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Mairi C Meehan, Natalie C Ban, Rodolphe Devillers, Gerald Singh, Joachim Claudet

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1 **How far have we come? A review of MPA network performance indicators in**
2 **reaching qualitative elements of Aichi Target 11**

3

4 Short title: Review of MPA network effectiveness indicators

5 Mairi C. Meehan^{1,2}, Natalie C. Ban², Rodolphe Devillers^{3,1}, Gerald Singh¹, Joachim Claudet⁴

6 1 - Department of Geography, Memorial University of Newfoundland, 232 Elizabeth Avenue, St.
7 John's, NL, A1B3X9, Canada

8 2 - School of Environmental Studies, University of Victoria, PO Box 1700 STN CSC, Victoria, BC V8W
9 2Y2, Canada

10 3 - Espace-Dev, UMR 228, Institut de Recherche pour le Développement (IRD), Maison de la
11 Télédétection, 500 rue Jean-François Breton, 34093 Montpellier, France

4 - National Center for Scientific Research, PSL Université Paris, CRIOBE, USR 3278 CNRS-EPHE-UPVD, Maison des Océans, 195 rue Saint-Jacques, 75005 Paris, France

Abstract

Effective networks of marine protected areas (MPAs) are explicitly recognized and called for in international biodiversity conservation strategies such as Aichi Target 11. While various indicators have been proposed to assess effectiveness of individual MPAs, no comprehensive set of indicators exists for MPA networks, particularly for qualitative targets. The qualitative elements recognize the value of social, economic, governance, and ecological factors in achieving effective biodiversity conservation. Here, we used a systematic literature review to identify indicators of MPA network effectiveness. We reviewed 64 publications and identified 48 indicators that could be aligned with the qualitative elements of Aichi Target 11. Results showed that assessments of MPA network effectiveness predominantly focused on effective management while neglecting equitable management, and integration into the wider land and seascape. Indicators tended to focus on ecological characteristics, overlooking the social, cultural and governance dimensions. Key challenges in addressing these gaps include identifying conflicting priorities and objectives in adjacent marine and land areas that interfere with cooperation and knowledge sharing, and ensuring representation from diverse areas with distinct social and ecological contexts. This study provides the first review of indicators for assessing MPA networks and should help assessing whether current and future targets are met.

12 Introduction

13 The protection of global marine and coastal ecosystems has garnered increased scientific
14 and political interest in the last decade, driven by international targets such as the

15 Convention on Biological Diversity's (CBD) Aichi Target 11 (CBD 2011; Sala et al. 2018).
16 Aichi Target 11 calls for "...at least 17 per cent of terrestrial and inland water areas, and 10
17 per cent of coastal and marine areas of particular importance for biodiversity and
18 ecosystem services [to be conserved through] effectively and equitably managed,
19 ecologically representative, well-connected systems of protected areas and other effective
20 area-based conservation measures, and integrated into the wider landscape and seascape"
21 (CBD 2011). The amount of area each country sets aside for terrestrial and marine
22 protected areas is the principal indicator for determining effectiveness of this approach
23 (Gannon et al. 2017; Adams et al. 2019). While focusing on the area alone makes it more
24 straightforward to assess and may help bolster political will, such a simple measure falls
25 short as a proxy for protected area effectiveness (DeSanto 2013; Devillers et al. 2015;
26 Zupan et al. 2018; Coad et al. 2019; Claudet et al. 2020). The six qualitative elements of
27 Aichi Target 11 (hereafter *qualitative elements*; 'areas of importance for biodiversity
28 conservation and ecosystem services', 'ecological connectivity', 'equitable management',
29 'effective management', 'integration into the wider land and seascape' and 'ecological
30 representation') are designed to ensure that established protected areas are effective
31 beyond consideration of the quantitative target by providing a conceptualization of how
32 MPA networks should attain biodiversity conservation (Rees et al. 2018; Geldmann et al.
33 2020).

34 contributes to a growing awareness that conservation strategies need to move beyond
35 protecting individual, isolated areas (CBD 2011; Adams et al. 2019). This is particularly
36 relevant for marine systems, which is the focus of this research. Marine Protected Areas
37 (MPAs) are established to safeguard threatened marine ecosystems and species from
38 destructive human activity (CBD 2011, 2018). A collection of individual MPAs intentionally
39 arranged into an organized group is considered an MPA network. MPAs within a network
40 thereby operate in a cooperative and synergistic manner (IUCN-WCPA 2008). As a result,
41 an MPA network is thought to be more than the sum of its parts (Grorud-Colvert et al.
42 2014). MPA networks are essential biodiversity conservation tools designed to improve
43 marine biodiversity protection by encompassing spatial scales that better reflect species'
44 life history distributions (Green et al. 2007). They can help mitigate the impact of climate
45 change through the application of network design elements such as replication,
46 representation, and connectivity (McLeod et al. 2009). MPA networks may also enable cost
47 sharing and collaboration among communities and conflict relief in high-use areas (White
48 et al. 2005). Target 11 also promotes conservation beyond geopolitical boundaries by
49 recognizing the crucial role of governance, economic, social and ecological factors working
50 in concert to influence ecological outcomes (Jones 2014; Hill et al. 2016; Gill et al. 2017;
51 Rees et al. 2018; Yates et al. 2019). Implementing effective MPA networks requires careful
52 consideration of these factors, also known as dimensions, that underlie the social and
53 ecological links within the ecosystem (McGinnis & Ostrom 2014). Therefore, here, we
54 define effectiveness as the degree to which MPA networks demonstrate characteristics
55 related to the six qualitative elements (Woodley et al. 2012; Gannon et al. 2017).

56 Monitoring and evaluation is an important step in deciphering whether a conservation
57 approach is reaching its objective(s) (Heink & Kowarik 2010; Conservation Measures
58 Partnership 2016). This process makes use of indicators to track progress of the project
59 and understand the impacts of the intervention and whether objectives are being attained
60 (Conservation Measures Partnership 2016). An indicator is a variable used to describe or
61 measure the status of a particular characteristic of a system over time, such as change in
62 abundance of a species (Hockings et al. 2000; Pomeroy et al. 2004; Claudet & Guidetti 2010;
63 Woodcock et al. 2017). Evaluations of MPA effectiveness exist for a range of objectives,
64 from effectiveness of community management on livelihoods, fisheries or agricultural
65 practices to the benefits provided by MPAs for ecosystem health and biodiversity (Coad et
66 al. 2013). Evaluating the effectiveness of MPA networks will require assessing individual
67 MPA contributions, as well as those specifically associated with networks. For instance, the
68 well-established ecological benefits of individual [fully protected] MPAs (Lester & Halpern
69 2008; Sala & Giakoumi 2017) and the factors such as size, age, socioeconomics and
70 governance that influence effectiveness across various scales (Charles & Wilson 2008;
71 Claudet et al. 2008; Corrigan et al. 2017; Hargreaves-Allen et al. 2017; Mizrahi et al. 2018)
72 have been validated in MPA networks (Lowry et al. 2009; Grorud-Colvert et al. 2014). As
73 such, individual MPAs may provide relevant insights for MPA networks (IUCN-WCPA
74 2008).

