Perspective

Scientific foundations for an ecosystem goal, milestones and indicators for the post-2020 Global Biodiversity Framework

Short title: Scientific foundations for an ecosystem goal

Authors

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Abstract
Despite significant conservation efforts, the loss of ecosystems continues globally, along with related loss of species and Nature's contributions to people. A new ecosystem goal and milestone, supported by clear targets and indicators, is urgently needed for the Convention on Biological Diversity's post-2020 Global Biodiversity Framework and beyond, to support efforts to abate climate change, and to achieve the UN Sustainable Development Goals. Here, we detail the scientific foundations for an ecosystem goal and milestones, founded on a theory of change, and review available indicators to measure progress. An ecosystem goal should include three core components: area, integrity, and risk of collapse. Targets, the actions necessary for the goals to be met, should address pathways to ecosystem loss and recovery, including retaining threatened ecosystems and intact areas, and restoring degraded ecosystems. Multiple indicators are needed to capture the different dimensions of ecosystem area, integrity and collapse risk across ecosystem types. Indicators should be selected for fitness-for-purpose and relevance to goal components, rather than constrained by currently available data. Science-based goals, supported by well-formulated action targets and fit-for purpose indicators, will provide the best foundation for future success in reversing biodiversity loss and sustaining human well-being.

Introduction

Human-driven loss of biodiversity – from genes and species to ecosystems – erodes the natural capital on which humanity depends. Global efforts to abate biodiversity loss, such as the Aichi Targets of the Strategic Plan for Biodiversity 2011-2020 [1] and UN Sustainable Development Goals (SDGs) [2], have largely failed to reach their aspirations [3,4]. Nonetheless, targets for species conservation and protected area coverage motivated action with recognised positive impacts [5-7], in part because they are clearly articulated and measurable [8]. A comparable cohesive vision for ecosystems is lacking, despite their being essential for sustaining species, ecological processes and functions, and ecosystem services on which people rely [9-11]. The need for a stronger focus on ecosystems is increasingly acknowledged by the scientific community [11,12] and in policy formulation, including the Post-2020 Global Biodiversity Framework of the Convention on Biological Diversity (CBD; Box 1) [3,13]. To be effective, an ecosystem goal, milestones, and action-based targets must be grounded in ecosystem science, and supported by a robust set of indicators for monitoring their progress.

The last decades have seen extensive progress in ecosystem science and tools for ecosystem-based approaches to conservation, which now allow central tenets of an ecosystem ***goal*** to be identified, along with associated ***milestones*** and ***action targets*** to achieve it, and ***indicators*** to measure progress towards the targets. Synthesis of ecological theory has led to practical and workable definitions of ecosystems, their collapse and their integrity (Box 2; Glossary, Table S1), while advances in mapping permit global-scale ecosystem monitoring [14-18]. Together these have enabled development of guidelines for ecosystem risk assessment, in the form of the IUCN Red List of Ecosystems standard (hereafter RLE) [9,19,20], already yielding positive conservation outcomes [21-23]. Further, improved understanding of the impacts of ecosystem loss on human well-being [10,24] has motivated the development of frameworks to account for both, such as natural capital accounting [25].

Here, we summarise the need for the global agenda to include a clear, coherent goal for ecosystems that can be applied across policy scales, from global, national to local. We outline the scientific foundations for an effective ecosystem goal and milestones. We argue that an ecosystem goal, regardless of the policy scale, must include three core components: halting and reversing loss in ecosystem area; halting and reversing declines in ecosystem integrity; and reducing risk of ecosystem collapse. Action targets and indicators must be explicitly aligned with these components, supported by a clearly described theory of change. Finally, we review potential indicators to track progress towards each component of an ecosystem goal, providing recommendations for an indicator set that is fit-for-purpose. We focus predominantly on 'natural' ecosystems [12]. Anthropogenic ecosystems and intensively managed landscapes (such as cities and farmlands) can also be important for biodiversity, including threatened species and remnant patches of natural ecosystems [26,27]. However, many of their values are better reflected in goals for species conservation, sustainable use and Nature's contributions to people, and associated targets (Box 1).

Our perspective is timely given global negotiations underway to design the Post-2020 Global Biodiversity Framework (see Box 1), which will replace the Strategic Plan Strategic Plan for Biodiversity 2011-2020 [1]. An effective post-2020 framework is needed to enable nations to plan clear actions to halt biodiversity loss at the genetic, species and ecosystem level [11,28-30]. The new goals, milestones, action targets and indicators of the post-2020 Framework will have far-reaching policy impacts beyond the CBD, including the implementation of the SDGs [2], especially life on land and in water (SDGs 14 and 15), the UN Decade on Restoration, and abating climate change under the Paris Climate Accord, amongst others [11]. Their framing will direct monitoring effort, data collation and synthesis, including assessments of biodiversity (such as IPBES)[3]. Ultimately, they will shape national and local policy, legislation, resourcing and management [31], and how people and society perceive and value biodiversity [32].

[here insert Box 1]

Box 1: An ecosystem goal in the Post-2020 Global Biodiversity Framework

The Post-2020 Global Biodiversity Framework will comprise a set of outcome-oriented goals for 2050 aligned with the Convention on Biological Diversity (CBD) objectives, to achieve its vision of 'living in harmony with nature'. The updated Zero Draft of the framework [13], released in August 2020, presented four 2050 goals with 2030 milestones (as 'stepping stones' towards the goals[12]), and 20 action-oriented targets for 2030 (hereafter targets) to achieve the goals and milestones. A globally-agreed goal for all ecosystems will strengthen the Post-2020 Framework [11]. Although several of the Aichi targets in the 2011-2020 Strategic Plan had implicit dependencies on ecosystems, explicit references were dispersed among multiple targets for particular ecosystem types (e.g., forests in Target 5 and coral reefs in Target 10), and not under the general goal for safeguarding biodiversity (Goal C), leaving many other ecosystem types without a clear point of reference.

Healthy ecosystems are fundamental to attaining CBD objectives, not only as an organisational level of biodiversity, but also because they underpin all three objectives: 1) conservation of biodiversity (from genes, species to ecosystems); 2) the sustainable use of its components; and 3) the access to and sharing of benefits to human well-being (Figure 1). Objectives 2 and 3 currently form the basis for Goals B and C of the updated Zero Draft [13]. The central role of ecosystems to the CBD objectives suggests a need for a unifying goal for ecosystems, alongside but separate from goals for species and genetic diversity [11,12] (similar to the UN Framework Convention on Climate Change's Paris Agreement, where three goals sit alongside each other). A single biodiversity goal (or 'apex' goal) would confound understanding of change in different levels of biodiversity, render it difficult to measure which parts of the goal have been achieved [8], hinder the design of management actions for ecosystems, species and human well-being, which may conflict [12], and may result in perverse outcomes [12,33]. The need for a clearly articulated ecosystem goal was acknowledged in early drafts of the post-2020 framework the Zero Draft, [34], but receded in the subsequent updated draft [13], where ecosystems were subsumed as habitat to support species and genetic diversity, rather than as a central goal that recognises contributions to all three objectives of the convention.

We propose the following wording for an outcome-oriented goal for ecosystems for 2050:

> ***Loss in area and integrity of all natural ecosystems is halted from 2020, and reversed by 2050, reducing their risk of collapse.***

We recommend two 2030 milestones to support the ecosystem goal:

A) Loss in area and integrity of all natural ecosystems is halted from 2020, preventing increases in risk of ecosystem collapse

B) By 2030, restoration actions are underway to reverse loss in area and integrity in all natural ecosystems.

Reversal of loss in both area and integrity require long-term action via restoration, and recovery may take decades, given time lags and uncertain outcomes of restoration efforts [35,36]. Therefore, aiming for reversal of loss in the longer term – beyond 2030 – is realistic and well-timed for measuring the outcome of actions under the UN Decade of Restoration (2020-2030). This first step is to prevent any further loss, relative to a 2020 baseline, forming the milestone and continuing in the 2050 goal. We have avoided including quantitative targets for restoration of area and integrity or reductions in risk of collapse, though these could be added. Such quantitative elements in goals tend to be arbitrary and politically, rather than scientifically, driven and negotiated, and can result in perverse outcomes [37]. To derive scientifically robust values for meaningful ecological outcomes would require specific and targeted research [38,39].

