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From Science to Evidence How Biodiversity Indicators Can Be Used for Effective Marine Conservation Policy and Management

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1 **From science to evidence – how biodiversity indicators can be used for effective marine**
2 **conservation policy and management**

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31 **Running title:** Marine biodiversity indicators for effective conservation

32 **Keywords:** ecosystem approach, assessment, monitoring, baselines, thresholds, policy
33 communication, cumulative effects

34 **Abstract**

35 Indicators are effective tools for summarising and communicating key aspects of ecosystem
36 state and have a long record of use in marine pollution and fisheries management. The
37 application of biodiversity indicators to assess the status of species, habitats, and functional
38 diversity in marine conservation and policy, however, is still developing and multiple
39 indicator roles and features are emerging. For example, some operational biodiversity
40 indicators trigger management action when a threshold is reached, while others play an

41 interpretive, or surveillance, role in informing management. Links between biodiversity
42 indicators and the pressures affecting them are frequently unclear as links can be obscured
43 by environmental change, data limitations, food web dynamics, or the cumulative effects of
44 multiple pressures. In practice, the application of biodiversity indicators to meet marine
45 conservation policy and management demands is developing rapidly in the management
46 realm, with a lag before academic publication detailing indicator development. Making best
47 use of biodiversity indicators depends on sharing and synthesising cutting-edge knowledge
48 and experience. Using lessons learned from the application of biodiversity indicators in
49 policy and management from around the globe, we define the concept of 'biodiversity
50 indicators', explore barriers to their use and potential solutions, and outline strategies for
51 their effective communication to decision-makers.

52

53 **Introduction**

54 Threats to marine biodiversity, from human activities such as fishing, shipping, coastal
55 development, and energy production and from indirect pressures, like climate change, are
56 increasing (Halpern et al., 2015), with only 13% of the world ocean still considered
57 unimpacted by humans, or 'wild' (Jones et al., 2018). The loss of marine biodiversity impacts
58 the resilience of ecosystems and the ability to maintain essential ecosystem services that
59 support human life, such as food provision and water quality maintenance (Worm et al.,
60 2006). The vulnerable state of global marine ecosystems and the need to sustainably
61 monitor, assess, and manage habitats and species is increasingly recognised (Addison et al.,
62 2017). Consequently, the assessment of the state of marine biodiversity, with associated
63 biodiversity management and conservation measures, is now explicitly articulated in
64 national (Department of Environmental Affairs and Tourism, 2004; Natural Resource
65 Management Ministerial Council, 2010; Defra, 2018), regional (Cartagena Convention, 1983;
66 European Commission, 2008b; 2011), and international (United Nations, 2010; United
67 Nations General Assembly, 2015) legislative mechanisms. These mechanisms address both
68 marine policy (the setting of regulation through legislation) and management
69 (implementation of management plans, monitoring, evaluation and reporting on the status
70 of the marine environment).

71 'Biodiversity' is "the variability among living organisms, from all sources, including, *inter*
72 *alia*, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which
73 they are part; this includes diversity within species, between species and of ecosystems"
74 (Convention on Biological Diversity (CBD); United Nations, 1992). In other words,
75 'biodiversity' refers broadly to all species and habitats in an ecosystem, rather than simply
76 the number of taxa. This definition is broad, encompassing all marine and coastal species
77 and habitats. It is impossible to monitor and assess the state of all aspects of marine
78 biodiversity, so the complexity of biodiversity is typically reduced in dimension by using
79 indicators to summarise its key aspects. Indicators are therefore frequently used in marine
80 policy and management to assess and communicate change in ecosystem state. They are
81 the primary tool for assessing progress towards the CBD Aichi targets, which aim to halt
82 global biodiversity decline (Balmford et al., 2005; Tittensor et al., 2014; United Nations

83 General Assembly, 2015). Indicators as a concept have been used for decades in marine
84 fisheries management (e.g., commercial fish stock management in South Africa and Europe
85 (Plagányi et al., 2007; ICES, 2018), ecosystem-based fisheries management in Australia, New
86 Zealand, the U.S.A., and Canada (Sainsbury et al., 2000; Link et al., 2002; Methratta and Link,
87 2006; Fu et al., 2015), in marine pollution regulation (e.g., assessment and management of
88 marine sediment pollution in the North Sea (OSPAR, 2017k), and pollution assessment of
89 fish, crustaceans, and molluscs in the Baltic Sea (HELCOM, 2018)).

90 Unlike more established indicators in marine fisheries and pollution regulation, which are
91 measurable against a clear objective or target, techniques to develop indicators and targets
92 and to assess the status of marine biodiversity to inform biodiversity management more
93 widely, however, are new but rapidly developing (e.g. Tam et al., 2017). In Europe, for
94 example, the Marine Strategy Framework Directive (MSFD) uses biodiversity indicators to
95 assess the state of marine habitats and species, with the overarching objective of achieving
96 ‘Good Environmental Status’ (GES) (European Commission, 2008b). Similarly in South Africa,
97 the National Biodiversity Strategy and Action Plan aims to achieve ‘Good Ecological
98 Condition’ which refers to ecosystems that are intact or largely intact with minimal
99 modification from a natural condition (Department of Environmental Affairs, 2015). In the
100 U.S., implementing the ecosystem-based approach to management has moved to the
101 forefront of efforts, including the development of quantitative indicators and criteria that
102 can be used to assess overall ecosystem status (Leslie and McLeod, 2007). Where ecological
103 data are lacking, such as in South Africa, expert judgement is often used to set targets for
104 marine biodiversity indicators (e.g. Driver et al., 2011; Department of Environmental Affairs,
105 2015). Under the MSFD, while some biodiversity indicators already have agreed quantitative
106 targets for individual regions (Defra, 2012; HELCOM, 2018), targets for other regions or
107 indicators are still in development. Approaches to indicator development and target setting
108 for effective management require not only a clear understanding of the system in question,
109 which might need substantial amounts of data in some cases, but also explicit policy goals or
110 objectives. These attributes may inhibit indicator development and policy uptake.

