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Ecological variables for developing a global deep-ocean monitoring and conservation strategy

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1 Submitted to Nature Ecol & Evol for consideration

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3 **Ecological variables for developing a global deep-ocean**  
4 **monitoring and conservation strategy**

5  
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41 **ABSTRACT**

42 The deep sea (>200 m depth) encompasses >95% of the world's ocean volume and  
43 represents the largest and least explored biome on Earth (<0.0001% of its surface). It  
44 also provides critical climate regulation and other ecosystem services. New species and  
45 ecosystems are continuously being discovered in the deep oceans, but commercial  
46 fisheries, deep-sea mining, and off-shore oil and gas extractions, along with pollution  
47 and global change effects, threaten this vast under-explored frontier region. The future  
48 of both benthic and pelagic deep-sea ecosystems depends upon effective ecosystem-  
49 based management strategies enhancing deep-sea conservation, yet we lack  
50 consensus on monitoring of the biological and ecological variables that reflect  
51 ecosystem status and are needed to support management and environmental  
52 decisions at a global scale. Here, we present and discuss the results of an Expert  
53 Elicitation of more than 110 deep-sea scientists to prioritize variables and parameters  
54 for the future of deep-sea monitoring. We identified five main scientific pillars that  
55 need to be further investigated for deep-ocean conservation: i) species and habitat  
56 biodiversity, ii) ecosystem function; iii) ecosystem health, impacts, and risk  
57 assessment; iv) climate change impacts, the adaptation and evolution of deep-sea life,  
58 and v) deep-sea ecosystem conservation. As observing and monitoring can provide the  
59 necessary scientific framework for scientists and policy makers to implement effective  
60 deep-sea conservation strategies at a global scale, the proposed variables should be  
61 further studied in the context of available sensor and other advanced technologies,  
62 which are becoming increasingly available.

63

64 **Key-words:** deep sea, monitoring, impacts, biodiversity, conservation, global change,  
65 adaptation and evolution.

66 Industrial activities spanning from fisheries to oil and gas extraction are  
67 accelerating anthropogenic pressures on the deep sea<sup>1-3</sup>, leading to the degradation of  
68 benthic and pelagic environments whose biological diversity remains largely unknown  
69 **(Box 1)**. Global decreases in marine ecosystem services, such as fisheries, that provide  
70 direct benefit to humanity have not spared deep-sea ecosystems<sup>4-7</sup>. In particular,  
71 species loss and deep-sea habitat destruction produce severe alteration of ecosystem  
72 functioning and reduce overall ecosystem goods and services<sup>2,8,9</sup>. In addition,  
73 cumulative marine impacts act synergistically with climate-induced changes in deep-  
74 ocean properties and processes, degrading environmental quality<sup>10-12</sup>.

75 Deep-sea biodiversity plays a central role in provisioning services (e.g.,  
76 fisheries, nutrition, bioprospecting), and species loss can greatly reduce ecosystem  
77 functions that support these services<sup>8,13</sup>. Furthermore, high biodiversity levels increase  
78 ecosystem resilience to perturbations<sup>14,15</sup>, elevating the importance of maintaining  
79 biodiversity as an important management objective in the pursuit of sustainable use of  
80 resources<sup>16,17</sup>. Sustaining healthy and productive deep oceans requires knowledge of  
81 baseline conditions and rates of ecosystem change **(Figure 1)**. In turn, the  
82 environmental status and resources of the coastal zones link with deep-sea  
83 ecosystems<sup>6,18</sup>. Bi-directional exchange of materials, nutrients, contaminants, and  
84 organisms between shallow and deep-sea ecosystems occurs widely in all oceans<sup>19-23</sup>  
85 and thus changes in one system may impact other ecosystems. Several ongoing  
86 initiatives are considering monitoring needs of baseline conditions and environmental  
87 impacts **(Box 2)**.

88 Here, we focus on the identification of a set of biological and ecological  
89 variables and parameters designed to capture the most relevant aspects of the biology  
90 and ecology of deep-sea ecosystems, thus enabling sound evaluation of their status.  
91 We have selected the proposed parameters and variables to address five pillars of  
92 knowledge needed for deep-sea ecosystem management and conservation: i) species  
93 and habitat biodiversity (including standardization of measures); ii) ecosystem  
94 functions; iii) ecological impacts, drivers, and stressors; iv) climate change effects on  
95 adaptive and evolutionary features; and v) deep-sea conservation. An international  
96 group of more than 110 deep-sea scientists with a broad range of scientific expertise in

97 deep-sea science identified these variables based on a Qualtrics<sup>24</sup> (see **Supplementary**  
98 **Methods**) survey, prioritized variables and parameters for each ecosystem pillar and  
99 discussed their potential use in future monitoring and conservation strategies,  
100 particularly in light of available technologies and their ongoing development. Finally,  
101 we identified those deep-sea areas globally, based on current knowledge that contain  
102 a high number of biodiversity hotspots and vulnerable ecosystems and could represent  
103 priority regions for future transnational deep-sea conservation actions.