How baselines for measuring change are set will affect outcomes. For example, any increases in area of ecosystems should stem from recovering ecosystems within a baseline distribution, such as pre-industrial transformation [19,40,41]. We advocate terminology along the lines of 'reversing loss' of ecosystems to avoid perverse outcomes of 'increasing area'. Increases in area of some natural ecosystems can come at the expense of others through encroachment; for example mangroves, which are in decline in some regions due to development and aquaculture, are expanding into saltmarsh in other regions, threatening these ecosystems [42]. Similarly, restoration of integrity requires baselines for composition, structure and function to measure success; these can stem from pre-intensification baselines, including Indigenous cultural or hybrid-historical baselines from contemporary areas [36,41,43].

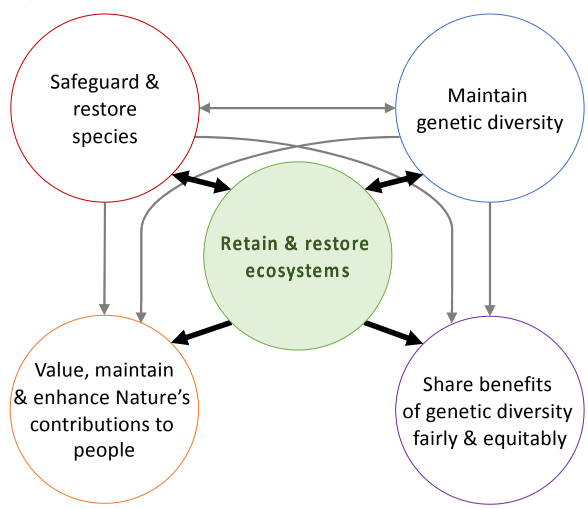

Figure 1. Sustaining natural ecosystems (green) is central to meeting all three CBD objectives and goals in the post-2020 framework (omitting the proposed goal relating to means of implementation [13]). Natural ecosystems support greater species and genetic diversity than anthropogenic ecosystems, zoos and captive breeding, and ex-situ genetic stores: <8% of species assessed as threatened on the IUCN Red List depend on anthropogenic habitats [44]); only 3% of 7000 useful wild

plants assessed have their diversity adequately safeguarded in seedbanks, botanic gardens and other ex situ conservation repositories [4,45]*, while domesticated animals make up <1% of species* [28]*; natural ecosystems comprise approx. 86% of ecosystem types* [16] *but only 50% of ice-free lands* [46]*. Ecosystems sustain landscape/seascape functions, ecosystem services and hence well-being* [10]*; some ecosystem functions do not depend on species, others are species-agnostic, and some species-dependent functions are disproportionately mediated by common species (relative to rare or threatened species).*

[here insert Box 2]

Box 2: Key definitions and theory to underpin an ecosystem goal (see also glossary in Table S1)

What is an ecosystem?

Ecosystems are made up of living components (biotic complexes and assemblages of species), the abiotic environment, the processes and interactions within and between the biotic and abiotic, and the physical space in which these operate [19,20]. Ecosystem types are differentiated from one another by a degree of uniqueness in composition, ecological processes and ecosystem function [16]. While there is inherent uncertainty in applying discrete ecosystem categories (and thus spatial boundaries) to natural continua [19], comparable definitions have stood up legally [47] and in practical implementation by governments world-wide [21,23,48]. Ecosystems present a useful model or abstraction of the complexities of the natural world [49]. Similar definitions are used for other, often synonymous terms, such as *ecological communities*, *habitats*, *biotopes* and *vegetation types* [19,48].

What is ecosystem collapse?

Ecosystem collapse is the endpoint of decline, where an ecosystem type loses its defining features (species, assemblages, processes and functions) and is replaced by a different, often depauperate, ecosystem type [19]. Defining collapse for a given ecosystem includes describing collapsed states and identifying quantitative thresholds for ecosystem-specific variables [50,51], through a combination of empirical data, ecological theory and expert judgement. Ecosystems can collapse globally, over their whole extent, or, more commonly, through local collapse over parts of their distribution. ***The risk of ecosystem collapse*** quantifies the likelihood that an ecosystem will collapse over a specified time frame. The *IUCN Red list of Ecosystems* (RLE) is the global standard for assessing collapse risk, and has been adopted in many countries [21]. The RLE assesses relative collapse risk, allocating ecosystem types into categories of risk (e.g. Endangered, Vulnerable) based on five criteria: A) loss of area, B) restricted distribution, C) change in the abiotic environment or processes, D) change in the biotic components and processes, and E) and quantitative estimate of risk based on a probabilistic model. ***Ecosystem resilience*** describes the ability of an ecosystem to absorb environmental change while maintaining characteristic composition, structure, and function [52]. Thus, a resilient ecosystem can withstand pressures that may lead to collapse, and can persists in the face of perturbation [53,54]. The term 'resilience' is used widely, but varies in its meaning and definition across disciplines, making it difficult to interpret and operationalise in practical settings [55,56], including biodiversity goals [57]. Relationships between ecosystem resilience and risk of collapse need further definition and research in the context of global biodiversity goals and monitoring, particularly in the context of social-ecological resilience [58].

What is ecosystem integrity?

We define ecosystem integrity as the degree to which a given ecosystem's characteristic *composition*, *structure* and *function* is maintained and supported [19,59]. *Composition* relates to the identity and variety of the biota, and includes aspects of species assemblages such as richness, relative abundance or cover, diversity and biomass [19,60]. *Structure* relates to the physical organisation and pattern, including attributes such as connectivity (physical measures, as opposed to species demographics), fragmentation, vegetation height, canopy cover, soil type, and snow cover [11,19,60]. *Ecosystem function* includes ecological and ecosystem processes, such as productivity, predator-prey interactions, disturbance regimes (e.g. fire, drought), hydrological processes, nutrient cycling, species movement and dispersal, and phenology [14,17,19,60,61]. These attributes of integrity (composition, structure and function) are not independent, and similar measures may address multiple attributes, depending on the scale of measurement [60]. Ecosystems with the highest integrity have composition, structure and function similar to reference or baseline states, typically minimally affected by industrial levels of human activity, such as modern agriculture and extraction such as timber harvest and overfishing. High ecosystem integrity does not exclude humans; Indigenous cultural management practices across much of the globe sustain ecosystem processes and diversity, providing a reference state for conservation and restoration [41]. The concept of ecosystem integrity can also be applied to anthropogenic ecosystems, albeit through different definitions, reference states and indicators for biodiversity and human well-being.

The core components needed for an effective and meaningful ecosystem goal

Change in ecosystem area

Change in ecosystem area (also referred to as extent or distribution) is core to measuring global change, and is the focus of many targets, policies and activities at global [12,13,25] and national scales [23,48]. Loss of ecosystem area can diminish the diversity of niches for species to occupy, alter the availability of resources within the ecosystem, reduce its carrying capacity for species, and increase the impacts of edge effects, restricting the abundance and diversity that native biota the ecosystem can support [62-64]. Declines in area are therefore strongly linked to reduced capacity to support biodiversity and the degradation of fundamental ecological processes, and thus ecosystem services [10,19]. Additionally, ecosystems that are widespread have a lower risk of collapse from stochastic threats or catastrophic events [65,66]. Recent advances in ecosystem mapping allow trends in an increasing array of ecosystem types to be monitored, from the level of ecosystem type to biome [16] (see section on indicators below).

Change in ecosystem integrity

Measuring change in area alone is insufficient to capture all important ecosystem changes. Drivers such as timber extraction, overfishing, change in trophic structure, and invasive species diminish ecosystem integrity, through changes in composition, structure and function (see definition in Box 2), that can culminate in ecosystem collapse [19]. Declines in ecosystem integrity (also referred to as ecosystem degradation) increase species extinction risk [67,68], disrupt ecological processes and functions [10], diminish resilience to environmental change, and reduce capacity to sustain species and ecosystem services [10,19]. The concept of integrity enables a goal to address loss and restoration, while emphasising the value of retaining intact areas. While measuring and managing ecosystems is complex due to their dynamics and nonlinear responses to drivers and management [69], an increasing scientific literature bridge the gap between theory and practical guidance on measuring integrity over time in different ecosystem types [17,18,70,71]. Because integrity encompasses composition, structure and function [19,60], ecosystem goals need not include separate reference to aspects of each, such as connectivity; such concepts should be integrated into indicators for the ecosystems where they are critical to integrity.