111 In June 2018, international developers and users of marine biodiversity indicators
112 participated in a symposium and focus group entitled “From science to evidence –
113 innovative uses of biodiversity indicators for effective marine policy and conservation” as
114 part of the 5th International Marine Conservation Congress (IMCC5) in Kuching, Malaysia.
115 The mission of the symposium and focus group was to form a community of practice for
116 both users and developers of biodiversity indicators for marine policy and conservation, and
117 to provide a forum to share successes and failures in developing and applying these
118 indicators. Themes emerged which are common across geographic regions and political
119 scales. This paper uses lessons learned from the application of biodiversity indicators in
120 policy from around the globe to define the concept of biodiversity indicators, explore and
121 discuss barriers and solutions to their use, and outline strategies for their effective
122 communication to policy-makers.

123 **Concept, use, and suitability of biodiversity indicators**

124 The wide definition of the terms 'indicator' and 'biodiversity', as well as their broad
125 applicability, can lead to confusion regarding the function of a biodiversity indicator. For
126 instance, indicators can be defined simply as a "quantitative or qualitative variable that
127 provides reliable means to measure a particular phenomenon or attribute" (USAID, 2009)
128 or, using a process-oriented definition, as a "quantitative or qualitative factor or variable
129 that provides a simple and reliable means to measure achievement, to reflect changes
130 connected to an intervention, or to help assess the performance of a development actor"
131 (OECD, 2002). In a marine context, indicators have been defined as a tool "to monitor and
132 assess the state of the marine environment and to manage human activities having an
133 impact upon it" (European Commission, 2008b). Under the Convention of Biological
134 Diversity (CBD), indicators are defined as tools "for assessing progress towards, and
135 communicating the 2010s target at the global level" (United Nations Environment
136 Programme, 2004), which hereby further extends their application and allows a broader use
137 of terminology.

138 A bibliographic analysis of > 2500 abstracts queried from the Web of Science database a
139 difference in treatment of the term 'biodiversity indicator' between academic scientists,
140 marine policy-makers and managers (Fig 1). In publications on marine systems, 'ecosystem
141 indicator' is used more commonly and synonymously with 'biodiversity indicator', though
142 the use of the 'biodiversity indicator' is increasing (see Fig. 1a). Overall, we found that
143 depending on the purpose, region, or policy context, indicator terminologies can differ
144 despite representing similar ecosystem/biodiversity components. Nevertheless, biodiversity
145 indicators are still often represented by conventional diversity indices such as species
146 richness or evenness. These indices can be highly useful for summarizing and assessing
147 community structures such as biogenic reefs or infaunal communities and linking them to
148 anthropogenic pressures such as trawling (Cook et al., 2013; Fariñas-Franco et al., 2014; van
149 Loon et al., 2018). To provide sufficient information on ecosystem dynamics and processes
150 for sound policy and management, however, other components such as biological trait
151 diversity and ecosystem functioning can be similarly useful (Díaz and Cabido, 2001; Juan et
152 al., 2007; Bremner, 2008; Pacheco et al., 2011).

153 The implementation of regional and international legislative frameworks has triggered a big
154 rise in developing biodiversity indicators to determine the state of the ecosystem and its
155 components in the last two decades. Publications on 'ecological', 'ecosystem', or
156 'biodiversity' indicators started to increase in the early 1990s after the United Nations
157 Conference on Environment and Development with the resulting ratification of the CBD (Fig.
158 1a) (United Nations, 1992) and the publication of the Organization for Economic Co-
159 operation and Development (OECD) core set of indicators for environmental performance
160 reviews (OECD, 1993). Publications addressing marine systems, however, started much
161 later, in the mid-2000s, and so represent only 18% of all articles on biodiversity indicators,
162 covering predominantly the temperate northern Atlantic ecoregion (see Fig. 1b).

163 While the term 'biodiversity' may refer strictly to the diversity of biological components in
164 an ecosystem, 'biodiversity' is increasingly used to reflect a much broader ecosystem view.
165 This broader definition includes trophic interactions, network structure and system stability

166 or resilience (e.g. Samhuri et al., 2009; Dakos, 2011), which is in line with the Convention
167 on Biodiversity's definition of 'biodiversity', above, and is often used by applied scientists,
168 policy-makers, and managers. It is this second definition of 'biodiversity' that is used
169 throughout this paper, due to its frequency of use in conservation. While we do not want to
170 ignite a discussion on terminology superiority, we want to highlight the importance of
171 understanding biodiversity in a wider context and propose a more flexible approach to the
172 term 'biodiversity indicator' that includes multiple concepts such as ecosystem structure
173 and functioning (as outlined by the Essential Biodiversity Variables for policy; Pereira et al.,
174 2013).

175 In recent decades, a variety of approaches for the use of indicators in the marine
176 environment have emerged, particularly in the temperate northern Atlantic ecoregion,
177 which is largely triggered by the implementation of regional and international legislative
178 frameworks (Fig. 1). Table 1 illustrates some examples of the applied versatility of
179 biodiversity indicators, providing a wide-range of evidence types, at different ecological and
180 spatial scales, for the assessment and management of marine biodiversity within the
181 context of the policy questions they aim to address.

182 Despite the wide range of applications of biodiversity indicators observed during recent
183 decades, specific selection criteria have been commonly accepted within the scientific
184 community to determine indicator suitability for operational use. These include
185 measurability, scientific basis, interpretability, and ease of communication, but also
186 sensitivity and responsiveness to environmental changes, specificity, robustness with well-
187 known pressure-state relationships, and links to identified targets and thresholds (e.g.
188 OECD, 1993; FAO, 1997; Rice and Rochet, 2005; Heink and Kowarik, 2010; Kershner et al.,
189 2011; Queirós et al., 2016; Otto et al., 2018a). Biodiversity indicators that address policy and
190 management goals are likely to be most effective if the relevant stakeholders and decision-
191 makers also perceive them to be credible, salient and legitimate (Cash et al., 2003; van
192 Oudenhoven et al., 2018). Linking indicators to environmental conditions and ideally to
193 management measures requires a good understanding of indicator responses to pressures
194 and a sound testing of indicator performance, which is often lacking for biodiversity
195 indicators (Rossberg et al., 2017). Thus, new modelling approaches and decision support
196 tools are emerging to tackle the performance evaluation of indicators for assessing the
197 health status of marine ecosystem and biodiversity components (Hayes et al., 2015; Lynam
198 et al., 2016; Otto et al., 2018a; Shin et al., 2018) (see also section *Linking biodiversity*
199 *indicators to ecosystem change*). To complement assessments of state, additional pressure
200 indicators can be useful, particularly to measure the impacts of human activities on the
201 system when there can be a long time-lag before natural processes can be expected to
202 respond (Rossberg et al., 2017).

