, function, or composition	2. Extent and Spatial Resolution	3. Temporal Resolution	4. Aggregation	5. Credibility \ Availability	6. Reference State
Ecosystem Structure						
Stand Structure						
Forest Structural Condition Index (Hansen et al. 2019)	Yes	Yes	Yes	Yes	Yes	No
Landscape Structure						
Lost Forest Configuration (Grantham et al. 2020)	Yes	Yes	Yes	Yes	Yes	Yes
Relative Magnitude of Fragmentation[1]	Yes	Yes	Yes	Yes	No	No
Ecosystem Function						
Productivity						
MODIS Net Primary Productivity (Running et al. 2004)	Yes	Yes	Yes	Yes	Yes	No
Carbon Storage						
Carbon Density (Spawn et al. 2020)	Yes	Yes	No	Yes	Yes	No
Natural Disturbance Regime						
MODIS Area Burned (Chuvieco et al. 2018)	Yes	Yes	Yes	Yes	Yes	No
Ecosystem Composition						
Populations						
Living Planet Index (Collen et al. 2009)	Yes	No	No	No	Yes	No
Red List Index[2] (Rodrigues et al. 2014)	Yes	No	No	Yes	Yes	No
Communities						
Species Habitat Index by group (Jetz et al. 2019)	Yes	Yes	Yes	Yes	Yes	Yes
Biodiversity Intactness Index (BII) (Tim Newbold et al. 2016)	Yes	Yes	Yes	Yes	Yes	Yes

Biodiversity Habitat Index (BHI) (Hoskins et al. 2020)	Yes	Yes	Yes	Yes	Yes	Yes
Bioclimatic Ecosystem Resilience Index (BERI) (Ferrier et al. 2020)(This is a combination of ecosystem structure and composition elements)	Yes	Yes	Yes	Yes	Yes	Yes

[1] https://portal.geobon.org/ebv-detail?id=4

[2] https://www.iucnredlist.org/

Table 3. Description of indicators recommended for ecosystem integrity in the context of the post 2020 GBF (denoted by green) and metrics that can currently be used to monitor ecosystem condition and have potential to be developed as indicators of ecosystem integrity (yellow).

Ecosystem Component / Indicator	Description	Data Inputs	Spatial / Temporal Resolution	Citation and Data Source
Ecosystem Structure				
🟨 Forest Structural Condition Index (FSCI)	Vegetation structure within forest stands. Inputs include canopy cover, canopy height, and time since disturbance. This is a dimensionless index from 1-18 with higher values denoting higher integrity. 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).	Landsat Sentinel-2 ICESAT-2	30 m 2012-2019 Tropical forests	Hansen et al. 2019[1]
🟩 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. Values range from 0 to 1 with 1 representing the greatest loss of connectivity. LFC is useful as a measure of forest fragmentation as an input to the Forest Landscape Integrity Index (Grantham et al. 2020).	Laestadius et al. 2011	300m 2019. Plans for annual updates.	Grantham et al. 2020[2]
Ecosystem Function				
🟨 MODIS Net Primary Productivity (NPP)	Functional measure of new biomass fixed by green plants through photosynthesis. Inputs include NVDI (from remotely sensed reflected near infrared and red light) to calculate GPP and respiration terms (from biomass- LAI relationships), whereby GPP- all plant respiration = NPP. Values may range from 180 to 3,500 or greater gCO$_2$m^{-1}year^{-1}, with high values	MODIS	1 km 2000-2020	Running et al. 2004[5] Scurlock and Olson 2013

	indicating high energy availability. 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 depending on the ecosystem (Radeloff et al. 2019) . It is important relative to ecosystem energy flow, carbon dynamics, food for consumers and decomposers, disturbance recovery, and nutrient cycling.			
MODIS Burned Area	Fire history relates directly to the function of a given ecosystems disturbance regime. Burning and quality information including date of burning and spatial extent of fires are available globally monthly at a spatial resolution of 250 m. Metrics include the estimated day of first detection, the confidence level, and land cover type burned. Fire return intervals, and percentage of land area burned can indicate ecosystem integrity when the intervals and percentages align with a historical range of variation. Under current future climatic projection, incorporation of fire into assessments of ecosystem function is imperative.	MODIS	250 m 2000-2020	Chuvieco et al. 2018[6]
Ecosystem Composition				
Species Habitat Index by group	Average decrease in suitable habitat and populations of amphibian, bird and mammal species and the resulting change in the ecological integrity of ecosystems. Species are modeled individually based on biophysical factors and land use change. The index varies from 0 to 100, with smaller values indicating lesser integrity. Can be expressed for single locations and countries and subset to represent specific taxonomic or ecological sets of species, e.g. those dependent on forests. .	Landsat, MODIS	1km 2000-2018	Powers & Jetz 2019, Jetz et al. 2019[8]