104

### 105 **Measuring deep-sea species and habitat biodiversity**

106 Measuring deep-sea biodiversity has been a major challenge for deep-sea  
107 science since the pioneering expeditions of the 19<sup>th</sup> century (**Box 2**). To identify the  
108 essential variables that capture the different components of deep-sea biodiversity and  
109 their potential use in habitat management and conservation, we prepared a list of all  
110 known major biological variables and ecological parameters. The prioritized list of  
111 biodiversity variables, both in the water column and on the seafloor, including  
112 sediments, determined by Expert Elicitation is presented in **Table 1**. Among the  
113 different biodiversity components, medium to large-sized organisms (i.e. from  
114 macrofauna to megafauna) were considered most relevant in both marine  
115 compartments. For the water column, bacteria also ranked very high, given recent  
116 evidence of their importance in ecosystem functioning. Mega-zooplankton and nekton  
117 (including micro-nekton) are also included because of their central role as mid-trophic  
118 level prey for species of economic and conservation concern, and for their key roles in  
119 the biological pump, which transports carbon to depth. The nekton interacts with  
120 many benthic and pelagic systems across depths<sup>25</sup> emphasizing the importance of  
121 quantifying nekton abundance and biodiversity, including their role in ocean health. In  
122 addition, citizens often appreciate the relevance of this component and prioritize its  
123 monitoring, especially when referred to iconic and flagship animals (e.g. deep-sea  
124 sharks, giant squids, sperm whales, Dumbo octopus, Yeti crabs, Blob fish, giant  
125 cnidarians), or species of commercial interest (e.g. red corals, blue and red shrimps,  
126 deep-sea lobsters, orange roughy and Alfonsino fish), as well as critical habitats and  
127 ecosystem engineers (e.g. deep-water corals, giant sponges) (**Figure 2**). Indeed, these

128 species play crucial functional roles, sometimes as habitat-forming species, and their  
129 visual appeal to a wide audience offers potential for outreach and raising awareness.

130         Unfortunately, although some ship-based water column time-series have been  
131 maintained for more than 50 years<sup>26</sup> most of the water-column monitoring has been  
132 performed in shallow waters and coastal areas in the North Atlantic and the Antarctic  
133 Ocean, but not in the deep sea. Ecologists recognize that deep-sea ecosystems host a  
134 huge microbial (i.e. viral and bacterial<sup>27</sup>), meiofaunal and macrofaunal biodiversity,  
135 which contributes to regulate deep-sea ecosystem functioning<sup>28-31</sup>. We therefore  
136 highlight these components as a priority in terms of their contribution to the  
137 functioning of deep-sea ecosystems. In this study, assemblage structure, species  
138 distributions, and habitat heterogeneity resulted as the most fundamental measures of  
139 deep-sea biodiversity. Conversely, the quantification of biodiversity in terms of derived  
140 indices (i.e. expected species richness and evenness) are ranked with a lower priority,  
141 because many different indexes can be utilized, in an interchangeable way.

142

### 143 **Measuring ecosystem functions in the deep sea**

144         Terrestrial ecologists quantify ecosystem processes by measuring rates of  
145 energy and material flow between biotic and abiotic compartments (e.g. biomass  
146 production, transport, decomposition or loss of organic matter, as well as nutrient  
147 regeneration). However, not all terrestrial functional variables transfer easily to marine  
148 ecosystems, and variables that capture deep-sea functions and processes can differ  
149 somewhat from those used in coastal environments<sup>32-34</sup>.

150         At some carbon-rich deep-sea ecosystems (e.g. hydrothermal vents, cold seeps  
151 and canyons/fjords, OMZs), the higher trophic levels do not fully use organic carbon  
152 pools (due to their highly refractory composition<sup>35</sup>), with consequent substantial  
153 organic carbon burial<sup>36-39</sup>. However, most deep-sea ecosystems are strongly carbon-  
154 limited because the 'rain' of organic matter from the surface photic layer decreases  
155 exponentially with depth<sup>40-42</sup>.

156         The Expert Elicitation ranked trophic structure of deep-sea assemblages as the  
157 highest priority variables for ecosystem function, followed by benthic faunal biomass  
158 and morpho-functional traits (**Supplementary Table 1**). While megafauna (e.g.

159 holothurians, sponges) may be important drivers in carbon energy transfer, smaller  
160 fauna can contribute significantly to overall benthic biomass in deep-sea ecosystems.  
161 For instance, meiofaunal biomass becomes comparable or higher than that of macro-  
162 and megafauna at depths greater than 1000 m<sup>43,44</sup>. Morpho-functional traits represent  
163 a key indicator for ecosystem functioning<sup>44</sup>, although a more specific metric needs to  
164 be developed.

165

### 166 **Measuring deep-sea ecosystem health, impacts, and risk assessment**

167 The European Marine Strategy Framework Directive<sup>45</sup>, through the descriptors  
168 of Good Environmental Status and the Essential Biodiversity Variables (EBV<sup>46</sup>), provides  
169 tools for assessing the health of marine ecosystems, but focuses mainly on coastal  
170 environments. However, some MSFD descriptors also offer utility for deep-sea  
171 ecosystems. For instance, the MSFD and its descriptors of good environmental status  
172 include criteria defining ecosystem health alterations (e.g. habitat damage, overfishing,  
173 sediment and seafood contamination, litter and noise).

174 In the present study, these variables were used for selecting those enabling the  
175 assessment of various kinds of impact on deep-sea ecosystems (**Supplementary Table**  
176 **2**) and the Expert Elicitation indicated that “habitat damage” was the most relevant  
177 indicator of impact, because many species depend on habitat integrity to complete  
178 their life cycle, to reproduce, and find refuge from predatio<sup>47,48</sup>. Species distributions  
179 also depend on habitat heterogeneity. Resource exploitation/extraction (i.e. fisheries,  
180 mining, and oil and gas extractions) determines physical impacts and can destroy  
181 habitat with consequent biodiversity loss<sup>49</sup>. The outcome of the Expert Elicitation,  
182 therefore, prioritizes these impacts as highest concern.

