

1 **Perspective**

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

4

5 **Short title: Scientific foundations for an ecosystem goal**

6

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45

46 **Acknowledgements:** This research was supported by: funding provided to IUCN by MAVA
47 Foundation (to EN); the Australian Research Council (FT190100234 to EN; DP170100609 to EN;
48 LP170101143 to EN, DAK, NM, JEMW, HG); and VESKI (Inspiring Women Fellowship to EN).

49

50 **Author contributions:** EN led the conception and writing of the paper; EN, JAR, CFS, SS and KW
51 undertook analysis and interpretation of data; all authors contributed to the drafting and writing.

52

53 **Abstract**

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

69

70

71 **Introduction**

72 Human-driven loss of biodiversity – from genes and species to ecosystems – erodes the natural
73 capital on which humanity depends. Global efforts to abate biodiversity loss, such as the Aichi
74 Targets of the Strategic Plan for Biodiversity 2011-2020¹ and UN Sustainable Development Goals
75 (SDGs)², have largely failed to reach their aspirations^{3,4}. Nonetheless, targets for species
76 conservation and protected area coverage motivated action with recognised positive impacts⁵⁻⁷, in
77 part because they are clearly articulated and measurable⁸. A comparable cohesive vision for
78 ecosystems is lacking, despite their being essential for sustaining species, ecological processes and
79 functions, and ecosystem services on which people rely⁹⁻¹¹. The need for a stronger focus on
80 ecosystems is increasingly acknowledged by the scientific community^{11,12} and in policy formulation,
81 including the Post-2020 Global Biodiversity Framework of the Convention on Biological Diversity
82 (CBD; Box 1)^{3,13}. To be effective, an ecosystem goal, milestones, and action-based targets must be
83 grounded in ecosystem science, and supported by a robust set of indicators for monitoring their
84 progress.

85

86 The last decades have seen extensive progress in ecosystem science and tools for ecosystem-based
87 approaches to conservation, which now allow central tenets of an ecosystem **goal** to be identified,
88 along with associated **milestones** and **action targets** to achieve it, and **indicators** to measure
89 progress towards the targets. Synthesis of ecological theory has led to practical and workable
90 definitions of ecosystems, their collapse and their integrity (Box 2; Glossary, Table S1), while
91 advances in mapping permit global-scale ecosystem monitoring¹⁴⁻¹⁸. Together these have enabled
92 development of guidelines for ecosystem risk assessment, in the form of the IUCN Red List of
93 Ecosystems standard (hereafter RLE)^{9,19,20}, already yielding positive conservation outcomes²¹⁻²³.
94 Further, improved understanding of the impacts of ecosystem loss on human well-being^{10,24} has
95 motivated the development of frameworks to account for both, such as natural capital accounting²⁵.

96

97 Here, we summarise the need for the global agenda to include a clear, coherent goal for ecosystems
98 that can be applied across policy scales, from global, national to local. We outline the scientific
99 foundations for an effective ecosystem goal and milestones. We argue that an ecosystem goal,
100 regardless of the policy scale, must include three core components: halting and reversing loss in
101 ecosystem area; halting and reversing declines in ecosystem integrity; and reducing risk of
102 ecosystem collapse. Action targets and indicators must be explicitly aligned with these components,

103 supported by a clearly described theory of change. Finally, we review potential indicators to track
104 progress towards each component of an ecosystem goal, providing recommendations for an
105 indicator set that is fit-for-purpose. We focus predominantly on ‘natural’ ecosystems¹².
106 Anthropogenic ecosystems and intensively managed landscapes (such as cities and farmlands) can
107 also be important for biodiversity, including threatened species and remnant patches of natural
108 ecosystems^{26,27}. However, many of their values are better reflected in goals for species
109 conservation, sustainable use and Nature’s contributions to people, and associated targets (Box 1).

110
111 Our perspective is timely given global negotiations underway to design the Post-2020 Global
112 Biodiversity Framework (see Box 1), which will replace the Strategic Plan Strategic Plan for
113 Biodiversity 2011-2020¹. An effective post-2020 framework is needed to enable nations to plan
114 clear actions to halt biodiversity loss at the genetic, species and ecosystem level^{11,28-30}. The new
115 goals, milestones, action targets and indicators of the post-2020 Framework will have far-reaching
116 policy impacts beyond the CBD, including the implementation of the SDGs², especially life on land
117 and in water (SDGs 14 and 15), the UN Decade on Restoration, and abating climate change under
118 the Paris Climate Accord, amongst others¹¹. Their framing will direct monitoring effort, data
119 collation and synthesis, including assessments of biodiversity (such as IPBES)³. Ultimately, they will
120 shape national and local policy, legislation, resourcing and management³¹, and how people and
121 society perceive and value biodiversity³².