Risk of ecosystem collapse

Global biodiversity goals must aim to reduce risks of ecosystem collapse, the point at which ecosystems lose characteristic features, species and functions (see Box 2). Comparable to addressing species extinctions [29,72], the foundation for global goals and targets such as Aichi Target 12 and SDG 15.5, avoiding ecosystem collapses is fundamental to sustaining biodiversity within and between ecosystems, as well as species and genetic diversity and human well-being [73]. Including collapse risk provides a benchmark for unacceptable declines in area and integrity, given that together they underpin the risk of collapse (Figure 2). Without reference to collapse risk, area and integrity could be misinterpreted to be fungible within and across ecosystems. The concept of 'risk' contributes a forward-looking and probabilistic dimension to trends in area and integrity [74], while providing a mean of assessing interactions between changes in area and integrity that may produce higher risks of collapse together than either on its own [75]. Conservation priorities can be informed by identifying ecosystems most at risk, while estimating changes in collapse risk through time can also inform assessment of the degree to which conservation actions were effective in reducing risks. Goal phrasing to capture the concept of collapse risk could include: reference to threatened ecosystems, or improving threat status (similar to terminology in the species goal [13]), identified using risk assessment approaches such as RLE; preventing collapse (comparable to preventing extinctions [13]); increasing viability or persistence, as the inverse to collapse risk; and, to a lesser extent, increasing resilience, although the relationship between ecosystem resilience and collapse risk is not yet well understood [58] (Box 2).

A theory of change to support an effective ecosystem goal, milestones, targets and indicators

To be effective, the relationship between goals, milestones, targets, and the indicators that support them must be clear. A theory of change is a conceptual modelling approach used to map pathways from intervention to impact, and makes the assumptions of cause and effect explicit [76,77], reducing the risk of ineffective or perverse conservation outcomes [38]. The Zero Draft of the post-2020 framework commendably recommends the use of a theory of change [13,34], but presents only a very simple, high-level model [76,77]. We propose a new theory of change to support an ecosystem goal, depicting the relationships among direct drivers of biodiversity loss [3], and among the goal components of ecosystem area, integrity and collapse risk (Figure 2). In this, drivers cause declines in integrity and area, in turn increasing risk of ecosystem collapse, and we identify pathways where targets can contribute to achieving the goal. Our model focusses on direct drivers (or threatening processes), and on ecosystem state; for simplicity it does not address more indirect or distal drivers such as growth in human population and consumption see, for example, [3,78,79]. More detailed and tailored models are needed to hone target design, improve understanding of linkages between other post-2020 goals and targets, and include beneficiaries and other actors [76,77]. Quantitative models, combined with scenarios of global change and management strategies, allow more detailed evaluation of the achievability of goals, and effectiveness of targets and indicators [38,80].

Our theory of change illustrates pathways by which effective and well-designed action targets can contribute to goal components (Figure 2): 1) retention of current ecosystem area and integrity through ecosystem management and by halting ongoing and/or future loss; and 2) restoration to increase area and/or integrity where ecosystems have been lost or degraded respectively; together these will reduce risks of ecosystem collapse. Retention of all remaining natural ecosystems is needed to meet the goal [30], across the spectrum of intact to highly threatened [81]. Halting ongoing declines in threatened ecosystems is urgent, as these ecosystems are at higher risk of collapse. Threatened ecosystems often persist in small remnant patches of high conservation value that is often overlooked, instead of being prioritised for protection and restoration [26,82]. Retaining remaining intact ecosystems is also essential, because they broadly buffer against loss of species, ecosystem function and services globally, and are more resilient to direct and indirect impacts of climate change [67,68,83]. Importantly, pro-active retention of ecosystems avoids the cost [84], uncertainty [43,85], low success rates [84,86,87], incomplete recovery [35,36], and decades-long lags [36,73,87,88] associated with restoration. While restoration provides the only pathway for recovery of ecosystems that are degraded or lost from a given area, particularly those that are most threatened [89], these factors mean that restoration cannot justify or compensate for continued loss or degradation of existing ecosystems [36,43,90]. Retention and restoration should be distinguished in separate targets or distinct target components to reflect differences in their short and long-term contributions to the goal and likelihood of success [35,36]

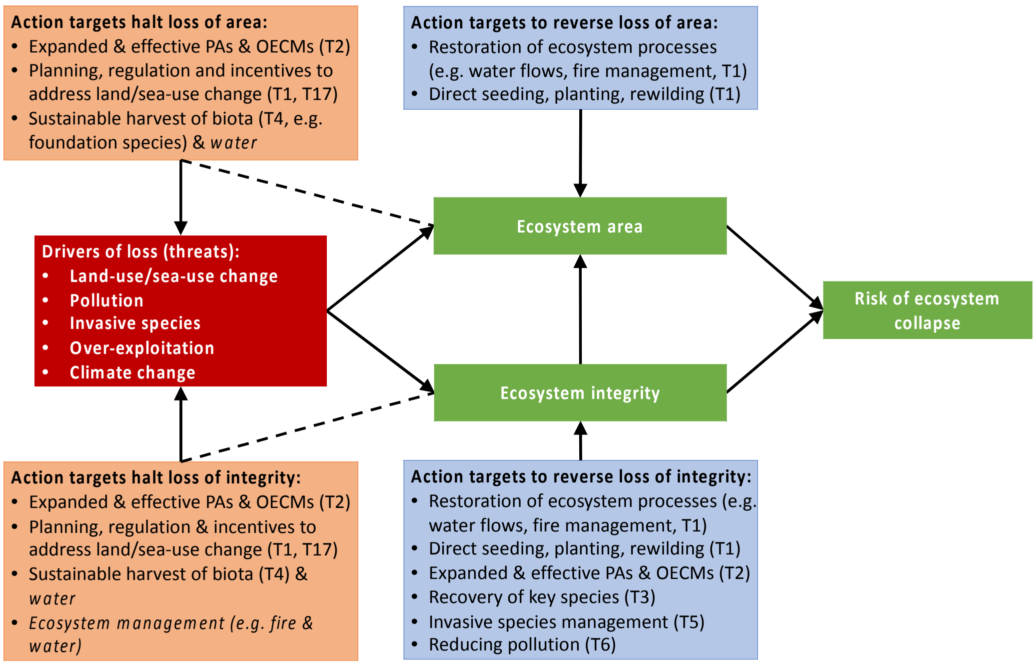

Figure 2. *Theory of change illustrating the relationships between the core components of an ecosystem goal (green), direct drivers of biodiversity loss (red), and pathways for action targets (orange and blue). This simple model shows how drivers [3] cause loss of area and integrity, in turn increasing risk of ecosystem collapse; declines in integrity can also lead to local collapse of an ecosystem in a given location, decreasing area. Action targets can act to 1) reduce drivers or their impacts (orange), thus indirectly halting loss (dashed line), and 2) restore area and/or integrity (blue) through restoration activities and by recovery after removal of threats. Examples of action targets are drawn from current post-2020 draft [13], with the corresponding target in brackets (e.g. denoted by T1 for Target 1); those in italics are not currently included in action targets, notably ecosystem management to halt loss in integrity, and extraction of abiotic ecosystem elements, e.g. water. OECMs = other effective area-based conservation measures; and PA = protected areas.*

Indicators to monitor progress towards an ecosystem goal

Criteria for meaningful indicators

An effective goals requires meaningful indicators to measure progress. We reviewed 25 indicators that have been proposed for the post-2020 goals [91-94] for their capacity to support an ecosystem goal (Table 1), focussing on monitoring ecosystem trends and state. Our review criteria included (see Table 1, and Supplementary Material S2 for methods and criteria):

1) **Alignment with goal components and threats, conceptualised in our proposed theory of change** (see Figure 2). We aligned indicators with each goal component of collapse risk, area and

integrity, further dividing integrity composition, structure, function [60], and identified indicators that measure drivers of biodiversity loss as a proxy for ecosystem loss. We also noted whether they were suggested for multiple goals or goal components to identify diffuse indicators which may lack specificity to particular goal components.