183 Ecosystem resilience also ranked amongst the high-priority variables because it  
184 represents the ability of an ecosystem to recover after impact cessation. However, this  
185 indicator, which depends on many other variables, still lacks adequate standardization  
186 either in how it is measured or in its metrics. For instance, one recent study proposed  
187 to use the rate of benthic faunal recovery after a disturbance event (e.g. mining), as an  
188 indicator of resilience<sup>50</sup>, but rates of recovery vary significantly with the biological

189 component considered (e.g. meiofauna vs. deep-water corals). Thus, this indicator  
190 requires further consideration before defining a standardized approach.

191 Contamination of sediments ranked next in importance for assessing  
192 ecosystem health, followed by the consequent eco-toxicological effects, indicating an  
193 increasing perception that pollution is expanding down to the deep sea<sup>51-53</sup>. Also,  
194 marine litter and sediment resuspension might have a significant effect on deep-sea  
195 ecosystems and, for this reason, have been ranked next as potential indicators of  
196 impact.

197 The Expert Elicitation demonstrates that shallow-water and deep-sea  
198 ecosystems are subjected to different risks/impacts. For instance, the loss of top  
199 predators and/or invasion by alien species are considered priority concerns in coastal  
200 ecosystems, but not (yet) in the deep sea. Similar differences exist in appreciating  
201 potential impacts of noise. Despite the recognition of marine soundscape concerns  
202 even at bathyal-abyssal depth<sup>54</sup>, no strong evidence of serious harm is perceived by  
203 deep-sea scientists contributing to the survey.

204

### 205 **Measuring climate change impacts, the adaptation and evolution of deep-sea life**

206 The constancy of temperature over time represents perhaps the best-known  
207 attribute of all deep-sea ecosystems (excluding hydrothermal vents), along with the  
208 effects of temperature changes across geographic gradients<sup>55-57</sup>. However, increases in  
209 deep-sea temperatures have accelerated in recent decades, resulting in significant  
210 shifts in biodiversity, even for variation on the order of 0.1°C<sup>4</sup>.

211 The rapid rates of ongoing changes in the deep sea<sup>58-59</sup> require that organisms  
212 adapt locally to changing conditions or migrate to more suitable environments<sup>60</sup>. In  
213 this scenario, the results of the Expert Elicitation (**Supplementary Table 3**) indicate  
214 that “bathymetric shifts” in species distribution and “local extinction” of deep-sea  
215 species ranked of highest priority as they represent simple and effective indicators of  
216 the response of deep-sea biota to deep-water warming. A generalized deepening of  
217 middle-slope communities (950–1250 m), especially decapods, reported in the  
218 Mediterranean<sup>61</sup> relates to the high sensitivity of deep-sea species to changing  
219 temperature and limited thermal tolerance<sup>12,62,63</sup>, potentially leading to local

220 extinctions<sup>64</sup>. Deep-water warming could also facilitate penetration of alien species  
221 pre-adapted to such conditions<sup>63</sup> and recent studies reported the presence of alien  
222 species even in the deep sea<sup>65</sup>. Reproduction potential and timing of reproductive  
223 activities are useful variables, because they relate to shifts in timing, amount, and  
224 composition of food inputs from the photic zone<sup>66-68</sup>. Body-size miniaturization has  
225 been also identified as a potentially sensitive variable due to the expectation that sea-  
226 surface warming, by increasing vertical stratification can reduce the food supply to the  
227 deep sea.

228       Oxygen can be another important driver of adaptation<sup>69</sup>. At low oxygen  
229 concentrations, eukaryotic biodiversity and biomass decrease, whereas microbes play  
230 an increasingly important role<sup>70</sup>. However, rates of expansion of OMZs in the deep may  
231 outpace the ability of these species to adapt. The same temporal issues apply to the  
232 growing impact of ocean acidification on deep-sea biogeochemical cycles and biota.  
233 The greatest impacts of acidification have been documented on aragonitic calcifying  
234 organisms such as habitat forming cold-water and red corals<sup>59,71,72</sup>, with further  
235 impacts implicated on other deep-sea taxa with calcareous skeletal elements such as  
236 mollusks, sponges and calcareous foraminifera.

237

### 238 **Measuring essential variables needed for deep-sea ecosystems conservation**

239       Oil, gas, and mineral extraction, as well as bottom trawl fisheries will potentially  
240 impact large portions of deep seabed areas (e.g. seamounts, hydrothermal vents, cold  
241 seeps, canyons and abyssal plains)<sup>11</sup>. These current and impending activities add  
242 urgency for action on deep-sea conservation, especially given the paucity of scientific  
243 data to identify priority and/or representative areas for protection<sup>73-77</sup>.

244       Ecological indicators for deep-sea ecosystem conservation should consider  
245 variables related both to biodiversity (i.e. species richness, abundance) and to the  
246 interconnection among deep-sea eco-regions and between shallow and deep-sea  
247 habitats. Other variables can be relevant, such as species rarity or endemism, and  
248 some indicators should quantify the capacity of a deep ecosystem to serve as a source  
249 area for biodiversity in surrounding (even remote) shallow and deep-sea ecosystems  
250 through connectivity (spill-over effects).