122
123 *[here insert Box 1]*
124

125 126 **Box 1: An ecosystem goal in the Post-2020 Global Biodiversity Framework**

127 The Post-2020 Global Biodiversity Framework will comprise a set of outcome-oriented goals for 2050
128 aligned with the Convention on Biological Diversity (CBD) objectives, to achieve its vision of ‘living in
129 harmony with nature’. The updated Zero Draft of the framework¹³, released in August 2020,
130 presented four 2050 goals with 2030 milestones (as ‘stepping stones’ towards the goals¹²), and 20
131 action-oriented targets for 2030 (hereafter targets) to achieve the goals and milestones. A globally-
132 agreed goal for all ecosystems will strengthen the Post-2020 Framework¹¹. Although several of the
133 Aichi targets in the 2011-2020 Strategic Plan had implicit dependencies on ecosystems, explicit
134 references were dispersed among multiple targets for particular ecosystem types (e.g., forests in
135 Target 5 and coral reefs in Target 10), and not under the general goal for safeguarding biodiversity
136 (Goal C), leaving many other ecosystem types without a clear point of reference.

137
138 Healthy ecosystems are fundamental to attaining CBD objectives, not only as an organisational level
139 of biodiversity, but also because they underpin all three objectives: 1) conservation of biodiversity
140 (from genes, species to ecosystems); 2) the sustainable use of its components; and 3) the access to
141 and sharing of benefits to human well-being (Figure 1). Objectives 2 and 3 currently form the basis
142 for Goals B and C of the updated Zero Draft¹³. The central role of ecosystems to the CBD objectives
143 suggests a need for a unifying goal for ecosystems, alongside but separate from goals for species and
144 genetic diversity^{11,12} (similar to the UN Framework Convention on Climate Change’s Paris
145 Agreement, where three goals sit alongside each other). A single biodiversity goal (or ‘apex’ goal)
146 would confound understanding of change in different levels of biodiversity, render it difficult to
147 measure which parts of the goal have been achieved⁸, hinder the design of management actions for
148 ecosystems, species and human well-being, which may conflict¹², and may result in perverse
149 outcomes^{12,33}. The need for a clearly articulated ecosystem goal was acknowledged in early drafts of
150 the post-2020 framework the Zero Draft,³⁴ but receded in the subsequent updated draft¹³, where
151 ecosystems were subsumed as habitat to support species and genetic diversity, rather than as a
152 central goal that recognises contributions to all three objectives of the convention.

153

154 We propose the following wording for an outcome-oriented goal for ecosystems for 2050:
155 **Loss in area and integrity of all natural ecosystems is halted from 2020, and reversed by**
156 **2050, reducing their risk of collapse.**

157

158 We recommend two 2030 milestones to support the ecosystem goal:

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

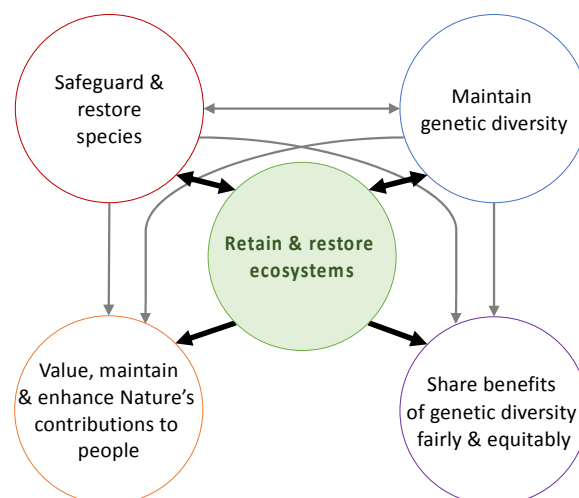
161 **B) By 2030, restoration actions are underway to reverse loss in area and integrity in all**
162 **natural ecosystems.**

163

164 Reversal of loss in both area and integrity require long-term action via restoration, and recovery may
165 take decades, given time lags and uncertain outcomes of restoration efforts^{35,36}. Therefore, aiming
166 for reversal of loss in the longer term – beyond 2030 – is realistic and well-timed for measuring the
167 outcome of actions under the UN Decade of Restoration (2020-2030). This first step is to prevent
168 any further loss, relative to a 2020 baseline, forming the milestone and continuing in the 2050 goal.
169 We have avoided including quantitative targets for restoration of area and integrity or reductions in
170 risk of collapse, though these could be added. Such quantitative elements in goals tend to be
171 arbitrary and politically, rather than scientifically, driven and negotiated, and can result in perverse
172 outcomes³⁷. To derive scientifically robust values for meaningful ecological outcomes would require
173 specific and targeted research^{38,39}.

174

175 How baselines for measuring change are set will affect outcomes. For example, any increases in area
176 of ecosystems should stem from recovering ecosystems within a baseline distribution, such as pre-
177 industrial transformation^{19,40,41}. We advocate terminology along the lines of ‘reversing loss’ of
178 ecosystems to avoid perverse outcomes of ‘increasing area’. Increases in area of some natural
179 ecosystems can come at the expense of others through encroachment; for example mangroves,
180 which are in decline in some regions due to development and aquaculture, are expanding into
181 saltmarsh in other regions, threatening these ecosystems⁴². Similarly, restoration of integrity
182 requires baselines for composition, structure and function to measure success; these can stem from
183 pre-intensification baselines, including Indigenous cultural or hybrid-historical baselines from
184 contemporary areas^{36,41,43}.