Local Biodiversity Intactness Index (BII)	Estimates how much of a terrestrial site's original biodiversity remains in the face of human land use and related pressures. Because LBII relates to site-level biodiversity, it can be averaged and reported for any larger spatial scale (e.g., countries, biodiversity hotspots or biomes as well as globally) without additional assumptions. The index expresses the average abundance and species richness of originally present species across a broad range of plant, invertebrate and vertebrate species, relative to abundance in an undisturbed habitat.	PREDICTS, 4 land use layers	1 km 2001=2020	Newbold et al. 2016[9]
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 three broad biological groups (plants, invertebrates, vertebrates)	Local ecosystem integrity (of 1km cells); modelled beta diversity (based on species occurrence records and abiotic environmental surfaces)	1 km 2005-2015 (2020 update in progress).	Hoskins et al 2020 and Mokany et al. 2020[10]
Bioclimatic Ecosystem Resilience Index (BERI) (This is a combination of ecosystem structure and composition elements.)	Assesses the extent to which a given spatial configuration of natural habitat will promote or hinder climate-induced shifts in biological distributions. Calculated as the connectedness of each cell to areas of natural habitat in the surrounding landscape which are projected to support a similar composition of species under climate change to that currently associated with the focal cell.	Local ecosystem integrity (of 1km cells); modelled beta diversity (based on species occurrence records and	1 km 2005-2015 (2020 update in progress)	Ferrier et al. 2020[7]

		abiotic environmental surfaces); plausible climate scenarios		

[1] https://figshare.com/projects/Forest_Integrity_Project/72164

[2] https://www.forestintegrity.com/

[3] https://dopa.jrc.ec.europa.eu/en/2017ecoregionprcon

[4] https://www.bipindicators.net/indicators/protected-area-connectedness-index-parc-connectedness

[5] https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/products/MOD17A3/

[6] https://modis-fire.umd.edu/ba.html

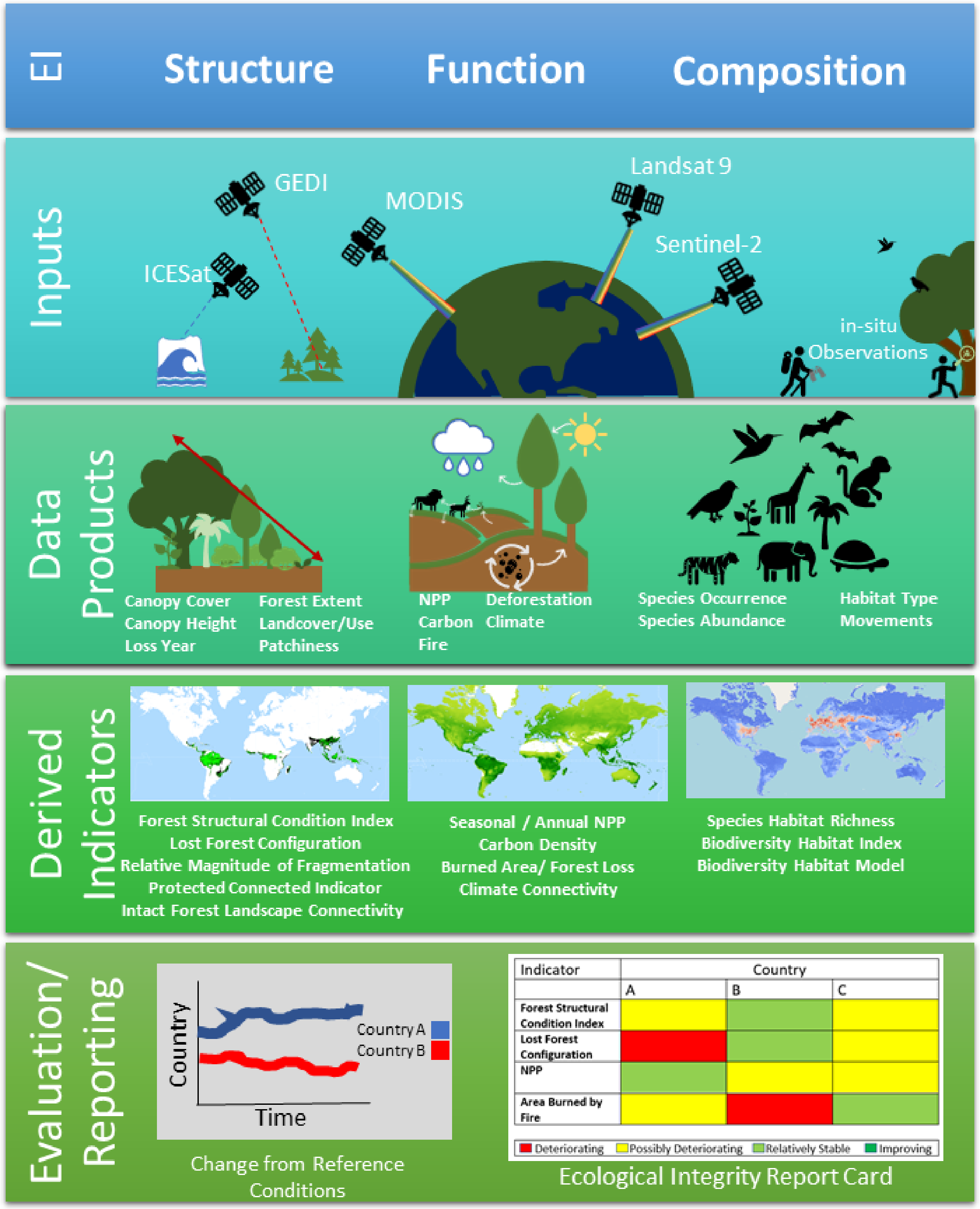
[7] https://www.bipindicators.net/indicators/bioclimatic-ecosystem-resilience-index-beri