2) **Relevance and ease of interpretation**. We recorded whether, for a given location or ecosystem type, indicator values can be interpreted in terms of proximity to ecosystem collapse without further research. Such information is needed to interpret state or trends, to understand how close given places or ecosystems are to ecologically meaningful thresholds, and to set trajectories or thresholds that indicate goal success or failure.
3) **Fitness for purpose.** We examined how extensively indicators had been tested, if at all, for performance with underlying changes in biodiversity, sensitivity to data bias, and accuracy.
4) **Data availability for applicability and use**. We assessed spatial and temporal coverage, and whether indicators are bottom-up (where data are collated by national governments and then provided to a central institution to calculate globally), or top-down (for example, calculated globally from a database or model managed by a central institution).

Availability and limitations of indicators

While indicators exist for all goal components, most are limited in scope (being specific to a realm or ecosystem type), and many have uncertain relevance or relationships to ecosystem collapse, making values difficult to interpret in an ecologically meaningful way (Table 1). Thus, many of the proposed indicators appear somewhat inadequate for understanding ecosystem change, particularly regarding ecosystem integrity (Table 1), which could compromise capacity to report meaningfully on core goal components. Only one indicator directly estimates **collapse risk**: the *Red List Index for Ecosystems (RLIE)*, an indicator comparable to the Red List Index for species [29]. The RLIE is derived from Red List of Ecosystems (RLE) data, and is currently available for a subset of regions or countries [21,95], with ongoing expansion in data availability.

Several indicators measure change in **ecosystem area** but most capture trends in specific ecosystem types, such as mangroves, wetlands, coral and forests (Table 1); the availability of area indicators continues to expand to more ecosystem types, (e.g., mudflats [14] and sea [96]), and thus we did not review all such indicators [91-93]. The *Ecosystem Area Index* is the only indicator that can encompass all ecosystem types, and can be disaggregated by ecosystem type or region as needed [95]. As with the RLIE, it is derived from RLE data, currently available for a subset of countries/regions [21,95]. However, the index can incorporate data from a range of sources, including national datasets [97], and other ecosystem area metrics such as those for specific ecosystem types, e.g., for forests [95,98]. Recent advances in global-scale ecosystem mapping are reducing the still significant limitations in accuracy, bias and data gaps [99-101]. A key remaining gap between these data and their reliable use is an explicit link between the features mapped and the ecosystems they are used to represent. For example, *Tree Cover Loss*, based on the Global Forest Watch dataset [61] does not distinguish between cover of different forest ecosystem types such as lowland tropical rainforests, seasonally dry tropical forests or anthropogenic plantations [102]. Growing agreement on classification schemes for ecosystems [16] and improved organisation of biodiversity data suitable for validating ecosystem maps will resolve this problem, and allow comprehensive and consistent maps of the world's ecosystems for monitoring ecosystem area within the coming years and decade [11].

Indicators capturing changes in **ecosystem integrity** are increasingly available (Table 1), but most are limited in scope and ecosystem relevance. The only indicator we reviewed that is applicable to all ecosystem types and has a well understood relationship with collapse is the *Ecosystem Health Index* (derived from RLE data), which aggregates ecosystem-specific indicators that are scaled relative to a specified collapse threshold [95]. Many integrity-associated indicators address composition (Table 1), but can be sensitive to data biases [103-106], lack validation or ground-truthing [107], and are difficult to relate to collapse without knowledge of which species are declining, by how much, and their functional impacts on ecosystems [54,108]. Similarly, generic measures of landscape structure (e.g., patterns of connectivity or fragmentation, used in several indicators in Table 1) should be used cautiously to infer ecosystem integrity or collapse risk without assessing impacts on processes such as functional connectivity [19]. Moreover, several composition indicators rely on land-use change to infer compositional change (e.g., the *Biodiversity Intactness Index*, BII, Table 1); while land-use change is indeed a primary driver of biodiversity loss, such indicators omit impacts of other drivers such as hunting and invasive species for ecosystems in which those processes may be important [109,110].

Multiple indicators based on **drivers of biodiversity loss** have been associated with ecosystem goal components, some derived from cumulative threat maps, while others combine threat maps with data such as structure or composition (Table 1). These indicators, which are available globally, provide useful information on areas where ecosystems are under pressure [78]. However, relating them to ecosystem integrity or collapse risk is challenging, because the relationships between drivers and ecosystem responses is non-linear, ecosystem-specific and complex [59]. Composite indicators (including those that combine pressure and state, such as ecosystem structure, e.g. *Forest Landscape Integrity Index*, Table 1) can be difficult to interpret, due to compensatory effects between their component sub-indicators [111]. Most driver-based indicators also only include a subset of direct drivers of biodiversity loss (typically land or sea use change or climate change), and thus may miss important drivers of ecosystem change [110].

Recommendations for indicator selection

From our synthesis of the scientific foundations for an ecosystem goal, and review of indicators suggested for supporting such a goal, we derive five key recommendations for the selection of indicators:

1. **An indicator set is needed to support an ecosystem goal.** Our review reveals that many indicators suitable for supporting an ecosystem goal are available, but none comprehensively assesses all goal components of area, integrity and collapse risk. An indicator set is required, in which the strengths and limitations of each indicator must be carefully scrutinized to ensure appropriate and accurate assessments of progress towards all components of an ecosystem goal.

2. **The indicators need to be specific to goal components, rather than correlated, redundant or general, in order to provide clear evidence of goal progressing**. For example, many of the composition-related indicators we reviewed have been associated with species goal components, where they are likely to have greater relevance and alignment; e.g., the *Red List Index* for species addresses species extinction risk (Table 1). Likewise, many of the driver-based indicators (such as *Human Footprint* or *Marine Cumulative Human Impacts* indices, Table 1) may be better aligned with specific action targets to reduce drivers of biodiversity loss than ecosystem goal components. We recommend indicators are allocated to goal components only where strongly relevant and aligned, to present the clearest picture of the ways in which biodiversity in changing and goals are progressing. Evaluating indicator alignment with particular goal and target components should form part of a comprehensive performance testing program to ensure that out indicator set as a whole is adequate for monitoring progress across all goals.

3. **Relevance and alignment to the ecosystem goal are as important in indicator selection as is current data availability.** Current data availability should be the secondary criterion for indicator selection, provided there is a clear path to improving coverage and scientific rigour. Our review showed that in many parts of the world and ecosystem types, there are trade-offs between

ecosystem relevance and data availability. Indicators with clearer relationships with collapse often have shorter time series, sub-global spatial coverage, or are realm- or ecosystem-specific, with more extensive data available for some ecosystems than others, which will require further investment and research. Indicators based on the IUCN Red List of Ecosystems (EAI, EHI and RLIE) show promise for providing a scientifically credible and practical basis for evaluating target progress by 2025 and beyond, but currently have limited data availability. Notably many indicators currently with limited data or under development will not only provide greater spatial scope, but are also likely to provide hindcast timeseries; for example, the tidal flats dataset published in 2019 maps change over the last 30 years [14], while the Red List of Ecosystems measures change in area and integrity over multiple timeframes [19]. Inevitably, not all countries will have access to working indicators for every goal component or ecosystem type straight away. A solution for interim reporting could be to use aligned and relevant indicators where available, while continuing investment in research, knowledge and data synthesis [112]. Given the current paucity of comprehensive global data for such indicators[3], more generic indicators of composition and structure and driver-based indicators may serve as proxies in the short-term.

4. **Greater testing and validation of indicators is required to understand their ecosystem relevance, reliability and ease of interpretation.** While most indicators we reviewed have been subjected to some testing, few have been rigorously assessed for their ability to measure ecosystem responses to different drivers or policy changes, their sensitivity to data gaps or bias, and how accurately they reflect the state of biodiversity, despite an increasing array of approaches and templates for doing so [113-116]. Indicators developed in an experimental setting may not meet standards for use in operational settings, where requirements for quality and timeliness is typically higher and often prescribed by government or administrative requirements [117]. Theoretical work and ground-truthing is therefore typically required to improve understanding of ecosystem relevance and validate indicator values to on-ground reference states [107,118]. Top-down indicators may provide useful estimates of broadscale patterns and consistency where crude global assessments are needed [119], but in many cases, their utility for local to country-scale assessments is limited by insufficient precision to detect trends with confidence, or trade-offs required to achieve global coverage [100,117].