75 While many studies propose indicators that can help assess the effectiveness of individual
76 MPAs (Woodcock et al. 2017), indicators for measuring network-specific elements (e.g.
77 connectivity, representativeness) are infrequently used in practice (Gannon et al. 2017;
78 Geldmann et al. 2020). Furthermore, a synthesis of indicators that can be used for
79 evaluating effectiveness of MPA networks in achieving (e.g. equity, land-sea integration)
80 are still needed (Geldmann et al. 2020). Here, we draw upon several existing MPA
81 evaluation frameworks to organize indicators and ensure a practical connection to existing
82 evaluation initiatives (Pomeroy et al. 2004; Leverington et al. 2010; Gannon et al. 2017).
83 These frameworks were developed over time, in consultation with global participants; as
84 such, they provide a context and structure for indicator organization. Furthermore, these
85 frameworks apply guidance for assessing management effectiveness which details six
86 management stages that outline the iterative process inherent in effective protected area
87 management (Hockings et al. 2000). Finally, the frameworks provide a categorisation of
88 indicators based on the social, ecological, economic, and governance dimensions previously
89 discussed.

90 The purpose of our literature review was to identify existing indicators from the MPA
91 network evaluation literature, then characterize the use of these indicators in evaluating
92 MPA network effectiveness toward achieving Target 11. MPA networks are multi-faceted,
93 and demonstrate complex social and ecological relationships influencing, and being
94 influenced by, these conservation measures (Corrigan et al. 2017; Rees et al. 2018). We
95 explored how indicators are used to measure each qualitative element, including the
96 dimensions (social, ecological, economic, and governance) and six management stages
97 (context, planning, process, input, output, and outcome) they are associated with. We
98 identified the gaps in the types of indicators used to evaluate MPA networks and their

99 diversity and distribution in evaluating the qualitative elements. The gaps identified
 100 through this review will enable further inquiry into the best approach to evaluate networks
 101 of MPAs.

102 **Methods**

103 We conducted a systematic literature review to identify indicators used to assess MPA
 104 network effectiveness in achieving the qualitative elements of (Moher et al. 2009). We
 105 searched peer-reviewed publications using Web of Science core collection database (1900
 106 to April 2019) and Elsevier’s Scopus database (1995 to April 2019) (see Table S1 for the
 107 search terms used). In addition, we used the citation tracing method (i.e., reviewing
 108 citations within selected publications) for relevant publications that were not captured in
 109 the original literature search. For all selected publications, we reviewed titles and abstracts
 110 to ensure that studies evaluated or discussed the effectiveness of some aspects of an MPA
 111 network or system of MPAs. To avoid the introduction of subjective error through
 112 interpretation, we accepted what each study identified as an MPA network, not further
 113 evaluating whether it fit our definition.

114 Publications that discussed MPA network design or the status of an area prior to MPA
 115 network implementation were excluded (Fig 1) as we wanted studies that specifically
 116 assessed the network after implementation. For each of the final publications selected, we
 117 recorded: (1) geographic location of the study; 2) the qualitative elements evaluated, (3)
 118 the management stages of each MPA network being evaluated, (4) the dimensions of each
 119 evaluation, and (5) the variables used to measure impact of MPA network on the
 120 qualitative elements.

121 We coded each paper for one or more of the six qualitative elements assessed (Table 1, Fig
 122 2). We then identified and coded each paper for the dimensions covered by the research
 123 (ecological, social, economic, or governance; Table 2). Finally, we coded the paper with its
 124 respective stage in the process of evaluation for effective management (i.e., context,
 125 planning, inputs, process, and outputs) as proposed in Hocking et al.’s (2000) framework
 126 for the assessment of protected area management effectiveness.

127 Table 1. Description of the six Aichi Target 11 qualitative elements used in this review; abbreviations used in some figures
 128 are in parentheses.

Aichi Target 11 qualitative element	Description
Areas of particular importance for biodiversity and ecosystem services	Areas of importance are considered “geographically or oceanographically discrete areas that provide important [biodiversity and ecosystem] services to one or more species/ populations of an ecosystem or to the ecosystem as a whole, compared to other surrounding areas or areas of similar ecological characteristics, or otherwise meet the criteria as identified in annex I to decision IX/20” (CBD 2008).
(Areas of Importance) Effectively managed	Effective management describes the extent to which management achieves goals and objectives designated for a particular area (Hockings et al. 2006). This includes design issues relating to both individual sites and protected area systems; adequacy and appropriateness of management systems and processes;

	effective public participation and social policy processes, and delivery of protected area objectives (Woodley et al. 2012).
Equitably managed (Equity)	Equitable management highlights the impact and benefit of conservation actions on human wellbeing and social systems, including: the fair distribution of economic benefits and livelihood opportunities (distributional equity); the process for involvement and inclusion of stakeholders in planning, implementing and administering (procedural equity); and the process of acknowledging and accepting the legitimacy of rights, values, interests, and priorities of different actors and respecting their human dignity (recognitional equity) (Juffe-Bignoli et al. 2014; Schreckenberg et al. 2016).
Ecologically representative (Representative)	Representativeness is considered the inclusion of areas that represent the entire suite of “different biogeographical subdivisions of the global oceans and regional seas that reasonably reflect the full range of ecosystems, including the biotic and habitat diversity of these marine ecosystems” (CBD 2008). Representative includes the element of replication to ensure risk is minimized in the event of unforeseen or catastrophic events (Rees et al. 2018).
Well-connected (Connectivity)	Connectivity in relation to MPA networks concerns the “linkages whereby protected sites benefit from larval and/or species exchanges, and functional linkages from other network sites” (CBD 2008).
Integrated into wider landscape and seascape (Integrated)	In recognition that Protected Areas cannot work in isolation, this element identifies the importance of integrating MPAs with other conservation and management tools, such as fisheries management or land use plans for land-based sources of pollution. Other considerations for this element include potential cumulative impacts stemming from climate change, ocean acidification, ocean noise, and pollution (Juffe-Bignoli et al. 2014; Rees et al. 2018).