203 Indicators that lack a clear link to a defined pressure however can still contribute effectively
204 to the assessment and management of biodiversity. These indicators without clear links to
205 defined pressures, known as 'surveillance indicators' (Shephard et al., 2015), may not be
206 able to be assessed against quantitative thresholds, but can still provide contextual
207 information on either wider ecosystem impacts of pressures or underlying environmental
208 change (Bedford et al., 2018). Critically, indicators used in a 'surveillance' context should still

209 increase the knowledge base from which to make management decisions. For example, a
210 suite of 'Essential Ocean Variables' for biodiversity and ecosystem change has been
211 identified by Miloslavich et al. (2018) to effectively reduce the complexity of ecosystem
212 processes for a summary of ecosystem state. Although not linked to specific defined
213 pressures, the impacts of both direct anthropogenic pressures and climate change on these
214 ecosystem processes can be monitored and assessed, providing holistic surveillance
215 information to support management.

216

217 **Biodiversity indicators in policy and management: needs, barriers, and solutions**

218 Indicator development is challenged by the need to establish associated targets, political
219 acceptance, and evaluation of confidence to support widespread use for management of
220 biodiversity (Table 2).

221 *Biodiversity indicators linked to policy and management*

222 Often, scientists develop biodiversity indicators in academia, usually to address a scientific
223 problem but also to assess the ecosystem status within the context of specific policies, and
224 then publish their results in the scientific literature. A recent review by Bal et al. (2018)
225 showed that indicators (in this case, those based on species traits) developed in academia
226 and reported in the scientific literature typically fail to address decision-making
227 requirements for biodiversity management, with only 21% of studies detailing how
228 indicators explicitly address policy objectives. This review clearly demonstrates the broad
229 use of the term 'indicator', but it also shows that the academic approach to indicator
230 development is often driven by scientific questions rather than a response to policy needs,
231 or if policy-focused takes place outside the policy process. In such cases indicators are
232 frequently not formally incorporated into the assessment of management objectives and
233 targets (Bal et al., 2018). Regardless of the scientific soundness of an indicator, or even the
234 appropriateness for a specific policy, the lack of involvement of end-users (e.g., marine
235 managers, policy-makers, and stakeholders) during the development of indicators may
236 result in unsuccessful implementation of the outputs or even the application and use of the
237 indicator itself.

238 A solution resulting in fit-for-purpose biodiversity indicators is to co-produce indicators, with
239 scientists providing the scientific input and decision-makers providing the policy steer
240 (Lemos and Morehouse, 2005; Hayes et al., 2015; Bolman et al., 2018; Cvitanovic and
241 Hobday, 2018; de Juan et al., 2018). Co-production spans the science-policy interface and is
242 an iterative process, with each party relying on the other's experience and expertise to gain
243 a deeper understanding of the current science and policy landscapes, opportunities, and
244 limitations (Lemos and Morehouse, 2005). The co-production of biodiversity indicators has
245 resulted in their successful use in marine policy and management (e.g., in Australia and
246 Europe; Pocklington et al., 2012; OSPAR, 2017d). For example, biodiversity indicators
247 developed for the 2017 OSPAR Intermediate Assessment followed this process (OSPAR,
248 2017d). The indicators were developed by scientists with significant and consistent input
249 from policy-makers to ensure the indicators fulfil policy obligations. As a result, the regional

250 biodiversity assessments can be used by EU member states for the fulfilment of the MSFD
251 (OSPAR, 2017d).

252 *Data requirements for biodiversity indicators*

253 A basic requirement when developing a biodiversity indicator is an understanding of the
254 types of data available and a critical evaluation of the temporal and spatial scales that are
255 appropriate for the ecological processes being assessed and the pressures on the marine
256 ecosystem. Large-scale monitoring programmes collecting time-series data are very rare,
257 particularly in offshore areas, mainly due to the costs of data collection (Koslow and
258 Couture, 2013). Marine monitoring needs to be well governed, cost-effective, organised,
259 transparent, open, designed on a scientific basis, and “fit for purpose” (Turrell, 2018).
260 Furthermore, data collection for biodiversity indicators ideally should be tailored to the
261 policy questions the indicator is trying to address, for example by developing relevant
262 sampling strategies and power analyses to establish the level of sampling effort required to
263 detect community change at a particular scale.

264 However, data-intensive indicators, even if they are high in confidence and accuracy, are not
265 always practical for large scale biodiversity assessments, such as required for management
266 of regional marine environments, especially for those ecosystem components for which
267 monitoring is expensive. This lack of practicality is a particular challenge for evaluating
268 ecological processes or distributional patterns of habitats or species which require
269 monitoring surveys over a large spatial area as compared to verifying the presence of, for
270 example, a sensitive species in an MPA (Barrio Froján, 2016).

271 The costs of data collection can pose a barrier to indicator development, particularly for low
272 income countries, which contain some of the world’s most diverse species and habitats
273 (Tittensor et al., 2010; Ramírez et al., 2017), but are generally poorly monitored due to
274 economic challenges and lack of infrastructure and scientific experts (Danielsen et al., 2000).
275 While high-income countries tend to pose more threats to marine ecosystems (Beck et al.,
276 2011; Thurstan et al., 2013; Halpern et al., 2015; Fariñas-Franco et al., 2018), a lack of
277 fundamental biodiversity research, capacity and coordination of information in low-income
278 countries makes them highly vulnerable, particularly to climate change (Bellard et al., 2014).
279 Many marine and coastal ecosystems are highly diverse, yet there is a lack of fundamental
280 biodiversity research required to understand processes and species distributions in the
281 marine environment (Griffiths et al., 2010). This lack of investment also extends to the
282 capacity and coordination of marine biodiversity information within and outside of the
283 scientific community which can prevent its use within decision-making (Atkinson et al., 2016).