5. **The connection between global indicators and national or local policy and reporting needs strengthening**, including the capacity for national indicators and data to feed into global indicators, and more appropriate scale and accuracy for local assessment. Most of the indicators reviewed rely on centralised databases or models (Table 1), tend to be mapped at relatively coarse spatial and thematic scales (Table S2.1), and may not be open source or publicly accessible [120], limiting their utility and accessibility for local practitioners and governments. Ideally, indicators should be scalable, where local or national data, which are typically more relevant to local policy and more accurate through inclusion of local knowledge and data [119,121], can feed into global level indicators [76]. Few of the indicators we reviewed can do this; instead most countries use their own indicators [121], presenting a mismatch in reporting that wastes effort, degrades consistency of reporting and reduces overall understanding. Defining and mapping ecosystems at national and global scales will be a vital first step to providing consistent underlying data for all ecosystem-based indicators, and a baseline for area and integrity; much progress has been made [11,21,97], but there is substantial work ahead. Progress can be strengthened through investment in biodiversity assessment, such as Red List of Ecosystems assessments, and ecosystem accounting at national and global levels [23,122].

Towards an effective, multi-scale agenda for sustaining ecosystems

A coherent and implementable ecosystem goal is fundamental to meeting all global environmental agendas. Achieving the vision of the Post-2020 Global Biodiversity framework – living in harmony with nature – depends on a meaningful and coherent goal for ecosystems (Box 1) , alongside equivalent goals for species and genes [12]. For the UN SDGs to be successful, functioning ecosystems must be recognised as the foundation of our societies, our economies, and well-being of all people [12], while achieving the UNFCCC's Paris Climate Accord relies on retaining or restoring natural ecosystems. The components of area, integrity and collapse risk are required to ensure a scientifically-sound, effective and measurable goal for ecosystems. While most global goals (including drafts of the post-2020 Framework) include ecosystem area and integrity, they fail to consider the endpoint of ecosystem decline that must be avoided – ecosystem collapse. A global commitment to preventing ecosystem collapse, comparable to avoiding species extinctions [29,72], is needed to ensure persistence of biodiversity, and the contributions to people that it provides. Clearly articulated theories of change provide a logical foundation for clarifying relationships between goals, milestones, and action targets [76,77,79], and ensure they are measured with suitable indicators, thus identifying gaps in knowledge and scope for further research.

An effective goal requires well-aligned indicators that capture the dimensions of ecosystem change and provide reliable measures of all goal components – ecosystem area, integrity and collapse risk. The indicator set should provide a concise and complementary set of measures of both loss and recovery, clearly illustrating whether goals and targets are on track. The indicator sets initially proposed for the post-2020 Framework were large, unfocussed, and potentially unwieldy [91,92], yet inadequate regarding their specificity, ecosystem relevance, data availability and coverage (Table 1, S1). A subsequent draft monitoring approach[93] proposed headline indicators for measuring only change in area of selected ecosystems, excluding indicators of integrity or collapse risk, and thus failing to meet core needs of an effective ecosystem goal. The importance of measuring change in ecosystem integrity and risk of collapse, in addition to area, means that the post-2020 monitoring framework must be forward-looking, and embrace emerging indicators that are fit-for-purpose in terms of ecosystem relevance, accuracy and specificity to goal components, rather than by constrained by current data availability. The latter will increase, and rapidly, but settling on an indicator set that is inadequate will hamper progress towards meeting goals, as well as measuring them.

Science-based goals for ecosystems are central to the environmental agenda, from global to national policy and action. Using ecosystems as building blocks allows scaling to local and national goals for individual countries [123], cities and businesses [124], and disaggregation by ecosystem, biome or realm for alignment with system-specific goals or policies, like the Ramsar Convention on Wetlands. The Post-2020 Global Biodiversity Framework offers an opportunity to not only set aspirations for the future of the planet, but also the actions that can achieve them. Previous goals including in the Strategic Plan for Biodiversity 2011–2020 set a clear agenda at global, national and local levels, enabling funding to flow with many benefits [5,7,11]. The Post-2020 goal and milestones can do the same for ecosystems, provided it addresses the key elements required to sustain ecosystems, with aligned action targets to achieve it and indicators to monitor successes and failures. Given the rate of biodiversity loss globally [3,4], the new Post-2020 goals provide a critical opportunity for world leaders to set a clear agenda for sustaining all ecosystems into the future.

Tables

Table 1: Summary of reviewed indicators

Table 1. Summary of the reviewed indicators that have been proposed for an ecosystem goal or goal components for the post-2020 Framework. Indicators were drawn from ecosystem components in Goal A (specifically A.1 on ecosystem area and A.2 on integrity) in the 1) drafts of the monitoring framework [91,93,94]*, 2) the draft indicator review [92]; and 3) sources such as the Biodiversity Indicator Partnership (https://www.bipindicators.net/) that collate biodiversity indicators. Note that the list of indicators reviewed is not exhaustive, particularly for ecosystem area. Columns summarise information on: 1) alignment with goal components of collapse risk, area and integrity, with integrity indicators further divided into composition, structure, function, and indicators of drivers of biodiversity loss as a proxy for ecosystem loss or degradation (noting that some indicators combine these, shown in brackets); 2) the number of goals or goal components the indicator has been associated with (including multiple ecosystem components, species or genetic goal components or goals related to Nature's contributions to people or benefit sharing); 3) whether indicator values have been related to ecosystem collapse thresholds, for a given location or ecosystem type, relating to relevance to the goals and ease of interpretation; 4) fitness-for-purpose: whether indicators have undergone performance testing for behaviour with underlying changes in biodiversity, sensitivity to data bias, and accuracy; 5) data availability for applicability and use, including the realm of application (M=marine, F=freshwater, T=terrestrial) as a proxy for spatial coverage, 6) current temporal coverage (length of the time series, and 7) whether reported annually, and whether there is global coverage for at least one time point); 8) whether indicators are bottom-up or top-down, where bottom-up indicators are those where data are collated by the national government then provided to a central institution to calculate globally; top-down indicators include those where empirical data collected locally are collated by a central institution, and where modelled indicators are calculated by a central institution, and may be disaggregated by country; some indicators are or can be both.*note MSA and LPI are listed in the updated November 2020 SBSTTA document [93], where it is unclear with which goal component it is associated.

Table 1.

Indicator	*Goal Component*	Number of goal components	Collapse related	Performance tested	Realm	Time-series length (y)	Annual	Global coverage for 1+ timepoints	Bottom-up or top-down
Risk of collapse									
Red List Index of Ecosystems (Rowland et al. 2020a)	Risk of collapse	2	Y	Y	M,T,F	1	N	N	Both
Ecosystem area									
Ecosystem Area Index (Rowland et al. 2020a)	Area	2	Y	Y	M,T,F	1	N	N	Both
Forest Area as a Proportion of Total Land Area (Keenan et al. 2015)	Area	2	N	Y	T	5	N	Y	Bottom up
Global Mangrove Watch (Bunting et al. 2018; Thomas et al. 2017)	Area	1	Y	Y	M	20	N	Y	Top down
Trends in Primary Forest Extent (Morales-Hidalgo et al. 2015)	Area	1	Y	Y	T	5	N	Y	Bottom up
Tree Cover Loss (Global Forest Watch; (Hansen et al. 2013)	Area	2	N	Y	T	20	Y	Y	Top down
Wetland Extent Trends Index (Darrah et al. 2019; Dixon et al. 2016)	Area	2	Y	Y	M,F	47	Y	Y	Top down
Ecosystem integrity									
Bioclimatic Ecosystem Resilience Index (BERI)	Composition (drivers)	1	N	N	T	15	N	Y	Top down
Biodiversity Habitat Index (Allnutt et al. 2008)	Composition (drivers)	3	N	N	T	15	N	Y	Top down
Biodiversity Intactness Index (Newbold et al. 2016)	Composition (drivers)	2	N	Y	T	45	Y	Y	Top down
Living Planet Index (McRae et al. 2017)	Composition	1*	N	Y	M,T,F	48	Y	Y	Top down
Mean Species Abundance (Alkemade et al. 2009)	Composition (drivers)	1*	N	N	T F	1	N	Y	Top down
Red List Index for species [125]	Composition	4	N	Y	M,T,F	23	N	Y	Both
Species Habitat Index (Gregory and van Strien 2010)	Composition	4	N	N	T	1	Y	N	Top down
Ecosystem Intactness Index (Beyer et al. 2019)	Structure (drivers)	1	N	Y	T	2	N	Y	Top down
Continuous Global Mangrove Forest Cover (Hamilton and Casey 2016)	Structure	2	Y	Y	M	12	Y	Y	Top down