129 We

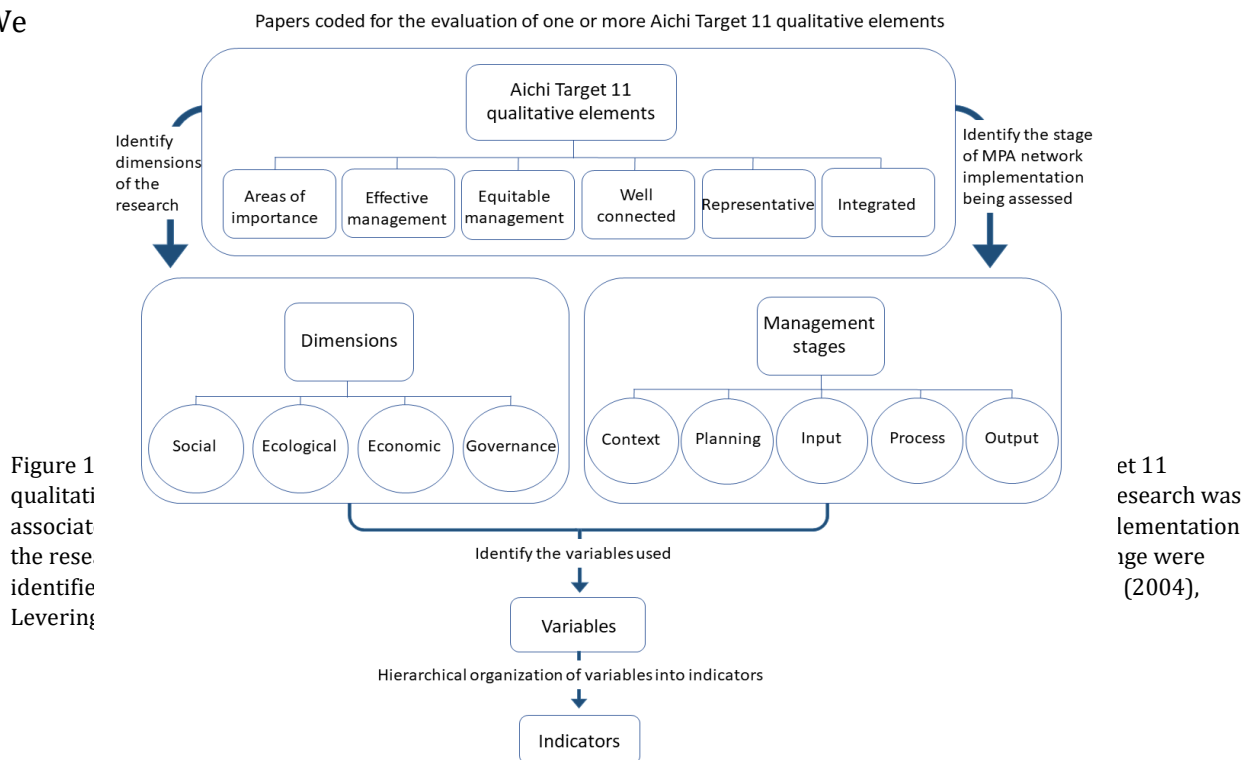


Figure 1
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(2004),

130 recorded the variable(s) used to evaluate each element of the MPA network (Table S2). We
131 consider a variable as a factor, trait, or condition that noticeably responds to a management
132 action and can therefore be used to measure the effect of that action. The distribution of

133 pink sea fans in southwest UK waters (Pikesley et al. 2016), for example, is considered a
 134 variable for assessing MPA network connectivity. Although variables may or may not be
 135 explicitly identified as such in the publications, we considered each measurement of a
 136 qualitative element as a variable (Pelletier et al. 2005). We organized each variable
 137 identified in a study into indicators, noting that some variables were already indicators, for
 138 example variable “distribution of pink sea fans” was organised into the indicator “species
 139 distribution” (See Table S2 for categorization). This classification was based on existing
 140 frameworks designed to assess individual MPAs (Pomeroy et al. 2004; Leverington et al.
 141 2010) and MPA networks (Gannon et al. 2017).

142 Table 2. Description of the terminology used in this paper.

Term	Description
Variable	An observed (quantifiable) factor, trait, or condition that responds to a local change such as implementation of a management action (Pelletier et al. 2005).
Indicator	An indicator is a suite of one or more qualitative or quantitative variables (social, environmental, etc.) used to measure the status or change over time of a particular characteristic of interest in an ecosystem (Pomeroy et al. 2004).
Dimension	Dimensions are the ecological, governance, social and economic factors inherent in social-ecological systems that influence and are influenced by a management action (Pomeroy et al. 2004). <ul style="list-style-type: none"> • The ecological dimension is important to understand the state of the system, the species or habitats of interest so that an intervention can proceed in an appropriate manner suitable to the needs of the species. • The governance dimension includes aspects that help maintain or influence legislation, management and decision-making. • The social dimension includes aspects of compliance, perceptions, and participation and engagement in resource management. • The economic dimension includes financial resources and capital necessary to implement and achieve conservation initiatives.
Management stage	Six management stages are considered important in the progress toward effective management of MPAs. They outline an adaptive process inherent in effective protected areas (context, planning, process, input, output, and outcome) design, implementation and management (Hockings et al. 2006). <ul style="list-style-type: none"> • Context refers to the underlying conditions associated with a protected area, including status and threats, and target species; the needs, abilities, and desires of the stakeholders. • Planning refers to establishing a clear objective, and issues of design, including preferred strategies or approaches to achieve the objective(s). • Input refers to the resources (financial, personnel, material) needed for the project to come to fruition. • Process relates to how the actions undertaken to achieve results- the adequacy of approaches in relation to the management objectives. • Output pertains to the goods and services produced to realize the MPA objectives. • Outcome relates to the highest level of results in relation to long term objectives- fully achieving Aichi Target 11.

143 We counted the number of times each element was assessed, the indicators used to assess
 144 it, and the dimensions and management stages associated with each indicator. Finally, we
 145 identified gaps in indicators used in the literature [to date] by evaluating the composition

146 of the indicators, specifically the dimensions and management stages associated with each
147 indicator. We then developed a flow diagram (SankeyMATIC, Bogart 2016) to show the
148 structure and distribution of the suite of indicators measuring the qualitative elements of

149 . This diagram reflects the frequency each indicator is linked to the management stages,
150 dimensions, and qualitative elements.

151 To support our general findings on the suite of indicators and to help highlight gaps in how
152 indicators are used to measure effectiveness, we calculated Shannon (H') diversity and
153 evenness (E). These metrics are commonly used in community ecology to characterize
154 species diversity, which we adapted to look at the diversity of indicators across qualitative
155 elements. Shannon diversity incorporates total number and distribution of individuals and
156 is sensitive to rare species, which is necessary to capture the rare presence of indicators for
157 some dimensions. To calculate Shannon's diversity, we used the formula: $H' = -\sum n_i/N * \ln$
158 (n_i/N) , where n_i is the number of indicators used to evaluate each individual quantitative
159 element i and where N is the total number of indicators used across all qualitative
160 elements. A high diversity score means that many different indicators are used to evaluate
161 a specific qualitative element, while a low score means that one or a few indicators are
162 used to evaluate an element. We also calculated Shannon Evenness (E) to quantify the
163 distribution of indicators used to measure each qualitative element, as $E = H' / \ln(S)$, where S
164 refers to the indicator richness, the number of different indicators used to measure a
165 qualitative element (Verberk 2011). A higher evenness score indicates that a given
166 qualitative element is assessed by a wide variety of indicators, with no indicator
167 dominating the evaluations. A low evenness score means that few (or one) indicator is used
168 predominantly to evaluate this element. These matrices show how the indicators were
169 distributed across each qualitative element. All analyses and figures (unless specified
170 otherwise) were done using R (R Core Team 2019; version 3.6.1) with package vegan 2.5-6
171 (Oksanen et al. 2019) and ggplot2 version 2_3.3.2 (Wickham 2016).