284 A solution to overcome data shortages or limitations to access, involves a pragmatic
285 approach to indicator construction, together with good use of existing ecological datasets
286 for the relatively new purpose of informing biodiversity indicators for policy and
287 management. Data limitations often can be overcome by constructing indicators with the
288 flexibility to use data from multiple sources (e.g. OSPAR, 2017g; h; b; a) or by using a risk
289 based approach to identify areas where targeted, more intensive monitoring should be
290 concentrated (Elliott et al., 2018).

291 Additional solutions include setting clear monitoring objectives and clearly articulating the
292 decision context that defines the temporal and spatial requirements for management
293 decisions. This will ensure that the data required to inform biodiversity indicators are
294 collected in a cost efficient manner (Turrell, 2018). In cases where extensive monitoring data
295 are needed but not practical to collect, the use of alternative data sources, such as Earth
296 observation, rather than data solely collected via *in situ* monitoring, can facilitate regional
297 biodiversity assessments (Bean et al., 2017; Strong and Elliott, 2017; Pettorelli et al., 2018).
298 For example, models combining physical, geological and biological parameters are currently
299 being used to evaluate the extent and distribution of benthic habitat types at regional scale
300 (OSPAR, 2017b). Furthermore, modelled species distributions can provide data to develop
301 indicators such as the presence/absence of species and biotopes based on their
302 environmental preferences for areas where survey data are missing or limited in extent
303 (Elith et al., 2006; Butchart et al., 2010). They can also help in identifying impact hot spots
304 and evaluating management actions (Guisan et al., 2013).

305 South African practice presents a possible solution to the challenges of monitoring marine
306 biodiversity (Atkinson et al., 2016). Broad scale assessments of the state of South African
307 marine ecosystems have been based on the Ocean Health Index method (Halpern et al.,
308 2008; Halpern et al., 2009) which uses cumulative human impacts in the absence of
309 spatially-extensive biodiversity monitoring data. This method can enable low income
310 countries and other regions with limited biodiversity data to arrive at an indicative national
311 scale assessment of biodiversity. The Ocean Health Index assumes that areas of high human
312 pressure are in poor ecological condition. While useful, the method may not capture fine-
313 scale natural variability, and can fail to identify areas of high resilience as well as the
314 presence of unique or vulnerable ecosystems. Nevertheless, South African policy-makers
315 have so far accepted this method of assessment, acknowledging the challenges and
316 limitations to assessing the condition of the marine environment for the entire exclusive
317 economic zone of South Africa using impact, or pressure, information in the absence of
318 biodiversity data (Driver et al., 2011; Department of Environmental Affairs, 2015). To
319 evaluate the outcomes of this practice, these methods should be verified with empirical
320 evidence at varying scales using ecological monitoring data where available (Sink et al.,
321 2012).

322 Involving the public in monitoring may be another cost-effective solution to the labour-
323 intensive data collection required to inform biodiversity indicators (Thiel et al., 2014;
324 Freiwald et al., 2018). Limitations on data collection are common, such as lack of
325 standardization and spatio-temporal coverage, particularly in geographical areas which are
326 greatly impacted but less accessible to the public. Despite these challenges, there are some
327 notable regional and global citizen science programmes that are increasing data coverage
328 for some aspects of the marine environment for use in policy and management such as:
329 collection of species data by volunteer scuba divers around the coast of Britain and Ireland
330 (<http://seasearch.org.uk/>); Reef Check and Reef Life Survey, which are global programmes
331 that monitor the health of temperate and tropical reefs (Hodgson, 2000; Stuart-Smith et al.,
332 2017); public monitoring of European seabirds (ICES, 2017); and a series of national citizen
333 science programmes for temperate rocky reefs in California (Gillett et al., 2012), subtidal

334 habitats in the UK (Bull et al., 2013), and marine biodiversity health in northern Italy
335 (Goffredo et al., 2010).

336

337 *Linking biodiversity indicators to ecosystem change*

338 Developing biodiversity indicators that are responsive to a defined anthropogenic pressure
339 or linking biodiversity indicator change to a single manageable pressure is often desired by
340 policy-makers but is scientifically challenging to achieve. Micheli et al. (2013) found that
341 ~60-99% of the territorial waters of EU member states were heavily impacted as a result of
342 multiple pressures, rather than one individual stressor. These multiple pressures, which
343 include climate change, can have cumulative and synergistic effects on biodiversity
344 components, reflected by indicator state (Côté et al., 2016). For example, warming
345 temperatures have been shown to interact with fishing pressure on temperate fish stocks
346 (Kirby et al., 2009) and with multiple stressors including pathogens on coral reef ecosystems
347 (Ban et al., 2014). Furthermore, biodiversity components are fundamentally linked through
348 trophic interactions, affecting biodiversity indicators. Torres et al. (2017) showed that no
349 pressure-state relationships for fish indicators in the Central Baltic Sea could be found
350 unless predator-prey feedback or density dependence was accounted for. These complex
351 and interacting drivers obscure the interpretation of change in biodiversity indicators. For
352 example, the limited understanding of the effects of environmental drivers on the variation
353 of Porifera and Anthozoa assemblages across the North of Scotland and Celtic Sea is
354 hindering the ability to accurately measure ecological responses of benthic rocky reef
355 indicators to direct anthropogenic pressures (Haynes et al., 2014).