Forest Landscape Integrity Index [126]	Structure (drivers)	1	N	N	T	1	Y	Y	Top down
Ecosystem Health Index (Rowland et al. 2020a)	Function (structure, composition)	2	Y	Y	M,T,F	1	N	N	Bottom up
Live Coral Cover (Obura et al. 2019)	Function (Area)	2	Y	Y	M	47	Y	Y	Top down
Proportion of land degraded over total land area (Sims et al. 2019)	Function	1	N	Y	T	15	N	Y	Bottom up
Vegetation Health Index (Kogan 1997)	Function	1	N	Y	T	38	Y	Y	Top down
Drivers of biodiversity loss									
Coral Reef Watch (Liu et al. 2006)	Drivers	0	Y	Y	M	32	Y	Y	Top down
Human Footprint (Venter et al. 2016)	Drivers	2	N	Y	T	2	N	Y	Top down
Marine Cumulative Human Impacts (Halpern et al. 2008)	Drivers	1	N	Y	M	2	N	Y	Top down
Ocean Health Index (Halpern et al. 2012)	Drivers	1	N	Y	M	7	Y	Y	Both

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Supplementary material for Nicholson et al. "Scientific foundations for an ecosystem goal"

Supplementary material includes:

S1 Glossary

S2 Supplementary methods: indicator review

S2.1 Criteria and assessment

S2.2 Results, see also Tables 1, S2.1 and S2.2.

Cited literature

Table S1 Glossary

Table S1. Glossary of key terms

Term	Definition	References
Biodiversity	Variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems. *Similar terms: biological diversity*	[1]
Realm	One of five major components of the biosphere that differ fundamentally in ecosystem organisation and function: terrestrial, freshwater, marine, subterranean, atmospheric.	[2]
Biome	A component of a realm united by one or a few common major ecological drivers that regulate major ecological functions, derived from the top-down by subdivision of realms.	[2]
Ecosystem	The living components (biotic complexes and assemblages of species), non-living components (abiotic environment), the processes and interactions within and between the biotic and abiotic, and the physical space in which these operate.	[3,4]
Ecosystem collapse	Transition beyond a bounded threshold in one or more indicators that define the identity and natural variability of the ecosystem.	[3,4]
Risk of ecosystem collapse	The likelihood that an ecosystem will collapse over a specified time frame, losing defining features, species and functions. *Similar terms: collapse risk*	[3,4]
Ecosystem composition	The identity and variety of biota in an ecosystem, including aspects of species assemblages such as richness, relative abundance or cover, diversity and biomass.	[3,5]
Ecosystem function	Biological, geochemical and physical processes that take place or occur within an ecosystem, such as productivity,	[3,5,6]

	predator-prey interactions, disturbance regimes (e.g. fire, drought). *Similar terms: ecosystem processes, ecological processes*	
Ecosystem integrity	The similarity of a given ecosystem's *composition*, *structure* and *function* to its natural range of variation in these characteristics. *Similar terms: intactness*	[3,7]
Ecosystem structure	The physical organisation and pattern of an ecosystem, including attributes such as connectivity (physical measures, as opposed to species demographics), fragmentation, vegetation height, canopy cover, soil type, and snow cover.	[3,5,8]
Ecosystem type	Ecosystem types are ecosystems differentiated from one another by a degree of uniqueness in biotic composition and ecological processes.	[2,3]
Natural ecosystem	Ecosystems composed of largely native species, structure, function and abiotic drivers, relative to pre-industrial or pre-intensification baselines. We acknowledge that ecosystems exist on a continuum of human influence, from those that exclude humans, through varying levels of influence (e.g., Indigenous traditional management), to anthropogenic ecosystems, such as plantations, croplands and urban areas.	[2,9,10]
Anthropogenic ecosystem	Ecosystems where biotic (and some abiotic) composition is the result of deliberate manipulation by people, often a stronger factor than climate or substrate, such as plantations, croplands and urban areas *Similar terms: managed ecosystems, anthromes*	[2,9-11]
Goal	Broad statement that describes a desired outcome or end state. *Similar terms: fundamental objective, aspiration*	[9,12]
Target	Means for achieving a goal; actions to operationalise or deliver the required biodiversity improvements *Similar terms: action target(s), sub-target, means objective*	[9,12,13]
Goal or target component	A part or 'clause' of a goal or target that addresses a single aspect of the more complex goal/target. A component may require very different indicators to monitor progress toward their achievement than other components of the goal or target. *Similar terms: element*	[14]
Indicator	Variable that represents another, often unobservable, variable of interest. *Similar terms: metric*	[15]
Indicator relevence	In the context of this article, for a given location or ecosystem type, indicator values can be interpreted in terms of proximity to ecosystem collapse or other relevant thresholds	
Restoration	The process of assisting the recovery of degraded or destroyed ecosystems and can be active (e.g. restoration of tidal flow, planting, invasive species management) or	[16]

	passive (e.g. removing threats to allow natural recovery via protected areas).	
Specificity	the quality of belonging or pertaining to a particular subject or thing	[17]
Theory of change	A theory of change is a conceptual modelling approach used to map pathways from intervention to impact, that makes the assumptions of cause and effect explicit; In the context of this article, theory of change takes the form of a conceptual model that clarifies the relationships between drivers of biodiversity loss, characteristics of ecosystem change, and the actions needed to achieve components of an ecosystem goal.	[18,19]

Supplementary material for Nicholson et al. "Scientific foundations for an ecosystem goal"

S2 Supplementary Methods: Indicator review

2.1 Criteria and assessment

We reviewed 25 indicators that have been proposed for the post-2020 goals [20-23] on their capacity to support an ecosystem goal (see Table 1, S2.1). Indicators were drawn from 1) ecosystem components in Goal A (specifically A.1 on ecosystem extent and A.2 on integrity) in the drafts of the monitoring framework [20,22,23], 2) the draft indicator review [21]; and 3) from sources such as the Biodiversity Indicator Partnership (https://www.bipindicators.net/) that collate biodiversity indicators. Note that the list of indicators reviewed is not exhaustive, particularly for ecosystem extent. This review focusses on indicators suggested for monitoring ecosystem trends and state, i.e. outcomes (e.g., Live Coral Cover), rather than actions (e.g., Protected Area Coverage).

We evaluated the indicators against criteria drawn from the scientific literature [15,24-26], some of which overlap with criteria identified in the draft post-2020 indicator review [21]. Each indicator was assessed by an individual author who conducted a search of literature, websites and reports, and then evaluated against a set of criteria using specified assessment guidelines (Table S2.2: Metadata). Each individual assessment was then cross reviewed by at least one other author.

Criteria fall under the following focal areas:

1) **Alignment with goal components and threats, conceptualised in our proposed theory of change** (see Figure 2). We evaluated the alignment of indicators with each goal component – collapse risk, area and integrity. We further divided the integrity metrics (after Noss 1990) into those that primarily measure composition, structure, function, and identified those that measure drivers of biodiversity loss as a proxy for ecosystem degradation. We also noted whether the indicators were suggested for multiple goals or goal components (in the draft of the monitoring framework [20,22,23] or draft indicator review [21]) to identify diffuse indicators may lack specificity to particular goal components, especially ecosystems.

2) **Relevance and ease of interpretation**. We recorded whether, for a given location or ecosystem type, indicator values can be interpreted in terms of proximity to ecosystem collapse (and thus losing characteristic features, species, and functions), without further research. That is, can a given metric indicate whether ecosystems are approaching collapse, or recovering away from collapse, and a threshold for collapse be identified? Can indicator values (e.g. 0, 1, or 0.5) be readily interpreted, in the context of collapse? Such information is needed to interpret state or trends, to understand how close given regions are to ecologically meaningful thresholds, and to set trajectories or thresholds that indicate goal success or failure.