172 **Results**

173 Our review identified 64 papers that discussed the effectiveness of an MPA network or
174 system of MPAs in reaching one or more qualitative elements. Our analysis of those papers
175 identified 223 variables, organized into 48 headline indicators that can help assess the
176 effectiveness of MPA networks in achieving qualitative elements. Each indicator identified
177 from the literature matches one or more qualitative elements. We found an uneven
178 distribution in the assessment of qualitative elements in the literature. MPA networks were
179 predominantly evaluated for management effectiveness. Ecological indicators identified in
180 our study are closely aligned with those of individual MPAs (Pomeroy et al. 2004;
181 Leverington et al. 2010) and with indicators previously identified for MPA networks
182 (Gannon et al. 2019). Publications reviewed focused on 34 MPA networks from 15

183 countries (Fig 3, Table S3), and four regions including the Mediterranean Sea (n=5),
 184 Northeast Atlantic (n=2), Western Pacific (n=1), Persian/Arabian Gulf (n=1), and three

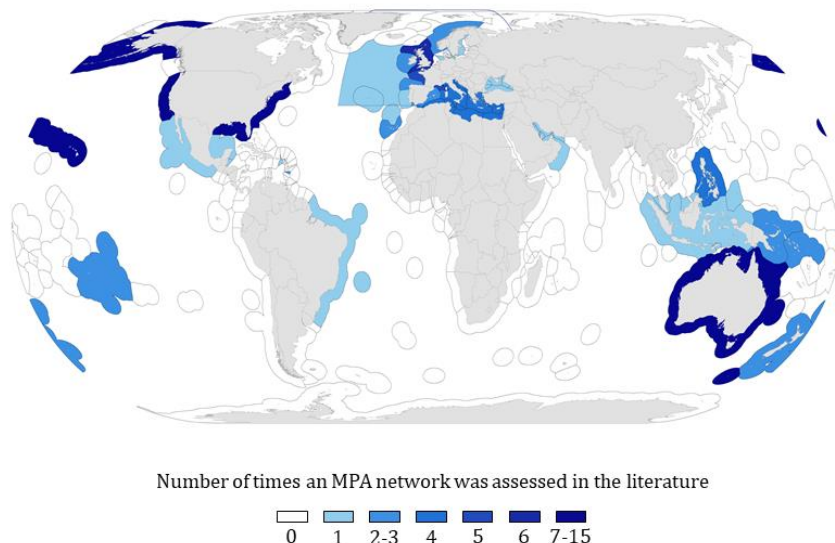


Figure 3. Exclusive economic zones (EEZs) of countries and regions that have MPA networks evaluated in our literature review. Color grades represent the number of times an MPA network was studied in the countries associated with the EEZ; OSPAR area beyond national jurisdiction (ABNJ) is also depicted, having been assessed once.

185 studies located in an area beyond national jurisdiction (ABNJ), the OSPAR network. Several
 186 studies were global in scope (n=5). We found that MPA networks in Australia were
 187 assessed most often (n=14), followed by the USA (n=11) (Fig 3). Several networks were
 188 assessed multiple times by various researchers, including the Great Barrier Reef and the
 189 Hawai’ian MPA networks (see Table S3 for list).

190

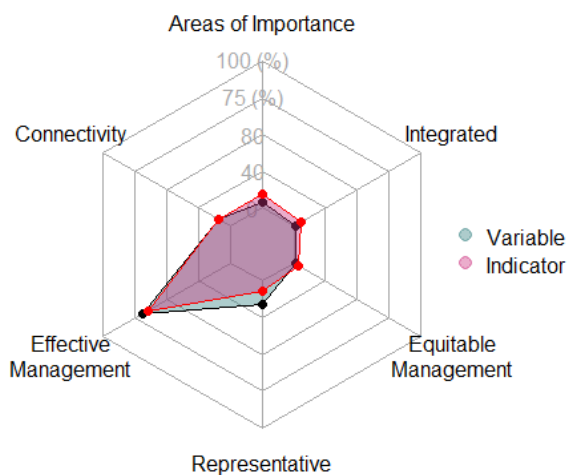


Figure 4. Proportion of indicators used to assess each Aichi Target 11 qualitative element. The blue line represents the proportion of times each qualitative element was evaluated in the studies reviewed. Qualitative elements were assessed a total of 223 times; this corresponds to the number of variables identified in the papers we reviewed. The orange line represents the proportion of indicators used to assess each qualitative element. A total of 48 headline indicators were identified.

191

192 Aichi Target 11 qualitative elements

193 ‘Effective management’ was the qualitative element assessed most thoroughly. This
 194 element was assessed 153 times, in 69% of all papers we reviewed with 65% of all
 195 indicators (Fig 4). Indicators used to evaluate effective management were associated with
 196 all dimensions and all management stages though disproportionately assessed ecological
 197 and governance dimensions (48% and 40% respectively) over social and economic
 198 dimensions (7% and 5% respectively; Fig. 5a). Output and process- associated indicators
 199 made up half of indicators used in evaluating effective management (31% and 21%,
 200 respectively), while outcome, context, planning and input made up the remainder (16%,
 201 14%,10% and 8% respectively, Fig 5b).