[8] https://www.bipindicators.net/indicators/species-habitat-index

[9] https://portal.geobon.org/ebv-detail?id=6

[10] https://www.bipindicators.net/indicators/biodiversity-habitat-index

Figures



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

🟥 Deteriorating 🟨 Possibly Deteriorating 🟩 Relatively Stable 🟩 Improving

Figure 1. Flow diagram of the recommended approach for tracking indicators of ecosystem integrity.

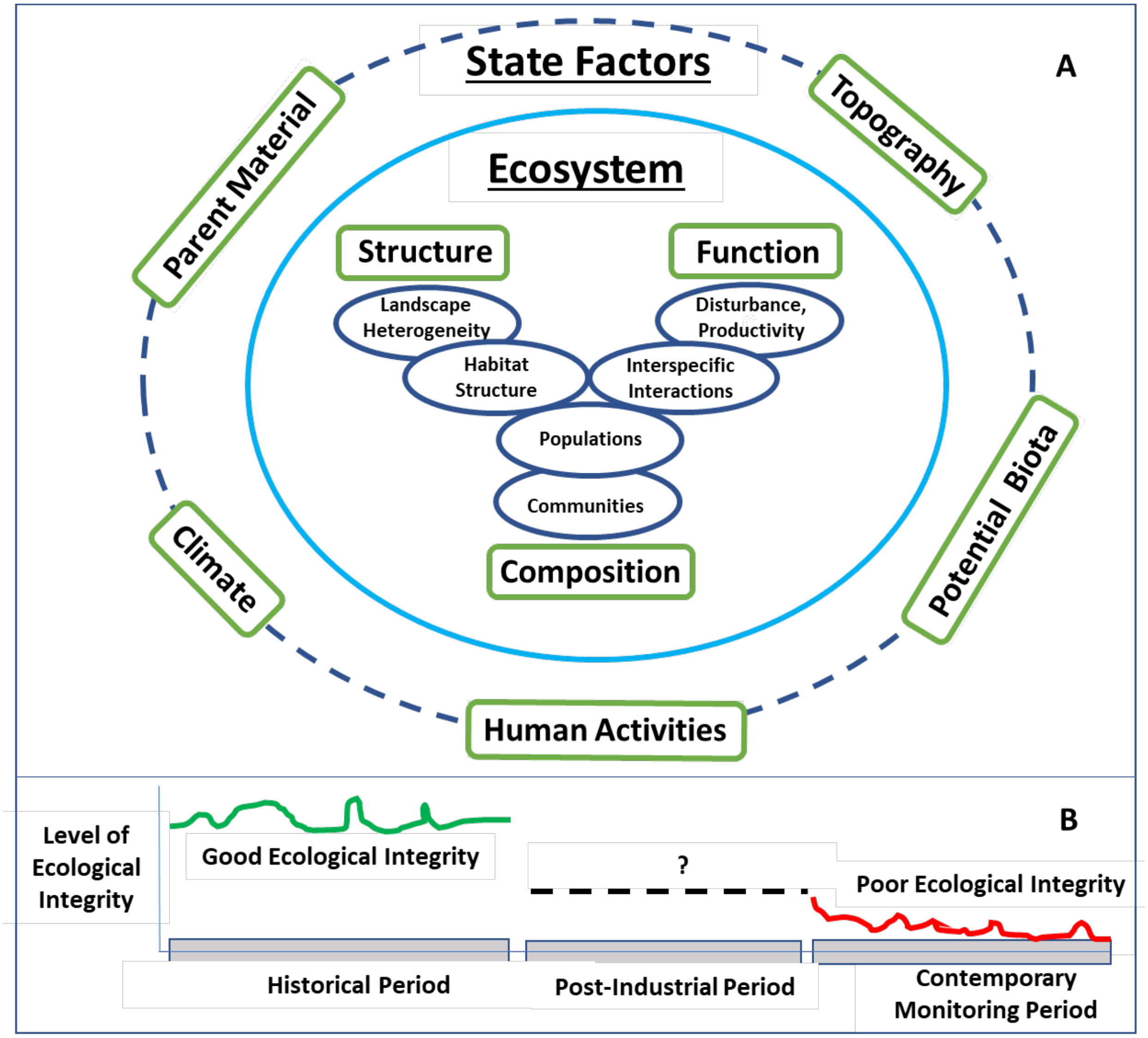


Figure 2. Representation of the concept of ecosystem integrity in the context of the ecosystem and controlling state