356

357 Multiple biodiversity indicators may respond to the same anthropogenic pressure.
358 Integrating information from a range of biodiversity indicators is a solution that can help to
359 provide an overall assessment of the ecosystem (Elliott et al., 2018) and clarify the main
360 drivers of change affecting a system (Smith et al., 2016). Although significant development is
361 often required, ecosystem modelling can provide a comprehensive means to detect change
362 in multiple biodiversity components and identify the important pathways by which impacts
363 from pressures can cascade through an ecosystem (Lynam et al., 2016). Thus embedding
364 indicators within a model framework can demonstrate key pressure-state linkages (Fulton et
365 al., 2005; Shin et al., 2018), although it must be noted that data quality may impact model
366 performance. Such models can then be used to examine the effects on biodiversity
367 indicators of potential management measures or climate change through scenario testing
368 (e.g. Mackinson et al., 2018; Queirós et al., 2018).

369 Another factor to consider when linking indicators to pressures is the non-linearity in marine
370 ecological systems. For some marine ecosystems abrupt community shifts have been
371 reported (e.g. Hare and Mantua, 2000; Frank et al., 2005) that can only be explained by non-
372 linear state responses to abrupt changes in pressures (Scheffer and Carpenter, 2003). Non-
373 stationarity, i.e. spatio-temporal change in the state-pressure relationship (Hunsicker et al.,
374 2016), impedes the development of robust indicators that behave in a consistent and

375 predictable way. A new tool, the R package 'INDperform' (Otto et al., 2018b) accounts for
376 these dynamics and allows the user to explicitly test for non-linear and non-additive
377 indicator-pressure relationships. The package builds on a quantitative framework for
378 selecting and validating the performance of indicators tailored to specific management
379 needs (Otto et al., 2018a) and offers additional functions to quantify the robustness of these
380 models, identify temporal indicator changes, test for indicator redundancy, and visualize
381 performances. While single indicator-pressure models, such as offered in INDperform, can
382 easily be applied to any number of indicators and pressures they cannot account for
383 synergistic or counteracting effects of multiple pressures or estimate trade-offs between
384 individual indicators. For this, more complex modelling tools are required, which in turn can
385 be difficult to communicate, may require many assumptions, and take longer to build
386 (Hyder et al., 2015).

387 *Using biodiversity indicators to measure progress towards policy goals*

388 Policy goals are often definitive, moving beyond broad-scale visions, and instead specifying a
389 target condition that needs to be reached to meet the goal. An example of this is “...the
390 abundance/extent, distribution and condition of marine species and habitats are in line with
391 prevailing environmental conditions” from Descriptor 1 Biological Diversity of the EU’s
392 Marine Strategy Framework Directive (2008/56/EC). Such an approach has long been used
393 to assess indicators of environmental quality, including concentration of contaminants in
394 water bodies (e.g. mercury, PCBs, nitrates) and of harmful gases in the air (e.g. carbon
395 monoxide, sulphur dioxide). For these indicators, laboratory tests establish safe limits which
396 can then be used to define desirable target levels for environmental conditions (European
397 Commission, 2008a). Setting quantitative targets that define a good or favourable condition
398 for biodiversity indicators, however, is much more challenging, as our understanding of
399 ecological processes influencing the recovery of species or habitats and the associated
400 ecosystems functions is more limited. Consequently, many biodiversity indicators currently
401 still lack associated defined targets (Teixeira et al., 2016).

402 The most common first step to defining targets for biodiversity indicators is to establish a
403 baseline against which future change in condition can be measured (Fig. 2). The most robust
404 approach to baseline setting is to first establish a ‘reference condition’ (Borja et al., 2012;
405 Greenstreet et al., 2012; OSPAR, 2012; Probst et al., 2013) or “natural range” (Rossberg et
406 al., 2017) which will enable the full effects and changes caused by anthropogenic pressures
407 to be evaluated (van Loon et al., 2018). Reference conditions can be derived from
408 information on species and habitats from areas where human pressure is considered
409 negligible or non-existent but that information must be shown to be applicable to other
410 areas (Borja and Tunberg, 2011). Reference conditions for marine biodiversity indicators,
411 however, can be difficult to identify as areas of the marine environment that have been
412 unimpacted by human pressures are increasingly scarce (Jones et al., 2018). Furthermore,
413 time-series for most indicators are not long enough to include a time when human impacts
414 were absent or negligible (Butchart et al., 2010; Dornelas et al., 2018). Unimpacted
415 conditions are particularly difficult to identify for mobile species such as birds, marine
416 mammals, fish and turtles because they move between impacted and unimpacted areas

417 (OSPAR, 2012). Modelling, however, can be used to predict reference conditions, based on
418 knowledge of human pressures and their impact on the state of the indicator (Borja et al.,
419 2012; Rossberg et al., 2017). Once reference conditions are established, targets can then be
420 set that are within a specified distance from them (OSPAR, 2012), where the acceptable
421 target range for this distance is dependent on the rate of recovery of the state in question
422 (Rossberg et al., 2017).

423 In the absence of empirical or modelled reference conditions, recent assessments of birds,
424 seals, and fish in the NE Atlantic have used the start of time-series to define baselines for
425 indicators (Fig. 2) (OSPAR, 2017i; j; c; f). The risk with this approach is that the baseline is set
426 at a value that represents a degraded condition which may or may not be within the
427 acceptable target range of the ecosystem state. If targets are then set close to the baseline
428 condition, this may jeopardise any improvement or recovery beyond that observed recently.
429 This concept is referred to as Shifting Baseline Syndrome (Pauly, 1995; Pinnegar and
430 Engelhard, 2008; Papworth et al., 2009) and can result in targets lacking in ambition
431 (Plummeridge and Roberts, 2017) or worse, 'locking in loss' (Maron et al., 2015). Objective
432 baselines and targets can be set once we improve our understanding of pressure-state
433 relationships and the influence of the environment on them. Duarte et al. (2009) caution
434 that it might not be possible for an indicator to return to a historic state because of
435 fundamental alterations to the ecosystem caused by long-term or chronic effects of
436 pressures or similarly changes in environmental conditions (Möllmann et al., 2009). In such
437 cases, baselines that denote reference conditions would need to be set at a theoretical
438 natural state, which could be achieved in the future if all current human impacts were
439 removed (Rossberg et al., 2017). If the policy goal is sustainable use, the indicator targets
440 should allow components of the ecosystem to achieve the theoretical natural state in a
441 societally acceptable period of time (such as within a human generation) if all current
442 human activities were to cease (Rossberg et al., 2017). To ensure the highest probability of
443 such a recovery, impacts by human activities on structure, productivity, function and
444 biological diversity of the ecosystem should be minimized (Garcia, 2003).