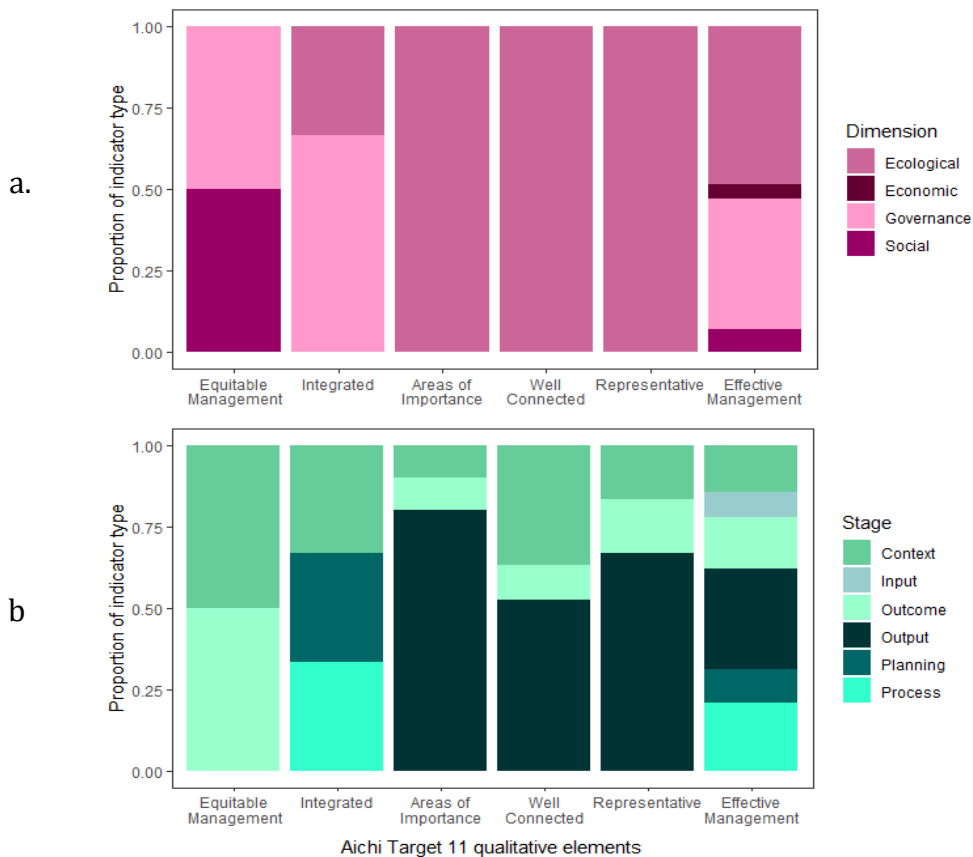


Figure 5. Proportion of indicators associated with the different dimensions (a) and management stages (b) used to measure each qualitative element. The various dimensions are represented in panel (a), the management stages are represented in panel (b).

202 Evaluations of ‘Equitable management’ were limited. ‘Equitable management’ was
 203 evaluated twice, with two indicators (in less than one per cent of all papers evaluated, Fig
 204 4). The indicators were used to assess the social and governance dimensions of this
 205 element (Fig 5a), with a focus on the context and outcome stages of management (Fig 5b).
 206 The social indicator “Perception of MPA effects on livelihood” measured the context of
 207 fishers’ satisfaction with the process of implementing an MPA network (distributional
 208 equity). The governance indicator “Level of stakeholder support and satisfaction in

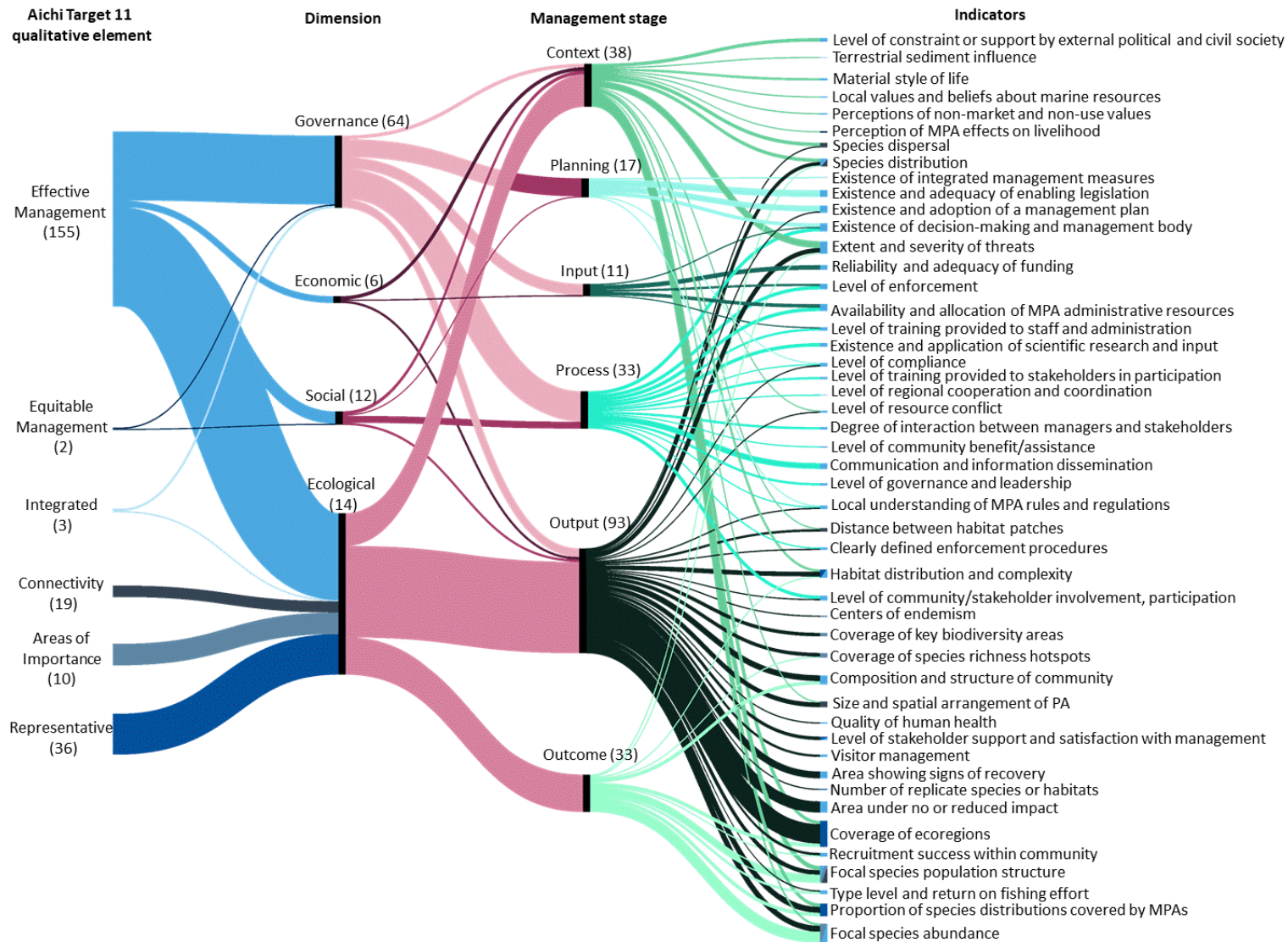


Figure 6. Flow diagram describing the use of indicators in evaluating the Aichi Target 11 qualitative elements with their associated dimensions and management stages. For definitions of the Aichi elements, see Table 1. The colors are a visual aid to decipher the Target 11 qualitative elements, dimensions, management stages and indicators, and correspond with color scheme in figures 5 and 7. Each node, represented by a rectangle, represents a qualitative element, dimension, management stage or indicator, as described in the diagram. The thickness of each line and node is proportional to the number of times (number in parentheses) an indicator was used to assess this component. Dimensions describe the governance, social, economic, and ecological factors that influence MPA networks. Management stages describe where in the process of MPA network implementation the indicators are being used (for definitions, see Table 2). The colors on the indicator nodes represent the Aichi Target 11 qualitative elements that each indicator was used to measure.