251 Current approaches for deep-sea conservation vary widely among proponents,  
252 with potential application of many approaches and tools to maintain the integrity of  
253 marine ecosystems (**Supplementary Table 4**). Along with the establishment of deep-  
254 sea marine protected areas, restrictions with respect to fishing gear, quotas, bycatch,  
255 and maximum sampling depth, among others, can reduce both removal of organisms  
256 and physical disturbance<sup>78-81</sup>). Temporal tools could also be considered, by defining  
257 periodic restriction in fishing and/or extraction, or rotation of exploited areas. At the  
258 same time, regulations for dumping, waste disposal, emissions, turbidity, and toxin  
259 release (e.g. Toxic Maximum Daily Loads for the open ocean) are also important<sup>82-84</sup>.

260 In the present study, a tentative global map of deep-sea ecosystems and  
261 priority areas that merit monitoring efforts based on these criteria is presented in **Box**  
262 **2**. The protection of the following deep-ocean ecosystems should be prioritized based  
263 on Expert Elicitation: i) ocean regions expected to experience direct impact from  
264 human disturbance (e.g. resource extraction or waste disposal); ii) seas and ocean  
265 areas indirectly impacted by human disturbance, given their increased vulnerability to  
266 climate change (including acidification and deoxygenation); iii), biodiversity hotspots  
267 and providers of important ecosystem services; and finally, iv) areas of interest  
268 because of previous catastrophic events (e.g., the region of the Gulf of Mexico  
269 impacted by the Deep-water Horizon accident).

270 The complexity of the subject and the presence of multiple stressors and  
271 cumulative impacts, makes spatial integration of all quantitative and qualitative  
272 information difficult, but this map offers a start for discussion, with expectation of  
273 subsequent refinement.

274 In this scenario, expert opinion suggests that the most important ecological  
275 indicators for conservation is the presence of vulnerable deep-sea species/habitats  
276 (i.e. groups of species or habitats that may be vulnerable to impacts from fishing  
277 activities<sup>85</sup>; as well as habitat-forming species (**Supplementary Table 5**).

278 Acknowledging considerable overlap in the geographic areas that support habitat-  
279 forming species and vulnerable habitats, we considered the two indicators separately  
280 because we anticipate that the extent of vulnerable marine ecosystems may exceed  
281 that of habitat-forming species. Scientific justification should form the basis for future

282 designations of MPAs, based on the understanding of the geographic ranges and  
283 population connectivity of a wide variety of taxa, in order to design spatial  
284 management measures at appropriate scales. The only problem with this view is that  
285 characterization of distributions, ranges, and connectivity for most deep-sea species  
286 will require considerable time and effort, for both common and rare species. Thus, we  
287 must start with the best available proxies derived from genetic analyses upon animal  
288 sampling.

289         Connectivity of deep-sea species represents another priority conservation  
290 consideration. Connectivity plays a key role in the resilience of deep-sea species,  
291 populations, communities, and ecosystems following a disturbance event<sup>86</sup>. Analysis of  
292 connectivity is particularly important for habitat-forming species, such as deep-water  
293 corals, for species that inhabit patchy habitats (e.g. hydrothermal vents, methane  
294 seeps, seamounts among others), and for species with long life spans. New molecular  
295 methods and biophysical modelling approaches now facilitate the synthesis of gene  
296 flow and connectivity knowledge from ecosystems traditionally challenging to sample  
297 and study<sup>87,88</sup>. Habitat and species diversity are intrinsically linked<sup>89</sup>, so that  
298 identification of priority areas must include the mapping of deep-sea biodiversity  
299 ‘hotspots’<sup>90,91</sup>. Experts ranked attention to spawning and nursery areas as important  
300 conservation interests, but with lower priority, presumably because of the limited  
301 knowledge on recruitment and nursery areas in deep-sea ecosystems. Growing  
302 knowledge of new discoveries, for example of elasmobranch use of vents and seeps as  
303 nursery habitat<sup>92,93</sup>, may elevate the importance of this feature.

304         Experts suggest that endangered species outrank emblematic/flag species in  
305 importance, indicating that the deep-sea scientific community attributes these deep-  
306 sea species to social commitment and politicization, often coinciding with iconic  
307 examples in shallower-water areas. Although iconic deep-sea species exist (see **Figure**  
308 **2**), the deep-sea research community struggles to evaluate levels of endangerment for  
309 most taxa where sampling and monitoring data remain scant. The scientific  
310 community therefore cannot promote the need for conservation using examples of  
311 endangered species as icons for social awareness, though it can promote awareness of

312 the amazing animals in the deep sea through use of iconic images. Long-term global  
313 observing can improve our ability to assess endangerment for larger taxa.

314

### 315 **Technologies enabling deep-sea ecological indicators measurement**

316 The specific features of deep-sea ecosystems and the measurement of a  
317 complex set of biological variables and ecological indicators require sophisticated  
318 monitoring technologies. A large part of the priority variables identified by experts use  
319 optoacoustic imaging tools (i.e. HD color, stereo 3D, as well as acoustic cameras<sup>94</sup>).  
320 High-definition videos improve understanding of organism-level biology and ecology  
321 (for macro- and megafauna), providing direct information on life-history traits as well  
322 as intra and interspecific interactions and trophic niches. As organism body size  
323 decreases, deep-sea monitoring becomes more difficult given the need to integrate  
324 high-resolution observation and collection of small organisms.