3) **Data scope, availability for applicability and use**. We assessed:
   - spatial or thematic coverage (in terms of realm, ecosystem type, taxanomic groups, and whether globally avaiable);
   - temporal coverage (length of time series and frequency of calculation);
   - whether the indicator is designed to be scalable (global to national/local or local/national to global).
   - whether indicators are bottom-up (where data are collated by national governments to attain a national value, then also provided to a central institution to calculate the indicator globally), or top-down (for example, calculated globally from a database or model managed by a central institution).
   - whether the indicator can be calculated from available data sources, versus linked to specific data or models.

- Whether the indicator relies on either empirical or modelled data.

4) **Fitness for purpose.** We examined how extensively indicators had been tested, if at all, for performance and behaviour with underlying changes in biodiversity, sensitivity to data bias, and accuracy (particularly for modelled or remotely sensed data).
   - Responsiveness, or magnitude and speed of indicator response to policy change, has been tested
   - Reliability, or capacity to accurately reflect the status and/or trends in the underlying biodiversity component of interest, has been tested. This includes acknowledging and estimating biases and/or variance in the trend and/or data, and/or sensitivity to data gaps or biases in underlying data.
   - Whether tested for capacity to differentiate between different drivers of change.

5) **Clarity of approach***:*
   - Metric aim is clearly stated in key literature
   - Clear and explicit methods have been peer-reviewed and published, or are available and accessible in some format.
   - Data and code are open access and accessible.
   - Sources of and potential types of uncertainty are acknowledged, and methods to estimate specific types of uncertainty or variability in metric value or underlying data are available, increasing ease of interpretation.
   - Metric is related to existing alternate metrics, as a measure of uniqueness or redundancy among existing biodiversity indicator suite.

While costs and scientific credibility are important characteristics of indicators [27], they are outside the scope of this work. However, we indirectly cover them in the above criteria (e.g. cost via data accessibility; credibility via uptake).

2.2 Review Results

Results of the review are shown in Tables 1 (main text), S2.1 and S2.2. Full reports on each indicator can be found in a publically available technical report [28].

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Y=Yes, N=No, P=Partially	Bioclimatic Ecosystem Resilience Index BERI	Biodiversity Habitat Index BHI	Biodiversity Intactness Index BII	Continuous Global Mangrove Forest Cover CGMFC	Coral Reef Watch CRW	Ecosystem Area Index EAI	Ecosystem Health Index EHI	Ecosystem Intactness index EIM	Forest Area as a Proportion of Total Land Area FAO	Forest Landscape Integrity Index FLII	Global Mangrove Watch GMW	Human Footprint HF	Live Coral Cover LCC	Living Planet Index LPI	Marine Cumulative Human Impacts MCHI	Mean Species Abundance MSA	Ocean Health Index OHI	Proportion of land degraded over total land area PLD	Red List Index for species R LI	Red list Index for Ecosystems RLIE	Species Habitat index SHI	Tree Cover Loss TCL	Trends in Primary Forest Extent TPF	Vegetation Health Index VHI	Wetland Extent Trends Index WETI
Ecosystem relevance																									
Measures ecosystem response	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Risk of ecosystem collapse	N	N	N	N	N	N	N	N	N	N	N	N	Y	N	N	N	N	N	N	Y	N	N	N	N	N
Ecosystem area	N	N	N	N	N	Y	N	N	Y	N	Y	N	Y	N	N	N	N	N	N	N	Y	Y	Y	N	Y
Integrity: composition	Y	Y	Y	N	N	N	Y	N	N	N	N	N	N	Y	N	Y	N	N	Y	N	Y	N	N	N	N
Integrity: structure	N	N	N	Y	N	N	Y	Y	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	N
Integrity: function	N	N	N	N	N	N	Y	N	N	N	N	N	Y	N	N	N	N	Y	N	N	N	N	N	N	N
Integrity: drivers of change (threats)	Y	Y	Y	N	Y	N	N	Y	Y	Y	N	Y	N	N	Y	Y	Y	N	N	N	Y	Y	N	N	N
Driver - land or sea use change	Y	Y	Y	N	N	N	N	Y	Y	Y	N	Y	N	N	Y	Y	Y	N	N	N	Y	Y	N	N	N
Driver - direct exploitation	N	N	N	N	N	N	N	N	N	Y	N	N	N	N	Y	N	Y	N	n	N	N	N	N	N	N
Driver - climate change	Y	N	N	N	Y	N	N	N	N	N	N	N	N	N	Y	Y	Y	N	N	N	Y	N	N	N	N
Driver - pollution	N	N	N	N	N	N	N	N	N	Y	N	N	N	N	Y	Y	Y	N	N	N	N	N	N	N	N
Driver - invasive alien species	N	N	N	N	N	N	N	N	N	Y	N	N	N	N	Y	N	N	N	N	N	N	N	N	N	N
Relatable to a collapse threshold	N	N	N	Y	Y	Y	Y	N	N	N	Y	N	Y	N	N	N	N	N	N	Y	N	N	Y	N	Y
Number of goal components	1	3	2	2	0	2	2	1	2	1	1	2	2	1	1	1	1	1	4	2	4	2	1	1	2
Scope, data availability and quality																									
Independent of specific data & models	N	N	N	N	N	Y	Y	Y	Y	N	N	Y	Y	Y	Y	N	Y	Y	Y	Y	N	N	Y	N	Y
Can be calculated at global scale now or in the future	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Taxa represented	Vertebrates, In	Vertebrates	vertebrates	Mangrove spec	Corals	All ecosyste	All ecosyste	Terrestrial e	All forest ec	All forest ecosy	mangrove e	NA	Coral specie	Vertebrates	NA	Mammals, I	Marine taxa	NA	Birds, mam	All ecosyste	Terrestrial s	Trees	Forest ecosyste	Plant specie	Wetland ec
Marine	N	N	N	Y	Y	Y	Y	N	N	N	Y	N	Y	Y	Y	N	Y	Y	Y	Y	N	N	N	N	Y
Terrestrial	Y	Y	Y	N	N	Y	Y	Y	Y	Y	N	Y	N	Y	N	Y	N	N	Y	Y	Y	Y	Y	Y	N
Freshwater	N	N	N	N	N	Y	Y	N	N	N	N	N	N	Y	N	Y	N	N	Y	Y	N	N	N	N	Y
Scalable spatially	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Empirical	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	N	Y	Y	Y	Y
Modelled	Y	Y	Y	N	N	Y	Y	N	N	N	N	N	N	N	Y	Y	Y	Y	N	Y	Y	N	N	N	N
Frequency: <=1 year	N	N	Y	Y	Y	N	N	N	N	N	N	N	Y	Y	N	N	Y	N	N	N	Y	Y	N	Y	Y
Frequency: >1 & <5 years	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Frequency: >=5 & <=10 years	Y	Y	N	N	N	N	N	N	Y	N	N	Y	N	N	Y	N	N	N	Y	N	N	N	Y	N	N
Frequency: single time point, varies spatially or temporally, or >10 years	N	N	N	N	N	Y	Y	Y	N	Y	Y	N	N	N	N	Y	N	Y	N	Y	N	N	N	N	N
Length of global time series (at intervals of one or more years)	15	15	45	12	32	1	1	2	5	1	20	2	47	48	2	1	7	1	23	1	1	20	5	38	47
Bottom-up or Top-down	Top-down	Top-down	Top-down	Top-down	Top-down	Both	Both	Top-down	Bottom-up	Top-down	Top-down	Top-down	Top-down	Top-down	Top-down	Top-down	Both	Bottom-up	Both	Both	Top-down	Top-down	Bottom-up	Top-down	Top-down
Clarity of approach and aims																									
Clearly stated objective/aim	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Transparent	Y	P	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y
Reproducible	N	N	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y
Uncertainty (what types, how represented, acknowledged?)	N	N	Y	N	Y	Y	Y	N	N	N	N	N	Y	Y	Y	Y	N	Y	Y	Y	N	N	N	N	Y
Is it related to other metrics?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y
Indicator perfomance tested for:																									
Responsiveness	N	N	N	N	Y	Y	Y	N	N	N	N	N	Y	Y	N	N	N	N	Y	Y	N	N	N	N	N
Reliability/sensitivity	N	N	Y	Y	Y	Y	Y	Y	Y	N	N	Y	Y	Y	Y	N	Y	y	Y	Y	N	Y	Y	Y	Y
Differentiates drivers	N	N	N	N	Y	N	N	N	N	N	Y	N	Y	N	N	N	N	N	N	N	N	N	N	N	N