210 management” assessed perceptions of stakeholders about the effect of MPA network
211 implementation in California (recognitional equity) (Fig 6, Table S2). Indicators used to
212 assess procedural equity and other aspects, such as equitable distribution of benefits,
213 human wellbeing were missing in this review.

214 ‘Areas of importance for biodiversity conservation’ was assessed 10 times using five
215 indicators (Fig 4). All of the indicators were used to assess the ecological dimension of this
216 element (Fig 5a). These indicators also most commonly focused on outputs (80% of the
217 indicators for this element; Fig. 5b) to evaluate effectiveness of MPAs in covering key
218 species and biodiversity areas. Indicators measured ecological outcomes (10%) for species
219 richness in areas of importance covered by an MPA. Indicators measuring ecological
220 context (10%) focused on distribution patterns of focal species in order to make decisions
221 on appropriateness of spatial arrangements (Péron et al. 2013).

222 ‘Ecological connectivity’ was evaluated 19 times, in less than 9% of all papers we reviewed.
223 All five indicators (Fig 4) used to evaluate this element focused in the ecological dimension
224 (Fig 5a). Output (53%), context (37%) and Outcome (11%) were the management stages
225 evaluated (Fig 5b). Ecological connectivity indicators focused on species and habitat
226 distribution and dispersal, and spatial arrangement of protected areas in a network (Fig 6;
227 Table S2).

228 ‘Ecological representation’ was assessed 36 times using four indicators (Fig 4). These
229 indicators were used to measure output (67%), outcome (17%), and context (17%) stages
230 of implementation solely within the ecological dimension (Fig 5). The indicator “Number of
231 replicate habitats” was not previously associated with indicators from existing frameworks.
232 This indicator was used to evaluate the effectiveness of a representative system in
233 minimising risk of negative impacts (Fernandes et al. 2005).

234 Integration into the wider landscape and seascape’ was assessed three times (Fig 4). One
235 ecological indicator was used to evaluate the influence of terrestrial sediments on an MPA.
236 Two governance indicators were used to measure planning and process stages of
237 integrated and transboundary management (Fig 6; Table S2), “Level of regional
238 cooperation and coordination” and “Existence of integrated management measures in
239 management plans”. The indicators used to evaluate integration were not identified in
240 existing frameworks. Indicators used to assess integrated practices regarding the land-sea
241 connection, and those to assess social aspects of integration such as community cohesion
242 or knowledge sharing are largely missing.

243 Indicator dimensions and management stages

244 Indicators were primarily associated with ecological and governance dimensions (20
245 indicators each), while indicators associated with economic and social dimensions were
246 more limited (4 and 6 indicators, respectively; Fig 6). Governance indicators were used in
247 the evaluation of every management stage. Social indicators were used to assess context,
248 input, process, and output stages of effective management and equitable management,

249 while economic indicators were used to assess context, input, and output stages of effective
 250 management. Output was the most commonly assessed management stage in MPA network
 251 evaluations. Outputs and outcomes were predominantly evaluated with ecological
 252 indicators. Input was the management stage assessed the least, evaluated in terms of
 253 governance and economics of effective management. Context was evaluated predominantly
 254 with ecological indicators representing all six qualitative elements (Fig 6). Planning and
 255 process stages were primarily evaluated with governance and social indicators.

256 Indicator diversity

257 Results from measuring diversity of each suite of indicators that represent a qualitative
 258 element (Table 3) allowed us to quantify how the indicators were distributed across each
 259 qualitative element (Table 3, Fig 7). Shannon diversity (H') confirmed that 'effective
 260 management', which was evaluated the most, had the greatest abundance and largest
 261 diversity of indicators ($H' = 3.3$). In contrast 'equitable management' was evaluated the
 262 least and had the lowest diversity of indicators ($H' = 0.69$). Diversity of indicators used to
 263 assess 'representativeness' was also low ($H' = 0.85$; Table 3). Diversity of indicators used to
 264 assess 'connectivity', 'areas of importance', and 'integration' were moderate with respect to
 265 the suite of indicators used to evaluate the qualitative elements ($H' = 1.5, 1.4, \text{ and } 1.1$
 266 respectively). Evenness scores range between 0.6 and 1. The small sample sizes, however,
 267 reduces the reliability of these findings.

268 Table 3. Shannon diversity and evenness of indicators for each qualitative element assessed

Qualitative element	S Indicator Richness	N Indicator Abundance	H' Shannon Diversity	E Shannon Evenness
Areas of Interest	5	12	1.42	0.88
Well Connected	5	19	1.49	0.93
Effective Management	35	153	3.29	0.92
Equitable Management	2	2	0.69	1
Integration	3	3	1.10	1
Representative	4	36	0.85	0.61

269

270 Unique indicators

271 Several studies used indicators not yet recognized in the MPA evaluation frameworks we
 272 used (Pomeroy et al. 2004; Leverington et al. 2010; Gannon et al. 2019). Three of these
 273 indicators relate to the element of integration: "Existence of integrated management
 274 measures", "Level of regional cooperation and coordination", and "Level of terrestrial
 275 sediment influence". One indicator relates to ecological representation: the "Number of
 276 replicate habitats" and one relates to the social dimension of effective management: "Level
 277 of compliance". "Level of compliance" was used three times to assess the influence of MPA
 278 networks on changing levels of compliance and poaching and, conversely how levels of

279 compliance influence effectiveness of MPA networks. Finally, 18 indicators used in the
 280 referenced frameworks were not mentioned in the literature we reviewed (see Table S5).
 281 These missing indicators include community social, cultural, economic and governance
 282 indicators as well as indicators measuring ecosystem services.

283 **Leading indicators**

284 The indicators most commonly used could form the basis of a core suite of indicators to
 285 evaluate MPA networks effectiveness (Table 4). Chief among these was “Coverage of
 286 ecoregions” used 23 times to evaluate representativeness. Another indicator for
 287 representativeness that was used more often than others was “Proportion of species
 288 distributions covered by MPAs” (Table 4). “Focal species abundance” and Focal species
 289 population structure” were the principal indicators for effective management (used 15 and
 290 13 times, respectively), followed by “Area under no or reduced impact” and “Extent and
 291 severity of threats” (used 10 and 11 times, respectively). Principal connectivity indicators
 292 include “Species distribution”, “Size and spatial arrangement of PAs” and “Species
 293 dispersal” (used 6, 5, and 4 times, respectively). “Coverage of species richness hotspots”
 294 and “Coverage of Key Biodiversity areas” were the principal indicators for Areas of
 295 Importance, used 4 and 3 times each, respectively. Indicators for Equitable management
 296 and Integration were limited; each used once (Table 4).