445 Where indicators are required to measure progress towards broad-level policy goals and
446 visions, trend-based targets provide an appropriate solution. Trend-based assessment
447 approaches are relatively simple to apply and communicate and are useful to inform on the
448 progress of management in helping to recover degraded habitats or ecosystems or depleted
449 species populations. For example, the Convention on Biological Diversity Aichi Target 12 is a
450 broad-level vision stating that "By 2020 the extinction of known threatened species has
451 been prevented and their conservation status, particularly of those most in decline, has
452 been improved and sustained" and is used to assess progress towards Strategic Goal C "to
453 improve the status of biodiversity by safeguarding ecosystems, species and genetic
454 diversity" (United Nations, 2010). Measuring progress towards this goal, however, does not
455 require indicators to reach a specified endpoint or target point, but instead assessment is
456 based on indicator trend.

457 An additional barrier to setting targets for biodiversity indicators is that political resistance
458 can be generated by a lack of agreement on the level of ambition by different parties, for

459 example, across different countries sharing the same sea area. This can stem from a lack of
460 understanding of what the indicator values signify and/or uncertainty around the
461 implications or consequences of missing a target. Failure to meet targets may carry
462 reputational risks or could lead to costly remedial measures such as changes in regulation or
463 management, which may create resistance to targets from industry. Some of these political
464 sensitivities can be alleviated through scientists working closely with policy leads to co-
465 produce SMART targets that make the most of the available evidence (Cvitanovic and
466 Hobday, 2018). For international targets, fora involving national representatives from
467 science and policy can help to achieve international consensus and ensure targets are
468 adopted by countries rather than imposed upon them (Heritier, 2002; OSPAR, 2017i; j; c; f).

469

470 Decision triggers are less contentious than firm targets and can provide a useful link from
471 monitoring data to management decisions. Decision triggers are becoming an appealing tool
472 for conservation managers to help support decision-making by providing clarity about when
473 and how to act; improving transparency of organizational decisions; removing the need for
474 guess work; guarding against the paralysing effects of uncertainty; and preventing negative
475 conservation outcomes (Addison et al., 2016). Decision triggers represent a point or zone in
476 the status of a monitored variable indicating when management intervention is required to
477 address undesirable ecosystem changes (Cook et al., 2016). Decision triggers can be set
478 using a number of methods, depending on the availability of scientific data and expertise,
479 the number of objectives for management and the resources available (Bie et al., 2018).

480

481 **Strategies for communicating biodiversity indicators to policy**

482 Effective communication of biodiversity indicators and assessments is integral to their
483 uptake by policy-makers and managers. Critically, the target audience must be identified so
484 indicator communication can be tailored appropriately. The group 'policy-makers' is often
485 used as a generic term for decision-makers at multiple levels, including local councillors,
486 environmental managers, civil servants, congress people, Members of Parliament (MPs),
487 and ministers, among others. These subgroups use biodiversity indicators in different ways
488 to make decisions and therefore require information in different formats with varying levels
489 of associated detail and specificity.

490 Regardless of the audience, biodiversity indicator communication must be clear, transparent
491 and easy to understand to support their legitimate use in decision-making. There are different
492 ways to present indicator results and assessments, each of which involves trade-offs
493 between the complexity of biodiversity information and the simplicity of the product
494 required for clear communication (Fig 3). The simplest methods of indicator communication
495 use traffic lights summaries (United Kingdom Marine Monitoring and Assessment Strategy,
496 2010; Driver et al., 2011; Karnauskas et al., 2017) or trend lines (WWF, 2016), which are
497 simple visual illustrations of indicator change and are easily understood by non-scientists.
498 These approaches often include composite indicators that are constructed by integrating
499 numerous indicators to provide a single value (e.g. the Ocean Health Index, 2017) or trend

500 (e.g. the Living Planet Index; WWF and ZSL, 2016). These products can deliver a simple but
501 powerful, attention-grabbing message to a wide and diverse policy- and decision-making
502 audience. However, the simplicity of these approaches, and lack of associated written
503 narrative, also brings a risk that the audience may misinterpret the message conveyed by
504 the indicator results. It is therefore the responsibility of scientists and managers to
505 communicate results unambiguously, in a way that effectively takes account of any
506 uncertainty in the results (Fischhoff and Davis, 2014).

507 Conversely, more complex communication methods such as summary report cards (e.g.
508 Carey et al., 2017; European Environment Agency, 2017; Marine Climate Change Impacts
509 Partnership, 2017) and narrative reports (e.g. Conservation of Arctic Flora and Fauna, 2017;
510 Evans et al., 2017; OSPAR, 2017d) can provide a strong written narrative and contextual
511 information, reducing the likelihood of misinterpretation by policy-makers. Protocol
512 documents (e.g. Ehler and Douvere, 2009) are even more detailed, acting as a 'user guide'
513 for indicators.

514 For all policy audiences, confidence in indicator assessments must also be clearly
515 communicated. Addison et al. (2017) suggest that confidence in indicator assessments can
516 be communicated through a variety of ways. For example, relatively simple categorical
517 estimates of confidence in scientific robustness and/or supporting data informing indicator
518 assessments can be applied. Some examples from Australia and Europe include reporting
519 simple 'high, medium, and low' confidence designations (e.g., Carey et al., 2017; OSPAR,
520 2017e), measuring comparability with previous assessments (e.g., designating current
521 indicator assessments as 'comparable', 'somewhat comparable', or 'not comparable' with
522 previous assessments (e.g., Evans et al., 2017)), and making the evidence (data, metadata,
523 reports, papers) used in assessment transparent and accessible (e.g., Ocean Health Index,
524 2017; OSPAR, 2017d).