Table S2.2. Assessment criteria for Table S2.1	
Assessment criteria	Assessment guidelines
Ecosystem relevance	
Measures ecosystem response	Y = the indicator measures ecosystem state or response to drivers by measuring change in the risk of ecosystem collapse, ecosystem area or integrity (via composition, structure or function); N = the indicator measures drivers of biodiveristy loss
Risk of ecosystem collapse	Y = the indicator quantifies status and/or trends in the risk of ecosystem collapse (i.e., the likelihood that an ecosystem will collapse over a specified time frame, losing defining features, species and functions); N = the indicator does not quantify status and/or trends in the risk of
Ecosystem area	Y = the indicator quantifies status and/or trends in ecosystem area (i.e., the extent or distribution across which the ecosystem spans); N = the indicator does not quantify status and/or trends in
Integrity: composition	Y = the indicator quantifies status and/or trends in ecosystem composition (i.e., the identity and variety of biota in an ecosystem, including aspects of species assemblages such as richness, relative abundance or cover, diversity and biomass); N = the indicator does not quantify status
Integrity: structure	Y = the indicator quantifies status and/or trends in ecosystem structure (i.e., the physical organisation and pattern of an ecosystem, including attributes such as connectivity (physical measures, as opposed to species demographics), fragmentation, vegetation height, canopy cover, soil type, and snow cover); N = the indicator does not quantify status and/or trends in ecosystem
Integrity: function	Y = the indicator quantifies status and/or trends in ecosystem function (i.e., the biological, geochemical and physical processes that take place or occur within an ecosystem, such as productivity, predator-prey interactions, disturbance regimes); N = the indicator does not
Integrity: drivers of change (threats)	Y = the indicator quantifies status and/or trends in the drivers of change (i.e., the threats that affect the system of interest); N = the indicator does not quantify status and/or trends in the
Driver - land or sea use change	Y = the indicator quantifies status and/or trends in sea or land-use change as a driver of change; N = the indicator does not quantify status and/or trends in sea or land-use change as a driver of
Driver - direct exploitation	Y = the indicator quantifies status and/or trends in direct exploitation as a driver of change (e.g., fishing, logging); N = the indicator does not quantify status and/or trends in direct exploitation as
Driver - climate change	Y = the indicator quantifies status and/or trends in climate change as a driver of change; N = the indicator does not quantify status and/or trends in climate change as a driver of change.
Driver - pollution	Y = the indicator quantifies status and/or trends in pollution as a driver of change; N = the indicator does not quantify status and/or trends in pollution as a driver of change.

Driver - invasive alien species	Y = the indicator quantifies status and/or trends in invasive alien species as a driver of change; N = the indicator does not quantify status and/or trends in invasive alien species as a driver of change.
Relatable to a collapse threshold	Y = the indicator is a generic or ecosystem specific measure that can it be related to thresholds of ecosystem collapse; N = it would rquire further research and analysis to relate the indicator to a
Number of goal components	the number of goals or goal components the indicator has been associated with (including multiple ecosystem components, species or genetic goal components or goals related to Nature's contributions to people or benefit sharing)
Scope, data availability and	
Independent of specific data & models	Y = the indicator can be calculated using data from a range sources and the source is not restricted; N = the indicator must be calculated with a specific dataset and/or model.
Can be calculated at global scale now or in the future	Y = the indicator can currently be calculated at the global level as there are methods and data available; N = the indicator cannot currently be calculated at a global level as methods and/or
Taxa represented	Text; The taxonomic group or groups that are included in the data used to calculate the indicator and that the indicator is designed to represent trends across.
Marine	Y = the indicator is designed to represent trends in marine species, environments or ecosystems; N = the indicator was not designed represent trends in marine species, environments or
Terrestrial	Y = the indicator is designed to represent trends in terrestrial species, environments or ecosystems; N = the indicator was not designed represent trends in terrestrial species,
Freshwater	Y = the indicator is designed to represent trends in freshwater species, environments or ecosystems; N = the indicator was not designed represent trends in freshwater species,
Scalable spatially	Y = the indicator can be aggreagated up (i.e., local or national data can feed into global level indicators) or disaggregated down (i.e., where data from the global indicator can be used to calculate local or national level indicators). N = the indicator cannot be aggregated up or
Empirical	Y = the indicator is calculated using timeseries of field data or remotely-sensed data; N = the indicator is not calculated using timeseries of field data or remotely-sensed data.
Modelled	Y = Indicator is calculated from modelled data
Frequency: <= 1 year	Y = the frequency at which the global version of the indicator is calculated to date is less than or equal to every 1 year; N = the indicator has not been calculated at less than equal to 1-yearly
Frequency: > 1 & < 5 years	Y = the frequency at which the global version of the indicator is calculated to date is between more than 1-yearly intervals and less than 5 yearly intervals; N = the indicator has not been calculated at more than 1-yearly intervals and less than 5 yearly intervals.

Frequency: >=5 & <=10 years	Y = the frequency at which the global version of the indicator is calculated to date is between more than or equal to 5-yearly intervals and less than or equal to 10 yearly intervals; N = the indicator has not been calculated at more than or equal to 5-yearly intervals and less than or
Frequency: single time point, varies spatially or temporally, or >10 years	Y = the global version of the indicator has been calculated to date for a single time point; the frequency at which the indicator is calculated varies spatially or temporally; and/or the indicator is calculated at a frequency of more than 10-yearly intervals.
Length of global time series (at intervals of one or more years)	Numeric; Number of years across which the indicator has been calculated. For example, if the indicator was calculated in 2000 and again in 2010, the length of the time series is 10 years.
Bottom-up or Top-down	Top-down = the indicator is calculated globally from a database or model managed by a central institution; Bottom-up = the data used to calculate the indicator are collated by national governments to attain a national indicator value, which is provided to a central institution to calculate the indicator globally; Both = the calculation of the indicator occurs in both bottom-up
Clarity of approach and aims	
Clearly stated objective/aim	Y = the aim of the indicator is clearly stated in key literature; N = no clear aim is stated.
Transparent	Y = the methods to calculate the indicator are published and clear; P = the methods are clear but not published; N = the methods of the indicator are no clear.
Reproducible	Y = the code and data used to calculate the indicator are shared and accessible; N = the code and
Uncertainty (what types, how represented, acknowledged?)	Y = there are methods used to allow uncertainty or variability in indicator outputs/ values or underlying data to be calculated that detail the types of uncertainty, how they are represented and acknowleded; N = uncertainty surrounding the indicator, data and methods are not used.
Used in BIP/SDG/CBD/GBO/IPBES documentation or reports?	Y = the indicator has been reported in documentation or reports of the Biodiversity Indicator Partnership (BIP), United Nations Sustainable Development Goals (SDGs), Convention on Biological Diveristy (CBD), Global Biodiversity Outlook (GBO) and/or Intergovermental Science-Policy Platform on Biodiversity and Ecosystem Services; N.= the indicator has not been reported
Is it related to other metrics?	Y = the indicator is related to any other indicators listed and assessed in this paper; N = the indicator is unique and not related to other indicators in the list of indicators included in the
Indicator perfomance tested for:	
Responsiveness	Y = The magnitude and speed of response policy change has been tested; N = The magnitude and speed of response policy change has not been tested.

Reliability/sensitivity	Y = the indicator has been tested for its reliability (i.e., the capacity of the indicator to accurately reflect the status and/or trends in the underlying biodiversity component of interest, such as estimating biases and/or variance in the trend and/or data) and/or sensitivity to data gaps or biases; N = the indicator has not been tested for the reliability nor sensitivity.
Differentiates drivers	Y = tested for capacity to differentiate between different drivers of change (i.e., the impact of driver on indicator is known, predictable and distinguishable from the impacts of other drivers)