297 Table 4. Most commonly used indicators identified from this review.

Qualitative element	Indicators	Count
Equitable Management	Level of stakeholder support and satisfaction in management	1
	Perception MPA effects on livelihood	1
Integrated	Existence of integrated management measures in management plans	1
	Level of regional cooperation and coordination	1
	Terrestrial sediment influence	1
Areas of Importance	Coverage of key biodiversity areas	3
	Coverage of species richness hotspots	4
Well Connected	Size and spatial arrangement of MPAs	5
	Species distribution	6
	Species dispersal	4
Representative	Coverage of ecoregions	23
	Proportion of species distributions covered by MPAs	11
Effective Management	Focal species abundance	15
	Focal species population structure	13
	Extent and severity of threats	11
	Area under no or reduced impact	10

298

299 **Discussion**

300 Despite the recent progress in designing and implementing MPA networks (Abecasis et al.
 301 2017; Gannon et al. 2019), marine ecosystem health continues to decline (Diaz et al. 2019).
 302 Assessing whether MPA networks are effective tools for biodiversity conservation is of

303 fundamental importance to help guide future conservation strategies (Grorud-Colvert et al.
304 2014). In addition to the 10% aerial target, the qualitative elements provide guidance on
305 how to safeguard marine biodiversity and ecosystem services. These qualitative elements
306 shift the narrative of conservation success from an ecological focus toward the
307 incorporation of human dimensions by acknowledging the relationship between the
308 protection of biodiversity and human wellbeing (Campbell & Vainio-Mattila 2016; Corrigan
309 et al. 2017; Rees et al. 2018; Adams et al. 2019; Brueckner-Irwin et al. 2019). Our review of
310 peer-reviewed publications found strong evidence of an uneven evaluation of effectiveness
311 across the qualitative elements, with many MPA network evaluations not addressing most
312 elements. While we should not expect an even distribution of indicators across those
313 elements, focus on the assessment of one element raises the risk of MPA networks not
314 meeting their expected goals. Such narrow focus may also distract from recognising
315 politically motivated implementation or infringements to social justice, which lead to
316 distrust, conflict and violations (DeSanto 2013; Dehens & Fanning 2018), and other
317 unintended consequences (Weeks et al. 2014; Geldmann et al. 2020).

318 In our study, we found effective management as being the most wholly assessed qualitative
319 element (Fig. 6). Indeed, effective management has generally become the most evaluated
320 qualitative element in conservation (Pelletier 2011), for which there are numerous
321 frameworks used throughout the world (Leverington et al. 2010). Effective management
322 provides a means to encourage transparency and accountability (Pelletier 2011), and can
323 help reduce the risk of creating 'paper parks' (Mascia et al. 2014; Gill et al. 2017). However,
324 an area that is effectively managed may not be effective at conserving biodiversity if, for
325 example, it has limited biological significance to start with (Devillers et al. 2015), is not
326 connected to one another in a functionally coherent manner (Woodley et al. 2012), is
327 biologically connected to an area with conflicting objectives (Sayles & Baggio 2017;
328 Mackelworth et al. 2019), or lacks adequate personnel or financial capacity to ensure goals
329 and objectives are able to be met into the future (Coad et al. 2015).

330 Gaps and challenges

331 We showed here that while evaluations of management effectiveness are complex and
332 contain a myriad of indicators, they still poorly incorporate social and economic
333 dimensions (see Fig. 6). Missing these factors may enhance the risks of creating MPA
334 networks that underperform relative to their promise (Coad et al. 2015; Corrigan et al.
335 2017; Di Minin & Toivonen 2017). In working toward the post-2020 agenda, the
336 conservation community will benefit from knowing how MPA networks are being
337 measured toward this (holistic) target. Our review found that indicators used to evaluate
338 input and planning toward MPA network implementation are limited. Input-related
339 indicators reflect capacity, including personnel and funding for management. Planning-
340 related indicators reflect how the mechanisms to achieve management occurs (Hockings et
341 al. 2000), such as design, and legislation or policy that enables the process to move forward
342 in a clear and transparent manner. Appropriate input and planning-related indicators are
343 imperative to successful conservation initiatives.

344 Effective management of MPA networks will also benefit from improved economic and
345 social indicators (See Fig. 5). Indeed shortage in capacity and financial resources have been
346 identified as critical impediments to attaining the post 2020 conservation goals (Coad et al.
347 2015; Gill et al. 2017). We found four indicators evaluating economic factors among MPA
348 networks covering a range of spatial scales, just one evaluated the adequacy of funding to
349 implement a national system of MPAs (Gerhardinger et al. 2011). Evaluations considering
350 both market and non-market values need to be mainstreamed into MPA network
351 effectiveness evaluations (Davis et al. 2019). Furthermore, while social dimensions such as
352 wellbeing, equity, cultural contexts, and indigenous engagement are enjoying increased
353 attention, means to measure the impact of MPA networks on these elements and their
354 influence on MPA success is yet underrepresented (Corrigan et al. 2017). Incorporating
355 these dimensions onto a cohesive monitoring and evaluation framework, albeit daunting,
356 will be necessary to achieve a post 2020 agenda (Addison et al. 2018).

357 Equitable management has been receiving increased attention (Hill et al. 2016; Dawson et
358 al. 2018; Law et al. 2018; Rees et al. 2018) including the development of indicators to
359 evaluate this element (Schreckenberg et al. 2016; Zafra-Calvo et al. 2017; Campbell & Gray
360 2018; Moreaux et al. 2018). We, however, found only two evaluations of equity. These two
361 instances focused on procedural and recognitional equity of stakeholder support and
362 participation in conservation actions (See Table 1 for definitions). The indicator of
363 recognition “Level of stakeholder support and satisfaction in management” does not
364 specifically address potential discrimination, inclusion, and respect for human rights, as
365 equity frameworks would suggest (Schreckenberg et al. 2016). The other indicator used to
366 assess distributional equity in MPA networks, “Perception of MPA effects on livelihood”,
367 assessed the perception of MPA effects on livelihood, but not the sharing of benefits among
368 actors, or mitigation of potential impacts as called for in equity frameworks (Franks &
369 Small 2016; Schreckenberg et al. 2016). Our results corroborate those of Moreaux et al.
370 (2018) who found that the existing assessment tools cannot adequately evaluate equity in
371 protected areas as they do not capture the complex underlying relationships fundamental
372 to this element. Evaluation of equity is resource intensive and cumbersome, and often
373 results cannot be comparable across sites within a network (Moreaux et al. 2018).