185

186 *Figure 1. Sustaining natural ecosystems (green) is central to meeting all three CBD objectives and*
187 *goals in the post-2020 framework (omitting the proposed goal relating to means of implementation*
188 *¹³). Natural ecosystems support greater species and genetic diversity than anthropogenic*
189 *ecosystems, zoos and captive breeding, and ex-situ genetic stores: <8% of species assessed as*
190 *threatened on the IUCN Red List depend on anthropogenic habitats⁴⁴); only 3% of 7000 useful wild*

191 plants assessed have their diversity adequately safeguarded in seedbanks, botanic gardens and other
192 ex situ conservation repositories^{4,45}, while domesticated animals make up <1% of species²⁸; natural
193 ecosystems comprise approx. 86% of ecosystem types¹⁶ but only 50% of ice-free lands⁴⁶. Ecosystems
194 sustain landscape/seascape functions, ecosystem services and hence well-being¹⁰; some ecosystem
195 functions do not depend on species, others are species-agnostic, and some species-dependent
196 functions are disproportionately mediated by common species (relative to rare or threatened
197 species).

198

199

200

201 [here insert Box 2]

202

203

204

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

206

207 **What is an ecosystem?**

208 Ecosystems are made up of living components (biotic complexes and assemblages of species), the
209 abiotic environment, the processes and interactions within and between the biotic and abiotic, and
210 the physical space in which these operate^{19,20}. Ecosystem types are differentiated from one another
211 by a degree of uniqueness in composition, ecological processes and ecosystem function¹⁶. While
212 there is inherent uncertainty in applying discrete ecosystem categories (and thus spatial boundaries)
213 to natural continua¹⁹, comparable definitions have stood up legally⁴⁷ and in practical
214 implementation by governments world-wide^{21,23,48}. Ecosystems present a useful model or
215 abstraction of the complexities of the natural world⁴⁹. Similar definitions are used for other, often
216 synonymous terms, such as *ecological communities*, *habitats*, *biotopes* and *vegetation types*^{19,48}.

217

218 **What is ecosystem collapse?**

219 Ecosystem collapse is the endpoint of decline, where an ecosystem type loses its defining features
220 (species, assemblages, processes and functions) and is replaced by a different, often depauperate,
221 ecosystem type¹⁹. Defining collapse for a given ecosystem includes describing collapsed states and
222 identifying quantitative thresholds for ecosystem-specific variables^{50,51}, through a combination of
223 empirical data, ecological theory and expert judgement. Ecosystems can collapse globally, over their
224 whole extent, or, more commonly, through local collapse over parts of their distribution. **The risk of**
225 **ecosystem collapse** quantifies the likelihood that an ecosystem will collapse over a specified time
226 frame. The *IUCN Red list of Ecosystems* (RLE) is the global standard for assessing collapse risk, and
227 has been adopted in many countries²¹. The RLE assesses relative collapse risk, allocating ecosystem
228 types into categories of risk (e.g. Endangered, Vulnerable) based on five criteria: A) loss of area, B)
229 restricted distribution, C) change in the abiotic environment or processes, D) change in the biotic
230 components and processes, and E) and quantitative estimate of risk based on a probabilistic model.

231 **Ecosystem resilience** describes the ability of an ecosystem to absorb environmental change while
232 maintaining characteristic composition, structure, and function⁵². Thus, a resilient ecosystem can
233 withstand pressures that may lead to collapse, and can persist in the face of perturbation^{53,54}. The
234 term 'resilience' is used widely, but varies in its meaning and definition across disciplines, making it
235 difficult to interpret and operationalise in practical settings^{55,56}, including biodiversity goals⁵⁷.
236 Relationships between ecosystem resilience and risk of collapse need further definition and research
237 in the context of global biodiversity goals and monitoring, particularly in the context of social-
238 ecological resilience⁵⁸.

239

240 **What is ecosystem integrity?**

241 We define ecosystem integrity as the degree to which a given ecosystem's characteristic
242 *composition, structure and function* is maintained and supported^{19,59}. *Composition* relates to the
243 identity and variety of the biota, and includes aspects of species assemblages such as richness,
244 relative abundance or cover, diversity and biomass^{19,60}. *Structure* relates to the physical organisation
245 and pattern, including attributes such as connectivity (physical measures, as opposed to species
246 demographics), fragmentation, vegetation height, canopy cover, soil type, and snow cover^{11,19,60}.
247 *Ecosystem function* includes ecological and ecosystem processes, such as productivity, predator-prey
248 interactions, disturbance regimes (e.g. fire, drought), hydrological processes, nutrient cycling,
249 species movement and dispersal, and phenology^{14,17,19,60,61}. These attributes of integrity
250 (composition, structure and function) are not independent, and similar measures may address
251 multiple attributes, depending on the scale of measurement⁶⁰. Ecosystems with the highest integrity
252 have composition, structure and function similar to reference or baseline states, typically minimally
253 affected by industrial levels of human activity, such as modern agriculture and extraction such as
254 timber harvest and overfishing. High ecosystem integrity does not exclude humans; Indigenous
255 cultural management practices across much of the globe sustain ecosystem processes and diversity,
256 providing a reference state for conservation and restoration⁴¹. The concept of ecosystem integrity
257 can also be applied to anthropogenic ecosystems, albeit through different definitions, reference
258 states and indicators for biodiversity and human well-being.
259