325 Camera fields of view at fixed stations can monitor biological features or  
326 ecosystems<sup>95</sup>. Combining mobile platforms of different operating capabilities with  
327 sensors at fixed stations could expand the monitoring radius. Combinations of  
328 different technologies can support the simultaneous monitoring of different portions  
329 of deep-sea ecosystems, including: i) pelagic; ii) epi-benthic; and iii) endo-benthic  
330 compartments (**Figure 3**). For example, stationary, high-frequency time-lapse imaging  
331 over a period of years from cabled observatories can quantify megafaunal species  
332 richness<sup>60</sup>, with rovers and crawlers expanding local data acquisition to greater  
333 distances (several tens of m<sup>2</sup>)<sup>23,94,96</sup>. Benthic landers<sup>97</sup> or AUVs and gliders could  
334 expand this observation capability across even wider spatial scales (several km<sup>2</sup>)<sup>98</sup>.  
335 Collection of environmental data in conjunction with these observations will be  
336 important.

337 In the near future, benthic assets at fixed cabled observatories, their moored  
338 profilers, and the mobile tethered platforms (e.g. crawlers) will also support 3-D  
339 exploration and monitoring of deep-sea ecosystems. Fixed monitoring networks for  
340 animal-borne telemetric and data-logging technologies will complement these efforts  
341 (e.g. Ocean Tracking Network program<sup>99</sup>).

342 Presently, no in-sediment imaging technology can assay infaunal diversity. This  
343 measure requires sorting and DNA sequencing coupled with morphological studies. In  
344 recent years, meta-barcoding and genomic analyses of deep-sea organisms have  
345 expanded our overall knowledge of taxonomy beyond laboratory-based approaches  
346 (see also the Global Genome Initiative – GGI<sup>98,100</sup>). For example, biodiversity  
347 assessments of pelagic (mostly surface) ecosystems, already use metagenomic  
348 analyses (i.e. sequencing the genome of all species in a sample) to assess microbial  
349 diversity (e.g. Tara, Malaspina, Bermuda Atlantic Time Series, SCOPE program at  
350 ALOHA), illustrating the potential for developing similar approaches for deep-sea  
351 monitoring. Some deep-sea projects (e.g. ABYSS and Deep CCZ) are applying  
352 metabarcoding methods to assess benthic faunal biodiversity at regional to global  
353 scales. The use of molecular tools for identifying small-sized organisms is becoming a  
354 priority given the high cost, intensive labor, and visual limitations associated with  
355 traditional microscopic approaches, but current databases remain poor, and  
356 methodologies require important refinement<sup>101,102</sup>. Acknowledging ongoing  
357 development of technologies enabling *in situ* analyses (e.g. species traceability with  
358 eDNA marker sequencing), these *in situ* technologies are not yet operational.  
359 Sophisticated technologies are needed for the measurement of the complex set of  
360 biological variables and ecological indicators in the deep sea, along with their present  
361 readiness level (see **Supplementary Table 6**).

362 The ocean observing community now supports an array of sensors and  
363 platforms (floats, moorings, ships) that predominantly measure physical and  
364 biogeochemical properties. The biologists have begun to address essential ocean  
365 variables in the context of the Global Ocean Observing System<sup>103</sup>, but the deep ocean  
366 is poorly represented by these. A major challenge is to integrate the priority  
367 variables/parameters identified here with ongoing observing programs.

368

## 369 **Conclusions and future perspectives**

370 All current scenarios of blue growth anticipate increased exploitation of deep-  
371 ocean resources, with associated impacts of unknown intensity on deep-sea  
372 ecosystems. For instance, manganese nodules are non-renewable and will eventually

373 disappear, possibly for millions of years. Deep-sea ecosystem management and  
374 conservation should consider similar evolutionary scales, sustaining biodiversity and  
375 ecosystem functions to preserve ecosystem services (including evolutionary potential).  
376 The increasing interest in deep-sea exploitation creates an urgent need to expand  
377 biological and ecological knowledge at appropriate spatio-temporal scales. Future  
378 deep-sea monitoring needs agreed standardized protocols. Given the spatial scale of  
379 the deep ocean, the management of its resources requires also a wide international  
380 collaboration either to address societal needs including for policy development, or for  
381 the need to build capacity for sharing advanced technologies and related costs.

382         The present study defines a list of Deep-sea Essential Ecological Variables  
383 (DEEV; see **Table 2**), needed in future protocols for deep-sea studies (including the  
384 enforcement of Early-Warning Response Protocols) that can be utilized in territorial  
385 waters, in the Exclusive Economic Zones and in Areas Beyond National Jurisdictions  
386 (ABNJ). The use of the variables and indicators proposed here will also increase our  
387 ability to identify vulnerable and representative deep-sea ecosystems and priority  
388 areas deserving protection. Another advantage of the list of variables proposed here is  
389 that they allow a comparison with existing data sets, data sharing as well as the  
390 contribution to open access data portals.

391         The specific features of deep-sea ecosystems make technologies a key aspect  
392 for implementing deep-sea monitoring and represent one of the key issue for the UN  
393 Decade of Ocean Science for Sustainable Development (2021-2030). Future  
394 technological development should address the cost-effective monitoring of essential  
395 variables. At the same time, identifying appropriate spatial and temporal (including  
396 historical) scales remains a challenge, which merits additional transnational efforts. We  
397 are confident that the endorsement and adoption of these deep-ocean essential  
398 variables by industry, governmental organizations, and Environmental Non-  
399 Governmental Organizations could optimize the cost-benefits and return of the future  
400 monitoring initiative, providing, for the first time, a common scientific framework at  
401 the global scale that will allow scientists and policy makers and authorities to  
402 implement deep-sea monitoring, conservation, and the sustainable management of  
403 deep-sea ecosystems.