525 Progress towards achieving any associated targets may also be appropriate to communicate
526 to policy-makers, including some measure of distance from the associated target as well as
527 an indication of management interventions needed to achieve the target in the future
528 (Andersen et al., 2014; HELCOM, 2018). Emphasising socioeconomic needs linked to
529 biodiversity indicators and assessment, such as ecosystem service provision, can help
530 articulate policy relevance and increase usefulness of biodiversity indicators and
531 assessments. Delivering the right indicator information in the right communication format
532 for the right audience is therefore key to successful use of biodiversity indicators and
533 assessments. For example, environmental managers who must make rapid management
534 decisions require a higher level of detail about indicator implementation and interpretation
535 than a national minister, who may only need to understand high-level information (Fig 3).

536 The co-development of indicators by scientists working closely with policy-makers can
537 facilitate feedback on product communication format to ensure that the final indicators or
538 assessment products are useful for policy-makers. Furthermore, indicator co-production
539 allows the articulation of scientific confidence limits and risks, enabling agreement on a way
540 to consider and express these limitations in assessments (Addison et al., 2017; Bolman et al.,
541 2018). This is a critical, and often iterative, step in biodiversity indicator and assessment

542 utility. Recent examples of this collaborative approach to indicator development are the
543 OSPAR Intermediate Assessment of the Northeast Atlantic (OSPAR, 2017d) and the HELCOM
544 Holistic Assessment of the Baltic Sea (HELCOM, 2018) where scientists worked closely with
545 policy-makers to develop a suite of marine biodiversity indicators. The science-policy
546 working groups co-developed communication products tailored to the requirements of two
547 levels of decision-makers. Firstly, a detailed assessment report containing information about
548 indicator development, assessment methods, and the interpretation of indicator results was
549 developed for government civil servants to use for reporting. Secondly, a two-page report
550 card for elected officials, containing simple figures, provided a high-level overview of
551 assessment results. Close working across the science-policy interface therefore resulted in
552 biodiversity assessment products which meet the needs of both policy audiences.

553 Lastly, evidence-based decision making is essential for effective biodiversity management in
554 the marine environment and in that sense promotes the use of user friendly mathematical
555 or statistical models, such as decision-support tools that can translate science into policy
556 (Pinarbaşı et al., 2017). Multifunctional decision support tools have been developed for a
557 wide range of components in marine management, some of which may be useful to
558 communicate results to decision-makers or to identify trade-offs and perform scenario
559 analyses. These types of DSTs are particularly useful for detecting changes in marine
560 ecosystems by performing scenario analyses on key drivers or biodiversity indicators within
561 marine systems.

562 Although the scientific process in developing a set of indicators may be complex, the
563 outputs should be simplified such that the outputs are connected to the human or social
564 context in which they will be used. Technical DSTs or complex indicators may result in a
565 disconnection between the objective of the indicator and its utilisation in the decision-
566 making process (Bolman et al., 2018). Therefore, simplifying complexity should rather focus
567 on the communication of the scientific outputs rather than on the actual development of
568 the indicators or tools. Communicating biodiversity indicators should include emphasising key
569 trends or sensitive parameters to communicate the dynamics within complex marine
570 systems, in the format most useful to different decision-makers (e.g. decision support tools,
571 report cards, or web-based interfaces).

572

573 **Conclusions**

574 As we enter the UN decade of ocean science for sustainable development (UNESCO, 2018) a
575 concerted effort will be required to develop strategies to meet the UN global goal to
576 “Conserve and sustainably use the oceans, seas and marine resources for sustainable
577 development” (Sustainable Development Goal 14 (United Nations General Assembly,
578 2015)). Marine biodiversity indicators are likely to be critical to meeting the targets
579 associated with this ambitious goal.

580

581 In the context of marine management, we highlight a holistic approach to understanding the
582 term ‘biodiversity indicator’ to include ecosystem structure and functioning. Several
583 challenges around biodiversity indicator development limit the widespread implementation

584 in biodiversity management. Firstly, the policy application of marine biodiversity indicators
585 varies across geographical regions and is currently most common in, but not limited to, high
586 income countries with established monitoring programs. Where marine biodiversity
587 indicators are in use for policy assessments, these indicators often use region-specific
588 terminologies and data requirements, and were created for specific policy drivers.
589 Additionally, marine ecosystems are complex, non-linear systems and links between internal
590 interactions and exogenous pressures frequently distort human intuition of the marine
591 system and hence management approaches. Marine management, and the development of
592 biodiversity indicators to support management, thus require methods of analysis and
593 decision-support tools that recognize multiple forms of complexity.

594
595 Formation of a community of practice was a key aim of this IMCC symposium and focus
596 group, and these sessions revealed that the concept of biodiversity indicators is most useful
597 when kept broad and flexible in both definition and application. A community of practice
598 will facilitate knowledge exchange between indicator users to find alternative solutions for
599 the common challenges outlined in this paper. Solutions to many of the challenges facing
600 the policy application of marine biodiversity indicators were discussed and further
601 developed and are now described in this paper. Some solutions require advanced numerical
602 expertise while others address barriers by adopting innovative solutions involving citizen
603 science data collection, combining multiple datasets to populate indicators, communicating
604 assessment results in audience-specific formats, and enhancing collaborations within the
605 international scientific community. The key to overcoming many barriers to biodiversity
606 indicator uptake is to include policy-makers from the start of indicator development to
607 ensure that implementation needs are met. It is our hope that the solutions outlined here
608 will support the use of biodiversity indicators for marine policy, management, and
609 conservation, helping us to meet the UN aspiration of the sustainable use of our oceans,
610 seas, and marine resources.

611

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626

627 **Author contribution statement**

628 A.M.G., I.M., C.V.H., J.B., S.O., P.A., and C.L. conceived and led the research and designed
629 and led authorship of the manuscript. G.P.N., E.V., K.S., D.B., E.M.W., and H.J.N. contributed
630 to research and manuscript authorship.