260

261

262 **The core components needed for an effective and meaningful ecosystem goal**

263

264 ***Change in ecosystem area***

265 Change in ecosystem area (also referred to as extent or distribution) is core to measuring global
266 change, and is the focus of many targets, policies and activities at global^{12,13,25} and national scales
267^{23,48}. Loss of ecosystem area can diminish the diversity of niches for species to occupy, alter the
268 availability of resources within the ecosystem, reduce its carrying capacity for species, and increase
269 the impacts of edge effects, restricting the abundance and diversity that native biota the ecosystem
270 can support⁶²⁻⁶⁴. Declines in area are therefore strongly linked to reduced capacity to support
271 biodiversity and the degradation of fundamental ecological processes, and thus ecosystem services
272^{10,19}. Additionally, ecosystems that are widespread have a lower risk of collapse from stochastic
273 threats or catastrophic events^{65,66}. Recent advances in ecosystem mapping allow trends in an
274 increasing array of ecosystem types to be monitored, from the level of ecosystem type to biome¹⁶
275 (see section on indicators below).
276

276

277 ***Change in ecosystem integrity***

278 Measuring change in area alone is insufficient to capture all important ecosystem changes. Drivers
279 such as timber extraction, overfishing, change in trophic structure, and invasive species diminish
280 ecosystem integrity, through changes in composition, structure and function (see definition in Box
281 2), that can culminate in ecosystem collapse¹⁹. Declines in ecosystem integrity (also referred to as
282 ecosystem degradation) increase species extinction risk^{67,68}, disrupt ecological processes and
283 functions¹⁰, diminish resilience to environmental change, and reduce capacity to sustain species and
284 ecosystem services^{10,19}. The concept of integrity enables a goal to address loss and restoration,
285 while emphasising the value of retaining intact areas. While measuring and managing ecosystems is
286 complex due to their dynamics and nonlinear responses to drivers and management⁶⁹, an increasing
287 scientific literature bridge the gap between theory and practical guidance on measuring integrity
288 over time in different ecosystem types^{17,18,70,71}. Because integrity encompasses composition,
289 structure and function^{19,60}, ecosystem goals need not include separate reference to aspects of each,
290 such as connectivity; such concepts should be integrated into indicators for the ecosystems where
291 they are critical to integrity.

292

293 ***Risk of ecosystem collapse***

294 Global biodiversity goals must aim to reduce risks of ecosystem collapse, the point at which
295 ecosystems lose characteristic features, species and functions (see Box 2). Comparable to addressing
296 species extinctions^{29,72}, the foundation for global goals and targets such as Aichi Target 12 and SDG
297 15.5, avoiding ecosystem collapses is fundamental to sustaining biodiversity within and between
298 ecosystems, as well as species and genetic diversity and human well-being⁷³. Including collapse risk
299 provides a benchmark for unacceptable declines in area and integrity, given that together they
300 underpin the risk of collapse (Figure 2). Without reference to collapse risk, area and integrity could
301 be misinterpreted to be fungible within and across ecosystems. The concept of ‘risk’ contributes a
302 forward-looking and probabilistic dimension to trends in area and integrity⁷⁴, while providing a
303 mean of assessing interactions between changes in area and integrity that may produce higher risks
304 of collapse together than either on its own⁷⁵. Conservation priorities can be informed by identifying
305 ecosystems most at risk, while estimating changes in collapse risk through time can also inform
306 assessment of the degree to which conservation actions were effective in reducing risks. Goal
307 phrasing to capture the concept of collapse risk could include: reference to threatened ecosystems,
308 or improving threat status (similar to terminology in the species goal¹³), identified using risk
309 assessment approaches such as RLE; preventing collapse (comparable to preventing extinctions¹³);
310 increasing viability or persistence, as the inverse to collapse risk; and, to a lesser extent, increasing
311 resilience, although the relationship between ecosystem resilience and collapse risk is not yet well
312 understood⁵⁸ (Box 2).