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762 **Author contributions**

763 R.D. conceived the idea. All authors contributed critically to the drafts and gave final  
764 approval for publication.

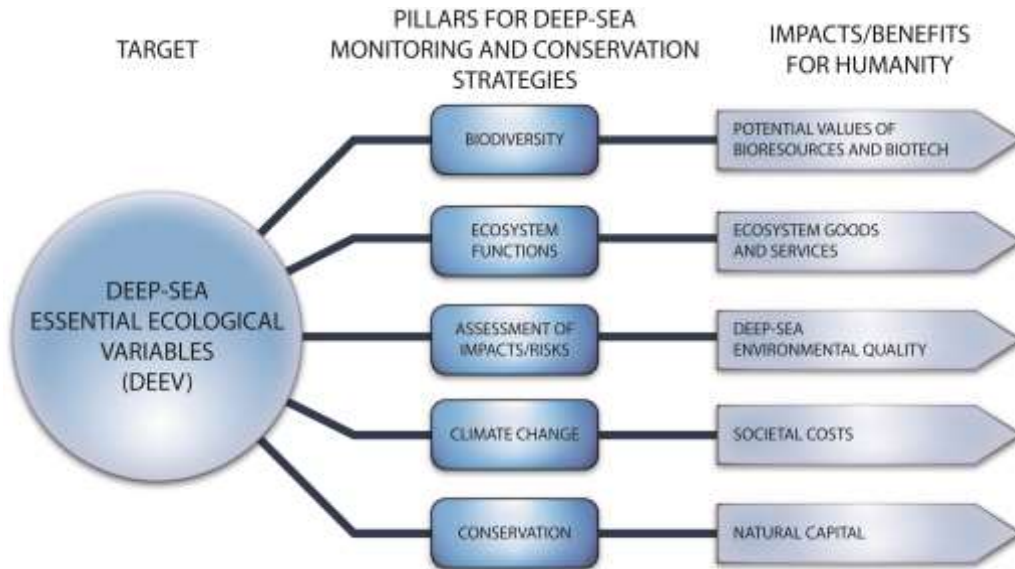
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766 **Competing interests**

767 The authors declare that they have no competing interests.

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776 **Figure 1.** Biology-focused deep-sea monitoring strategy based on internationally  
777 standardized variables. This monitoring strategy will facilitate the achievement of  
778 important societal and industrial objectives, including the discovery of the largest  
779 remaining fraction of unknown biodiversity on Earth, the development of new deep-  
780 sea technologies and exploitation of biotechnological potential, the maintenance of  
781 deep-ocean goods and services, the achievement of sustainable development goals,  
782 and finally the mitigation of global change.

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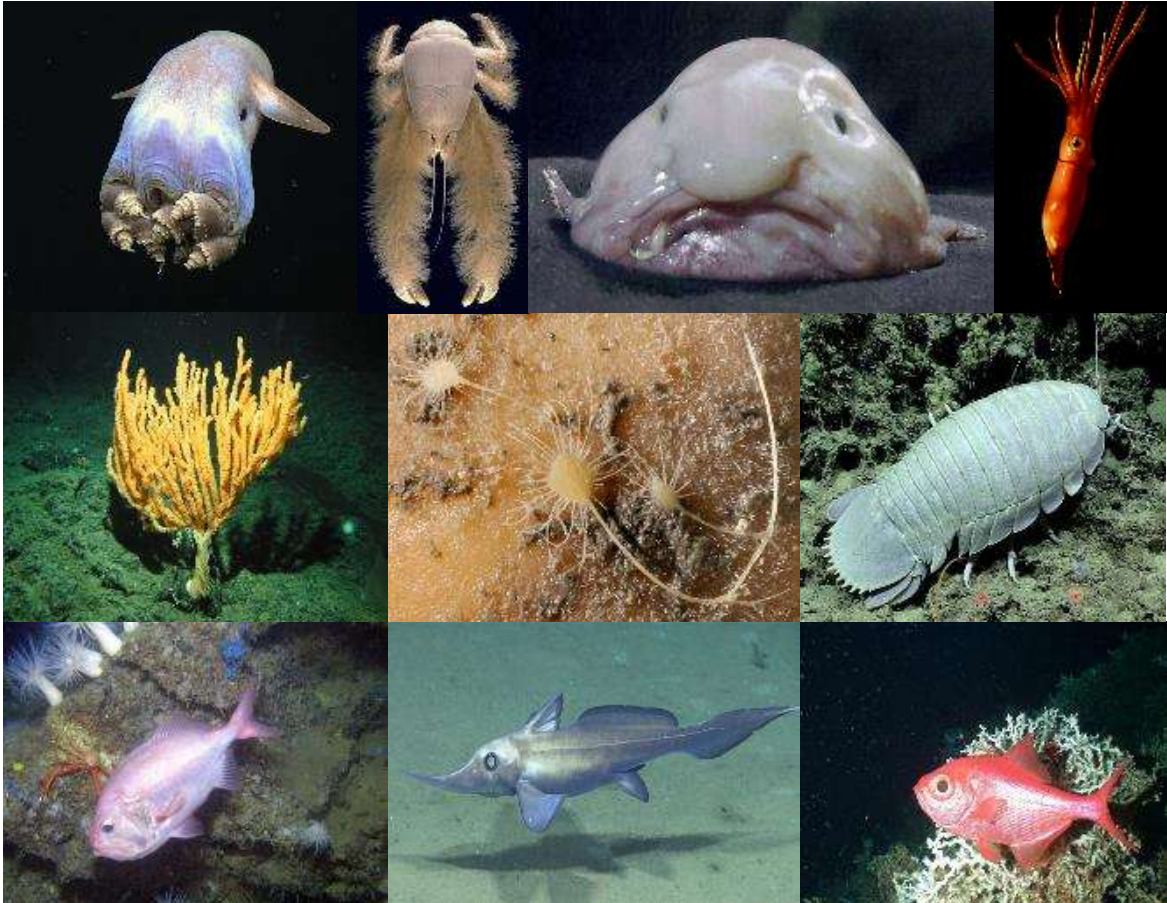
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806 **Figure 2.** An example of iconic and flag species that inhabit deep-sea ecosystems. From  
807 left to right, from the top to the bottom: *Grimpoteuthis robson* (Dumbo octopus), *Kiwa*  
808 *hirsuta* (Yeti crab), *Psychrolutes marcidus* (Blob fish), *Architeuthis sanctipauli* (Giant  
809 squid), *Isidella tentaculum*, *Abyssocladia polycephalus*, *Bathynomus giganteus*,  
810 *Hoplostethus atlanticus* (Orange roughy), *Harriotta raleighana*, *Beryx decadactylus*.