factors. (A) An ecosystem is characterized by its structure, function, and composition as influenced by broad-scale state factors such as climate. (B) Ecosystem integrity represents the 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 ecosystem integrity during a contemporary monitoring period

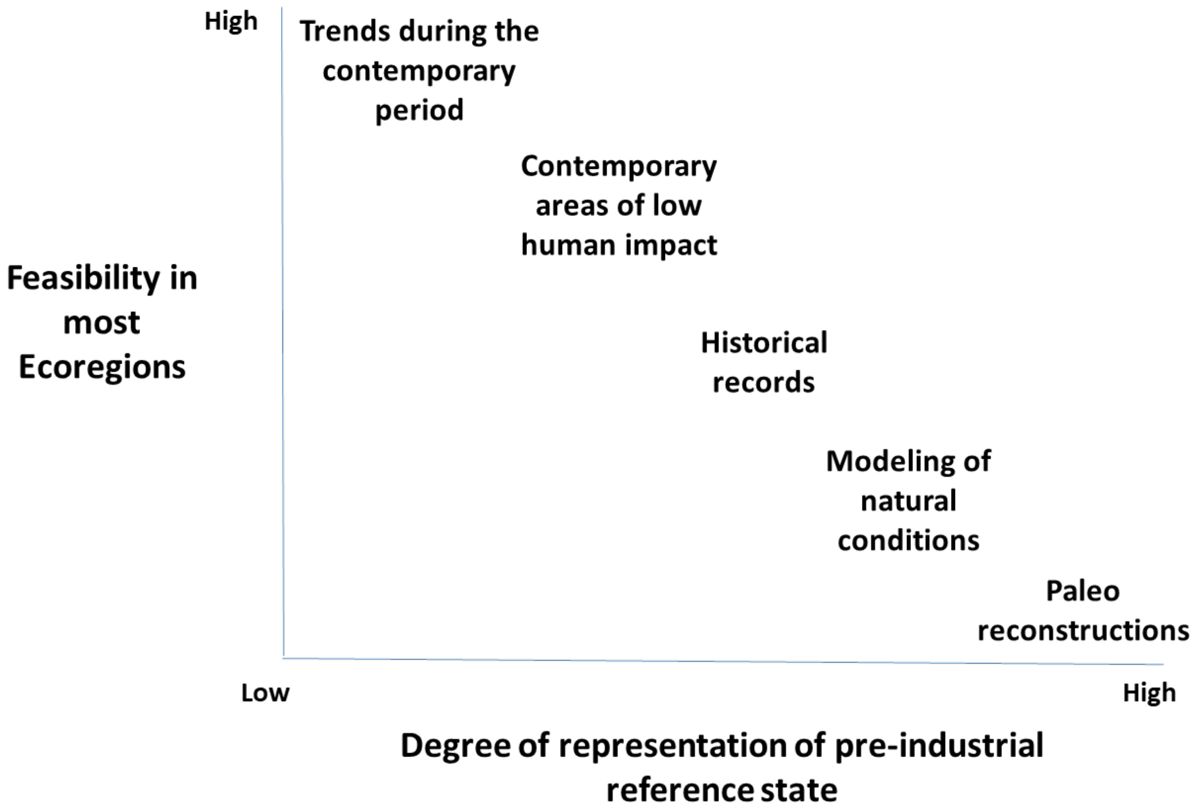


Figure 3. Various methods of establishing reference state for ecosystem integrity. These are expressed along gradients of degree of representation of the natural reference state and feasibility of implementing the method in most contemporary ecosystems.