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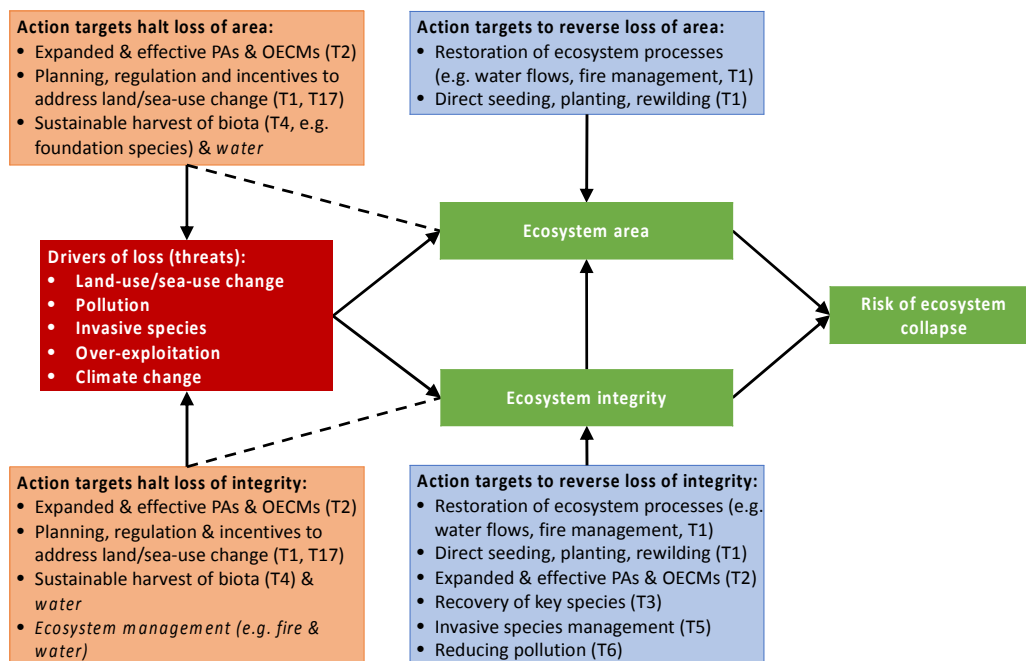
314 **A theory of change to support an effective ecosystem goal, milestones, targets and indicators**

315 To be effective, the relationship between goals, milestones, targets, and the indicators that support
316 them must be clear. A theory of change is a conceptual modelling approach used to map pathways
317 from intervention to impact, and makes the assumptions of cause and effect explicit^{76,77}, reducing
318 the risk of ineffective or perverse conservation outcomes³⁸. The Zero Draft of the post-2020
319 framework commendably recommends the use of a theory of change^{13,34}, but presents only a very
320 simple, high-level model^{76,77}. We propose a new theory of change to support an ecosystem goal,
321 depicting the relationships among direct drivers of biodiversity loss³, and among the goal
322 components of ecosystem area, integrity and collapse risk (Figure 2). In this, drivers cause declines in
323 integrity and area, in turn increasing risk of ecosystem collapse, and we identify pathways where
324 targets can contribute to achieving the goal. Our model focusses on direct drivers (or threatening
325 processes), and on ecosystem state; for simplicity it does not address more indirect or distal drivers
326 such as growth in human population and consumption see, for example,^{3,78,79}. More detailed and
327 tailored models are needed to hone target design, improve understanding of linkages between other
328 post-2020 goals and targets, and include beneficiaries and other actors^{76,77}. Quantitative models,
329 combined with scenarios of global change and management strategies, allow more detailed
330 evaluation of the achievability of goals, and effectiveness of targets and indicators^{38,80}.

331

332 Our theory of change illustrates pathways by which effective and well-designed action targets can
333 contribute to goal components (Figure 2): 1) retention of current ecosystem area and integrity
334 through ecosystem management and by halting ongoing and/or future loss; and 2) restoration to
335 increase area and/or integrity where ecosystems have been lost or degraded respectively; together
336 these will reduce risks of ecosystem collapse. Retention of all remaining natural ecosystems is
337 needed to meet the goal³⁰, across the spectrum of intact to highly threatened⁸¹. Halting ongoing
338 declines in threatened ecosystems is urgent, as these ecosystems are at higher risk of collapse.
339 Threatened ecosystems often persist in small remnant patches of high conservation value that is
340 often overlooked, instead of being prioritised for protection and restoration^{26,82}. Retaining
341 remaining intact ecosystems is also essential, because they broadly buffer against loss of species,
342 ecosystem function and services globally, and are more resilient to direct and indirect impacts of

343 climate change^{67,68,83}. Importantly, pro-active retention of ecosystems avoids the cost⁸⁴, uncertainty
 344^{43,85}, low success rates^{84,86,87}, incomplete recovery^{35,36}, and decades-long lags^{36,73,87,88} associated
 345 with restoration. While restoration provides the only pathway for recovery of ecosystems that are
 346 degraded or lost from a given area, particularly those that are most threatened⁸⁹, these factors
 347 mean that restoration cannot justify or compensate for continued loss or degradation of existing
 348 ecosystems^{36,43,90}. Retention and restoration should be distinguished in separate targets or distinct
 349 target components to reflect differences in their short and long-term contributions to the goal and
 350 likelihood of success^{35,36}
 351



352 **Figure 2.** Theory of change illustrating the relationships between the core components of an
 353 ecosystem goal (green), direct drivers of biodiversity loss (red), and pathways for action targets
 354 (orange and blue). This simple model shows how drivers³ cause loss of area and integrity, in turn
 355 increasing risk of ecosystem collapse; declines in integrity can also lead to local collapse of an
 356 ecosystem in a given location, decreasing area. Action targets can act to 1) reduce drivers or their
 357 impacts (orange), thus indirectly halting loss (dashed line), and 2) restore area and/or integrity (blue)
 358 through restoration activities and by recovery after removal of threats. Examples of action targets
 359 are drawn from current post-2020 draft¹³, with the corresponding target in brackets (e.g. denoted by
 360 T1 for Target 1); those in italics are not currently included in action targets, notably ecosystem
 361 management to halt loss in integrity, and extraction of abiotic ecosystem elements, e.g. water.
 362 OECMs = other effective area-based conservation measures; and PA = protected areas.
 363