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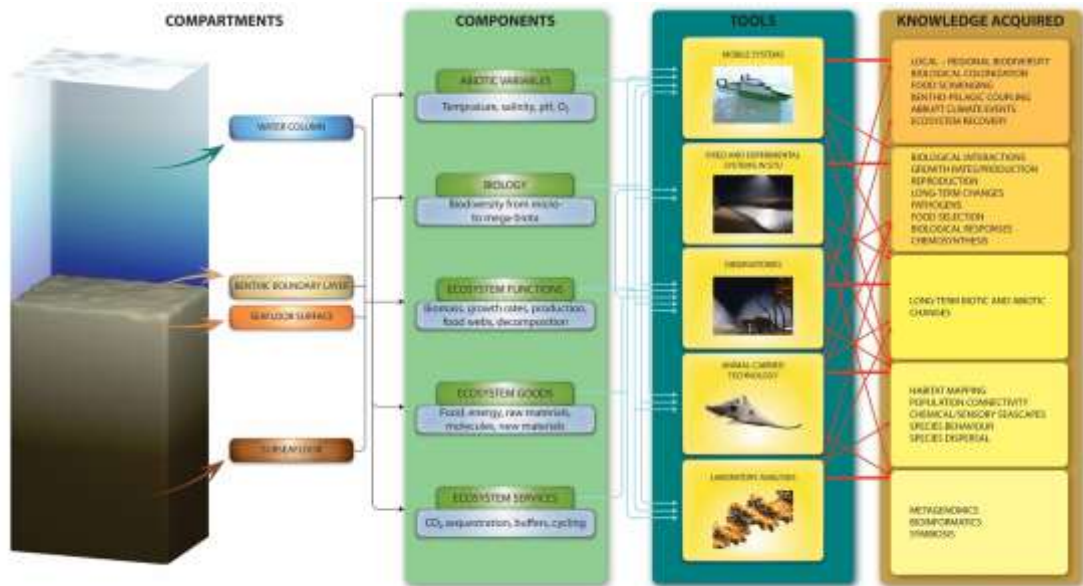
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824 **Figure 3.** A conceptual diagram illustrating the potential technological development  
825 planned to acquire knowledge for sustainable use/management of deep ocean use.  
826 The illustration includes: the deep-sea compartments of interest (left column), the  
827 abiotic and biotic components (central-left column), potential tools and intelligent  
828 technologies needed to investigate the deep ocean (central-right column), and the  
829 potential knowledge acquired (right column).

830

831 **Table 1.** Deep-sea essential ecological variables for monitoring biodiversity in the  
 832 water column and seabed, as well as the associated metrics (Expert Elicitation, n=112).

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834

<i>Biodiversity water column</i>	<i>Priority</i>
Nekton	Very high
Bacteria	Very high
Macrozooplankton/Micronekton	High
Megazooplankton	Medium
Mesozooplankton	Medium
Microzooplankton	Medium
Protozoa	Low
Archaea	Very low
<i>Biodiversity in sediments/on the seafloor</i>	
Epibenthic large and sessile megafauna	Very high
Macrofauna	High
Meiofauna	Medium
Nekto-benthos	Medium
Bacteria	Medium
Protozoa	Low
Archaea	Very low
<i>Biodiversity measures</i>	
Assemblage structure	Very high
Species distribution	Very high
Habitat heterogeneity	High
Population size (N)	Medium
Species richness	Medium
ES(100)	Low
Phylogenetic distinctness	Low
Endemism	Low
Rarity	Very low
Evenness	Very low

835

836 **Table 2.** Summary of actions required for deep-sea monitoring of the most important  
 837 essential ecological variables (i.e. ranked as “Very high” in the Expert Elicitation) for  
 838 the five pillars of knowledge (see **Supplementary Tables** from 1 to 3 and 5). Developed  
 839 monitoring actions utilize high-resolution technologies (see types and current level of  
 840 technological development in **Supplementary Table 6**).