374 It is well known that protected areas managed in isolation without consideration of issues
375 happening in surrounding areas such as pollution, habitat destruction and overfishing
376 reduces success of the protected area (Agardy et al. 2011). There has been a surge in
377 funding allocated to integrating and mainstreaming protected areas with agricultural
378 sectors (Bacon et al. 2019). The increased commitments by countries toward this element
379 have been met with major limitations (Maxwell et al. 2020). Conflicting priorities,
380 contradictory objectives, and competing interests across different sectors and adjacent
381 regions (Jones 2001; Álvarez-Romero et al. 2011; Gannon et al. 2019) as well as the lack of
382 indicators for assessing the integration of protected areas into the wider landscape and
383 seascape challenge the realisation of this element (Bacon et al. 2019). We identified three
384 indicators used to evaluate integration (Fig 6). These unique indicators focused on

385 governance and land-sea interactions, yet they did not consider measures of integrated
386 practices, community cohesion, knowledge sharing, or distribution of land-based impacts
387 (Partelow et al. 2015; Jupiter et al. 2017).

388 Another challenge is identifying a suite of indicators that addresses areas of particular
389 importance for ecosystem services. We identified several indicators that captured aspects
390 of areas of importance for biodiversity conservation, while indicators used to evaluate
391 ecosystem services were absent from the literature we reviewed. The gap in assessments
392 may be due to the lack of a generally accepted approach to measure the suite of services
393 provided by an ecosystem (Gannon et al. 2019). Many ecosystem services do not have a
394 comprehensive suite of indicators to measure them. Indicators that do exist are often
395 inadequate to fully represent the complexity of benefits provided to, and used by, society
396 (McMichael et al. 2005; Brown et al. 2014), especially in the marine realm (Townsend et al
397 2018).

398 We identified several leading indicators used to evaluate MPA networks, but recognize that
399 these are unlikely to be comprehensive and will require further refinement. We recognise
400 the indicators missing or under-represented in this review (Table S5) may characterize
401 fundamental components of terrestrial and marine protected area networks and hence
402 help assess whether or not these networks are fulfilling their objectives. In particular,
403 recent initiatives identifying indicators for equitable management (Zafra-calvo et al. 2017)
404 and integration (Bacon et al. 2019) will help identify priority indicators for evaluation of
405 MPA networks against the qualitative elements (Geldmann et al. 2020). Our findings can
406 also be complemented in the future by using other sources, such as grey literature (e.g.
407 technical reports), local management plans, regional strategies, national action plans, and
408 expert opinions, to identify and categorise a core suite of headline indicators to evaluate
409 MPA networks effectiveness.

410 General implications and future work

411 Our study adds to the growing literature looking at MPA networks effectiveness. Other
412 reviews of MPA networks have focused on site specific objectives (Sciberras et al. 2013;
413 Davis et al. 2014) or on planning and design (Abesamis et al. 2006). Evaluating
414 effectiveness in the way we did has both advantages and limitations. Each qualitative
415 element was treated independently, allowing for targeted evaluation of progress and may
416 provide insight into the individual contributions of these elements to the whole. In reality,
417 the qualitative elements should work interdependently to successfully conserve
418 biodiversity. The complex and dynamic relationships inherent in protected area networks
419 warrants a holistic, system-level approach to fully appreciate the interactions between the
420 various elements that influence success (Marshall et al. 2016; Mahajan et al. 2019).
421 Assessing the independent and combined contributions of each element and their
422 associated dimensions as a system will have implications for both management and policy.
423 Future work will also benefit from resolving the geographic imbalance in MPA networks
424 identified for this review. Including the management stages that indicators are associated

425 with helps to identify the underlying mechanisms of effectiveness - how and why an MPA
426 network is effective. Knowing the management stages associated with indicators can
427 provide insight to identify entry points for targeted interventions, thereby improving
428 successful outcomes for future iterations of the intervention. This adaptive approach is
429 essential to ensure MPA networks are delivering successful conservation outcomes
430 (Hockings et al. 2000; Geldmann et al. 2020). The various perspectives regarding
431 ecological, economic and social contexts, and matters of governance from different
432 geographic provinces will ultimately provide insight into the factors that influence MPA
433 network success (Di Marco et al. 2017; Venter et al. 2018). Indeed countries appear to be
434 shifting away from quantitative aerial commitments in favor of the qualitative elements
435 (Adams et al. 2019; Bacon et al. 2019), which acknowledges the relationship between the
436 protection of biodiversity and human wellbeing (Rees et al. 2018). This is likely to come
437 through implementation and integration of other effective area-based conservation
438 measures (OECMs; CBD 2018). While we did not include OECMs in this review. We note the
439 importance of these measures for conservation, particularly with respect to governance
440 and social dimensions in attaining an effective, representative, and equitable global
441 protected area estate (Corrigan et al. 2017; Bacon et al. 2019).

442 Conclusion

443 It is not surprising that ecological outputs are most often assessed to determine MPA
444 network effectiveness since MPAs are meant to protect biodiversity and ecological
445 processes. However, achieving ecological outcomes often depends on an array of social,
446 economic and governance factors (Ban et al. 2019; Brueckner-Irwin et al. 2019; Hockings et
447 al. 2019; Yates et al. 2019). Evaluating these factors may help understand root causes of
448 stakeholder cooperation and acceptance, and improve concerns of legitimacy (Dehens &
449 Fanning 2018) and equitable sharing of benefits (White et al. 2005; Franks & Small 2016).
450 Indeed, linked social and ecological dynamics were recognized as influencing conservation
451 effectiveness in some of the literature reviewed (e.g. Van Lavieren & Klaus 2013).

452 Our review highlighted an imbalance in the assessment of protected areas' effectiveness in
453 conserving and protecting areas of high biodiversity importance in a sustainable manner.
454 Here, we provided, to the best of our knowledge, the first systematic review of indicators
455 used to assess MPA networks. This is a first step towards providing guidance for assessing
456 MPA networks on a global scale. We found that current assessments of MPA networks are
457 largely built on assessments used for individual MPAs. This is perhaps unsurprising as
458 individual MPAs contribute to MPA networks and MPA network assessments have
459 developed from the assessment of individual MPAs. However, MPA networks were
460 envisioned to recognize the larger systems in which individual MPAs exist. This may
461 require assessment criteria that includes structure for interacting systems that does not
462 treat MPA networks as a form of individual MPAs or a collection of independent MPAs. Our
463 results indicate that the monitoring and evaluation of MPA networks largely overlook the
464 qualitative elements of equity in management and how MPA networks are integrated into
465 the wider land and seascape. Additionally important social and economic attributes are

466 seldom measured in MPA networks performance evaluations. Assessment of MPA network
467 performance using a more suitable and balanced suite of indicators will be key to ensure
468 that MPA networks can help protect marine ecosystems more effectively.

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