364
 365

366 Indicators to monitor progress towards an ecosystem goal

367

368 Criteria for meaningful indicators

369

An effective goals requires meaningful indicators to measure progress. We reviewed 25 indicators
 370 that have been proposed for the post-2020 goals⁹¹⁻⁹⁴ for their capacity to support an ecosystem goal
 371 (Table 1), focussing on monitoring ecosystem trends and state. Our review criteria included (see
 372 Table 1, and Supplementary Material S2 for methods and criteria):

373

373 1) Alignment with goal components and threats, conceptualised in our proposed theory of

374

change (see Figure 2). We aligned indicators with each goal component of collapse risk, area and

375 integrity, further dividing integrity composition, structure, function⁶⁰, and identified indicators
376 that measure drivers of biodiversity loss as a proxy for ecosystem loss. We also noted whether
377 they were suggested for multiple goals or goal components to identify diffuse indicators which
378 may lack specificity to particular goal components.

379 2) **Relevance and ease of interpretation.** We recorded whether, for a given location or ecosystem
380 type, indicator values can be interpreted in terms of proximity to ecosystem collapse without
381 further research. Such information is needed to interpret state or trends, to understand how
382 close given places or ecosystems are to ecologically meaningful thresholds, and to set
383 trajectories or thresholds that indicate goal success or failure.

384 3) **Fitness for purpose.** We examined how extensively indicators had been tested, if at all, for
385 performance with underlying changes in biodiversity, sensitivity to data bias, and accuracy.

386 4) **Data availability for applicability and use.** We assessed spatial and temporal coverage, and
387 whether indicators are bottom-up (where data are collated by national governments and then
388 provided to a central institution to calculate globally), or top-down (for example, calculated
389 globally from a database or model managed by a central institution).

390

391 **Availability and limitations of indicators**

392 While indicators exist for all goal components, most are limited in scope (being specific to a realm or
393 ecosystem type), and many have uncertain relevance or relationships to ecosystem collapse, making
394 values difficult to interpret in an ecologically meaningful way (Table 1). Thus, many of the proposed
395 indicators appear somewhat inadequate for understanding ecosystem change, particularly regarding
396 ecosystem integrity (Table 1), which could compromise capacity to report meaningfully on core goal
397 components. Only one indicator directly estimates **collapse risk**: the *Red List Index for Ecosystems*
398 (*RLIE*), an indicator comparable to the Red List Index for species²⁹. The RLIE is derived from Red List
399 of Ecosystems (RLE) data, and is currently available for a subset of regions or countries^{21,95}, with
400 ongoing expansion in data availability.

401

402 Several indicators measure change in **ecosystem area** but most capture trends in specific ecosystem
403 types, such as mangroves, wetlands, coral and forests (Table 1); the availability of area indicators
404 continues to expand to more ecosystem types, (e.g., mudflats¹⁴ and sea⁹⁶), and thus we did not
405 review all such indicators⁹¹⁻⁹³. The *Ecosystem Area Index* is the only indicator that can encompass all
406 ecosystem types, and can be disaggregated by ecosystem type or region as needed⁹⁵. As with the
407 RLIE, it is derived from RLE data, currently available for a subset of countries/regions^{21,95}. However,
408 the index can incorporate data from a range of sources, including national datasets⁹⁷, and other
409 ecosystem area metrics such as those for specific ecosystem types, e.g., for forests^{95,98}. Recent
410 advances in global-scale ecosystem mapping are reducing the still significant limitations in accuracy,
411 bias and data gaps⁹⁹⁻¹⁰¹. A key remaining gap between these data and their reliable use is an explicit
412 link between the features mapped and the ecosystems they are used to represent. For example,
413 *Tree Cover Loss*, based on the Global Forest Watch dataset⁶¹ does not distinguish between cover of
414 different forest ecosystem types such as lowland tropical rainforests, seasonally dry tropical forests
415 or anthropogenic plantations¹⁰². Growing agreement on classification schemes for ecosystems¹⁶
416 and improved organisation of biodiversity data suitable for validating ecosystem maps will resolve
417 this problem, and allow comprehensive and consistent maps of the world's ecosystems for
418 monitoring ecosystem area within the coming years and decade¹¹.

419

420 Indicators capturing changes in **ecosystem integrity** are increasingly available (Table 1), but most are
421 limited in scope and ecosystem relevance. The only indicator we reviewed that is applicable to all
422 ecosystem types and has a well understood relationship with collapse is the *Ecosystem Health Index*
423 (derived from RLE data), which aggregates ecosystem-specific indicators that are scaled relative to a
424 specified collapse threshold⁹⁵. Many integrity-associated indicators address composition (Table 1),
425 but can be sensitive to data biases¹⁰³⁻¹⁰⁶, lack validation or ground-truthing¹⁰⁷, and are difficult to

426 relate to collapse without knowledge of which species are declining, by how much, and their
427 functional impacts on ecosystems^{54,108}. Similarly, generic measures of landscape structure (e.g.,
428 patterns of connectivity or fragmentation, used in several indicators in Table 1) should be used
429 cautiously to infer ecosystem integrity or collapse risk without assessing impacts on processes such
430 as functional connectivity¹⁹. Moreover, several composition indicators rely on land-use change to
431 infer compositional change (e.g., the *Biodiversity Intactness Index*, BII, Table 1); while land-use
432 change is indeed a primary driver of biodiversity loss, such indicators omit impacts of other drivers
433 such as hunting and invasive species for ecosystems in which those processes may be important
434^{109,110}.