631

632 **Figure legends:**

633 **Figure 1:** Bibliographic analysis of publications on biodiversity, ecological, or ecosystem
634 indicators in general and for marine systems specifically. a) The number of publications
635 using one of the indicator terms (biodiversity (green shading), ecosystem (blue shading), or
636 ecological (grey shading) indicator(s)) between 1975 and 2017 (total of 2502), and the
637 number of publications using these terms in relation to marine systems only (white trend
638 line; total of 457), shown in relation to the years when three significant international or
639 regional legislative frameworks were implemented. b) The geographic distribution of a
640 subset of 1430 publications across marine ecoregions (Spalding et al., 2007), extracted from
641 publication abstracts and keywords. The bibliographic data were queried from the Web of
642 Science database (accessed last Sept 18th, 2018).

643 **Figure 2.** Establishing baselines and setting targets under two scenarios of biodiversity data
644 availability. a) The relative condition of the indicator is known, with data available
645 representing unimpacted conditions (reference conditions). In this case, an indicator target
646 can be set as a range of indicator values within a specified distance from the baseline
647 reference conditions. b) The relative condition of the indicator is not known, and no data
648 representing reference conditions are available. In this case, time-series data are used to
649 establish baseline conditions and set targets. Baselines can be set using 1) historical data,
650 such as from an alternative data source or model, 2) the earliest time-series data available,
651 or 3) data representing current conditions. Targets can then be set as a range or as an
652 ‘improving’ trend from baseline state.

653

654 **Figure 3.** Indicator communication formats should vary in level of technical detail depending
655 on the policy audience.

656

657 **Table 1.** Applications of biodiversity indicators relevant to marine environments and global marine
658 conservation policy and management. Citations preceded by “e.g.” reflect one example of many.

659

Indicators used for assessments	Examples of application	Spatial scale of application (presented in order of cited publications)
Status of, or changes in, species, habitats, or ecosystems	(Beaugrand, 2005; Rochet et al., 2005; Blanchard et al., 2010; Shin et al., 2010; Shephard et al., 2014; Probst and Stelzenmüller, 2015)	North Atlantic Ocean; France; Global; Global; Celtic Seas and Greater North Sea; North Sea
Track and communicate trends in quantity and quality of ecosystem services	(van Oudenhoven et al., 2018)	European seas
Signals prior to or after trending or oscillating changes	(e.g. Lindegren et al., 2012; Cline et al., 2014)	Baltic Sea; Global (lakes);
Impact of an anthropogenic pressure on the ecosystem	(Shannon et al., 2010; Henriques et al., 2014; Coll et al., 2016)	Global; Portugal; Global
Ecosystem stability or resilience	(e.g. Samhoury et al., 2009; Vasilakopoulos et al., 2017)	Global; Mediterranean Sea

Oceans at different spatial scales	(e.g. Blanchard et al., 2010; Halpern et al., 2012; Coll et al., 2016; Uusitalo et al., 2016; Torres et al., 2017)	Global; global; global; regional (European); single ecosystem (Baltic Sea)
Ocean biological indicators at different organizational levels (single species, individual guilds, entire food webs and trophic interactions)	(Teixeira et al., 2016; McQuatters-Gollop et al., 2017)	Global with European focus; European

660

661 **Table 2.** Needs, barriers and solutions to the development and use of marine biodiversity indicators.

662

Need	Barrier	Solution
Biodiversity indicators linked to policy and management	Siloed development of indicators, resulting in indicators that do not meet the needs of decision-makers.	Co-production of indicators by scientists and decision-makers (Lemos and Morehouse, 2005).
Appropriate biodiversity data are required to inform indicators	Insufficient data to capture spatial and temporal variability of marine ecosystems due to: <ul style="list-style-type: none"> – High costs of data collection. – Vast scales (spatial and temporal) over which ecological processes and patterns occur. – Non-policy oriented focus of historic data collection. – Lack of capacity for marine management infrastructure. 	<p>Pragmatic approach to indicator design that supports the combination and repurposing of existing data sets (OSPAR, 2017g; h; b; a).</p> <p>Risk-based approach to target intensive monitoring in order to answer specific and clear policy question (Elliott et al., 2018; Turrell, 2018).</p> <p>Use of earth observation and models to supplement <i>in situ</i> data (Elith et al., 2006; Butchart et al., 2010; Bean et al., 2017; Strong and Elliott, 2017; Pettorelli et al., 2018).</p> <p>Use of human impact (pressure) data where biodiversity monitoring data are unavailable (Halpern et al., 2012).</p> <p>Use of citizen science programmes for data collection (Hodgson, 2000; Goffredo et al., 2010; Gillett et al., 2012; Bull et al., 2013; ICES, 2017; Stuart-Smith et al., 2017).</p>
Linking biodiversity indicators to ecosystem change	<p>Biodiversity indicator respond to multiple pressures, including climate change, making it difficult to identify causes of change</p> <p>Systems may respond non-linearly to pressures, obscuring indicator interpretation</p>	<p>Integration of biodiversity indicators during assessments increases confidence in identify causes of change (Smith et al., 2016).</p> <p>Ecosystem modelling to identify the important pressure-state pathways (Fulton et al., 2005; Lynam et al., 2016; Shin et al., 2018).</p> <p>A range of modelling tools can examine non-linear indicator-pressure relationships (e.g. Hyder et al., 2015; Otto et al., 2018a; Otto et al., 2018b).</p>
Using biodiversity indicators to measure progress towards policy goals	<p>Setting targets for biodiversity indicators is challenging due to:</p> <ul style="list-style-type: none"> - Difficulty in identifying reference conditions - Political resistance to targets 	Reference conditions can be constructed based on spatial or time-series data or using models (Borja and Tunberg, 2011; Borja et al., 2012; OSPAR, 2017i; j; c; f; Rossberg et al., 2017) allowing targets to be set at an acceptable distance from the reference conditions.

		<p>Trend based approaches do not require indicators to reach a specified endpoint or target point (Butchart et al., 2010).</p> <p>Close science-policy collaboration can produce evidence-based SMART targets (Heritier, 2002; Cvitanovic and Hobday, 2018).</p> <p>Decision triggers may be used instead of targets to trigger management action (Addison et al., 2016)</p>
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