435

436 Multiple indicators based on **drivers of biodiversity loss** have been associated with ecosystem goal
437 components, some derived from cumulative threat maps, while others combine threat maps with
438 data such as structure or composition (Table 1). These indicators, which are available globally,
439 provide useful information on areas where ecosystems are under pressure⁷⁸. However, relating
440 them to ecosystem integrity or collapse risk is challenging, because the relationships between
441 drivers and ecosystem responses is non-linear, ecosystem-specific and complex⁵⁹. Composite
442 indicators (including those that combine pressure and state, such as ecosystem structure, e.g. *Forest*
443 *Landscape Integrity Index*, Table 1) can be difficult to interpret, due to compensatory effects
444 between their component sub-indicators¹¹¹. Most driver-based indicators also only include a subset
445 of direct drivers of biodiversity loss (typically land or sea use change or climate change), and thus
446 may miss important drivers of ecosystem change¹¹⁰.

447

448 **Recommendations for indicator selection**

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

452

- 453 1. **An indicator set is needed to support an ecosystem goal.** Our review reveals that many
454 indicators suitable for supporting an ecosystem goal are available, but none comprehensively
455 assesses all goal components of area, integrity and collapse risk. An indicator set is required, in
456 which the strengths and limitations of each indicator must be carefully scrutinized to ensure
457 appropriate and accurate assessments of progress towards all components of an ecosystem
458 goal.
- 459 2. **The indicators need to be specific to goal components, rather than correlated, redundant or**
460 **general, in order to provide clear evidence of goal progressing.** For example, many of the
461 composition-related indicators we reviewed have been associated with species goal
462 components, where they are likely to have greater relevance and alignment; e.g., the *Red List*
463 *Index* for species addresses species extinction risk (Table 1). Likewise, many of the driver-based
464 indicators (such as *Human Footprint* or *Marine Cumulative Human Impacts* indices, Table 1) may
465 be better aligned with specific action targets to reduce drivers of biodiversity loss than
466 ecosystem goal components. We recommend indicators are allocated to goal components only
467 where strongly relevant and aligned, to present the clearest picture of the ways in which
468 biodiversity in changing and goals are progressing. Evaluating indicator alignment with particular
469 goal and target components should form part of a comprehensive performance testing program
470 to ensure that out indicator set as a whole is adequate for monitoring progress across all goals.
- 471 3. **Relevance and alignment to the ecosystem goal are as important in indicator selection as is**
472 **current data availability.** Current data availability should be the secondary criterion for indicator
473 selection, provided there is a clear path to improving coverage and scientific rigour. Our review
474 showed that in many parts of the world and ecosystem types, there are trade-offs between
475
476

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 years¹⁴, while the Red List of Ecosystems measures change in area and integrity over multiple timeframes¹⁹. 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 synthesis¹¹². Given the current paucity of comprehensive global data for such indicators³, 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 so¹¹³⁻¹¹⁶. 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 requirements¹¹⁷. 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 needed¹¹⁹, 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 accessible¹²⁰, 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 indicators⁷⁶. Few of the indicators we reviewed can do this; instead most countries use their own indicators¹²¹, 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

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

542
543 An effective goal requires well-aligned indicators that capture the dimensions of ecosystem change
544 and provide reliable measures of all goal components – ecosystem area, integrity and collapse risk.
545 The indicator set should provide a concise and complementary set of measures of both loss and
546 recovery, clearly illustrating whether goals and targets are on track. The indicator sets initially
547 proposed for the post-2020 Framework were large, unfocused, and potentially unwieldy ^{91,92}, yet
548 inadequate regarding their specificity, ecosystem relevance, data availability and coverage (Table 1,
549 S1). A subsequent draft monitoring approach ⁹³ proposed headline indicators for measuring only
550 change in area of selected ecosystems, excluding indicators of integrity or collapse risk, and thus
551 failing to meet core needs of an effective ecosystem goal. The importance of measuring change in
552 ecosystem integrity and risk of collapse, in addition to area, means that the post-2020 monitoring
553 framework must be forward-looking, and embrace emerging indicators that are fit-for-purpose in
554 terms of ecosystem relevance, accuracy and specificity to goal components, rather than by
555 constrained by current data availability. The latter will increase, and rapidly, but settling on an
556 indicator set that is inadequate will hamper progress towards meeting goals, as well as measuring
557 them.

558
559 Science-based goals for ecosystems are central to the environmental agenda, from global to national
560 policy and action. Using ecosystems as building blocks allows scaling to local and national goals for
561 individual countries ¹²³, cities and businesses ¹²⁴, and disaggregation by ecosystem, biome or realm
562 for alignment with system-specific goals or policies, like the Ramsar Convention on Wetlands. The
563 Post-2020 Global Biodiversity Framework offers an opportunity to not only set aspirations for the
564 future of the planet, but also the actions that can achieve them. Previous goals including in the
565 Strategic Plan for Biodiversity 2011–2020 set a clear agenda at global, national and local levels,
566 enabling funding to flow with many benefits ^{5,7,11}. The Post-2020 goal and milestones can do the
567 same for ecosystems, provided it addresses the key elements required to sustain ecosystems, with
568 aligned action targets to achieve it and indicators to monitor successes and failures. Given the rate
569 of biodiversity loss globally ^{3,4}, the new Post-2020 goals provide a critical opportunity for world
570 leaders to set a clear agenda for sustaining all ecosystems into the future.

571

572 **Tables**

573 **Table 1: Summary of reviewed indicators**

574 Table 1. Summary of the reviewed indicators that have been proposed for an ecosystem goal or goal
575 components for the post-2020 Framework. Indicators were drawn from ecosystem components in
576 Goal A (specifically A.1 on ecosystem area and A.2 on integrity) in the 1) drafts of
577 the monitoring framework^{91,93,94*}, 2) the draft indicator review⁹²; and 3) sources such as the
578 Biodiversity Indicator Partnership (<https://www.bipindicators.net/>) that collate biodiversity
579 indicators. Note that the list of indicators reviewed is not exhaustive, particularly for ecosystem
580 area. Columns summarise information on: 1) alignment with goal components of collapse risk, area
581 and integrity, with integrity indicators further divided into composition, structure, function, and
582 indicators of drivers of biodiversity loss as a proxy for ecosystem loss or degradation (noting that
583 some indicators combine these, shown in brackets); 2) the number of goals or goal components the
584 indicator has been associated with (including multiple ecosystem components, species or genetic
585 goal components or goals related to Nature's contributions to people or benefit sharing); 3) whether
586 indicator values have been related to ecosystem collapse thresholds, for a given location or
587 ecosystem type, relating to relevance to the goals and ease of interpretation; 4) fitness-for-purpose:
588 whether indicators have undergone performance testing for behaviour with underlying changes in
589 biodiversity, sensitivity to data bias, and accuracy; 5) data availability for applicability and use,
590 including the realm of application (M=marine, F=freshwater, T=terrestrial) as a proxy for spatial
591 coverage, 6) current temporal coverage (length of the time series, and 7) whether reported annually,
592 and whether there is global coverage for at least one time point); 8) whether indicators are bottom-
593 up or top-down, where bottom-up indicators are those where data are collated by the national
594 government then provided to a central institution to calculate globally; top-down indicators include
595 those where empirical data collected locally are collated by a central institution, and where
596 modelled indicators are calculated by a central institution, and may be disaggregated by country;
597 some indicators are or can be both.*note MSA and LPI are listed in the updated November 2020
598 SBSTTA document⁹³, where it is unclear with which goal component it is associated.

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Table 1.

<i>Indicator</i>	<i>Goal Component</i>	<i>Number of goal components</i>	<i>Collapse related</i>	<i>Performance tested</i>	<i>Realm</i>	<i>Time-series length (y)</i>	<i>Annual</i>	<i>Global coverage for 1+ timepoints</i>	<i>Bottom-up or top-down</i>
<i>Risk of collapse</i>									
Red List Index of Ecosystems (Rowland et al. 2020a)	Risk of collapse	2	Y	Y	M,T,F	1	N	N	Both
<i>Ecosystem area</i>									
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
<i>Ecosystem integrity</i>									
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
<i>Drivers of biodiversity loss</i>									
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 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. <i>Similar terms: biological diversity</i>	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. <i>Similar terms: collapse risk</i>	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

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	predator-prey interactions, disturbance regimes (e.g. fire, drought). <i>Similar terms: ecosystem processes, ecological processes</i>	
Ecosystem integrity	The similarity of a given ecosystem’s <i>composition, structure</i> and <i>function</i> to its natural range of variation in these characteristics. <i>Similar terms: intactness</i>	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 <i>Similar terms: managed ecosystems, anthromes</i>	2,9-11
Goal	Broad statement that describes a desired outcome or end state. <i>Similar terms: fundamental objective, aspiration</i>	9,12
Target	Means for achieving a goal; actions to operationalise or deliver the required biodiversity improvements <i>Similar terms: action target(s), sub-target, means objective</i>	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. <i>Similar terms: element</i>	14
Indicator	Variable that represents another, often unobservable, variable of interest. <i>Similar terms: metric</i>	15
Indicator relevance	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

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	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

S2 Supplementary Methods: Indicator review

2.1 Criteria and assessment

We reviewed 25 indicators that have been proposed for the post-2020 goals²⁰⁻²³ 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 review²¹; 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 review²¹. 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 review²¹) 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, taxonomic groups, and whether globally available);
 - 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.

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- 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 indicators²⁷, 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 report²⁸.

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Table S2.2. Assessment criteria for Table S2.1	
Assessment criteria	Assessment guidelines
<i>Ecosystem relevance</i>	
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 biodiversity 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 require 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 aggregated 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 acknowledged; 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 Intergovernmental 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 performance 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)