Pillar of knowledge	Essential ecological variables	Monitoring approach
<b>Biodiversity</b>	Assemblage Structure	Computing species distribution and assemblage structure per sampling zone and summing up the data for the whole area
	Species Distribution	
<b>Ecosystem functions</b>	Trophic structure	Classifying and quantifying feeding-oriented interactions (i.e. listing food items for trophic niche characterization), combining the use of direct ethological observations as well as statistical proxies (i.e. <i>via</i> recurrent species spatiotemporal co-presence). The food web architecture could be then inferred by joining together trophic niche data for all species
	Benthic faunal biomass	Biovolume estimates (e.g. class size frequencies from individuals body length)
	Morpho-functional traits	Classification of species morphological adaptations according to a variable level of dependency upon the substrate (i.e. from endo-benthos as burrowers and buriers to epi-benthos as sheltering taxa, and ending with nekton-benthos freely swimming in the BBL or benthopelagos moving into the water column)
<b>Impact/risk assessment</b>	Habitat damage	The analysis of seascapes changes based on habitat mapping approaches and georeferenced photomosaic compositions
	Resilience (recovery rate)	Multivariate analysis time series counts for species depicting fluctuations according to concomitant oscillations of key environmental drivers (e.g. temperature and oxygen maxima and minima)
<b>Adaptation &amp; Evolution</b>	Shifts in bathymetric distribution	Assessing changes in the geographic, bathymetric, and endemic detection of individuals (both juveniles and adults).
	Local extinctions	Richness data comparison over consecutive years and identification of abundance decreasing trends. Changes in richness due to disappearing or not previously detected species.
<b>Conservation</b>	Vulnerable deep-sea habitats	Quantifying density and distribution patterns of dominant (i.e. abundant) sessile species as "Facies" (e.g. sea pens, cold water corals, sponges, tube worms, bivalves) per each sampling area
	Habitat forming species	

841

843 **Box 1. Main threats for deep-sea ecosystems**

844 The deep oceans are increasingly impacted by human activities. Here the four major  
845 threats for deep-sea species/habitats/ecosystems are presented, although they are  
846 treated individually, their effects can be cumulative and multiple threats can be  
847 interactive.

848 **Climate change.** Ocean warming is expected to reduce surface ocean production<sup>104</sup>  
849 and hence the POC flux (i.e., food supply) to the deep-sea life<sup>41</sup>, altering structural and  
850 functional variables of deep-sea assemblages<sup>105-107</sup>. Temperature changes in the deep-  
851 sea influence key life-history traits (i.e. reproductive effort, larval development<sup>63,108,109</sup>  
852 longevity, and metabolic rates, and body size of deep-sea organisms<sup>110</sup>). Higher  
853 temperatures increase deep-sea respiration, thus exacerbating the effects of food  
854 limitation<sup>111</sup>. Such changes are expected to select the species pre-adapted to new  
855 condition<sup>55</sup>, thus increasing beta diversity over time<sup>112</sup>. Moreover, climate change will  
856 presumably cause oxygen decline and expand OMZs<sup>69</sup>, accelerate organic matter  
857 biogeochemical cycling, miniaturize organism size and increase mortality of deep-sea  
858 biota, potentially resulting in extinctions in species with limited dispersal capabilities,  
859 or where suitable habitats become unavailable. Also, ocean acidification reduces the  
860 calcification capacity of corals and crustaceans, alters their metabolism<sup>113</sup>, and  
861 dissolves the non-living components of coral reefs<sup>72</sup>.

862 **Oil/gas extraction and mining.** The substantial development of methane hydrate  
863 extraction and deep-sea mining is exacerbating conservation concerns despite the  
864 absence of baseline ecological knowledge<sup>37</sup>. The impact of proposed large-scale deep-  
865 sea mining and oil and gas drilling offshore activities can potentially transform deep-  
866 sea ecosystem structure and functions irreversibly<sup>114,115</sup>, removing most life locally,  
867 possibly leading to “desertification” of the ocean<sup>9</sup>. Such environmental degradation  
868 associated with exploitation has well-known parallels on land, where poor  
869 environmental practices have promoted land degradation and eventual desertification  
870 in many terrestrial ecosystems<sup>98,116-118</sup>. The potential consequences of this degradation  
871 can add tensions between the pressure to develop industrial exploitation rapidly and  
872 the desire to establish robust and quantitative baseline knowledge on the status of  
873 deep-sea ecosystem goods and services<sup>3,119</sup>.

874 **Deep-sea fishery.** Historically established deep-sea fisheries have a proven capacity to  
875 remove slow-growing, long-lived species<sup>120</sup> and many habitat-forming organisms from  
876 the seafloor<sup>121</sup>, greatly altering habitat properties (e.g. removal and resuspension of  
877 bottom sediment<sup>122</sup>). Further, many deep-sea commercial species congregate in large  
878 numbers around seamounts to feed and spawn, making them extremely vulnerable to  
879 overfishing (the case of Patagonian toothfish and orange roughy fished to commercial  
880 extinction in just a few years). Presently, most deep-water species are likely to be over-  
881 exploited, as ca. 40% of the world’s fishing grounds are now in waters deeper than 200  
882 m<sup>123</sup>.

883 **Contaminants and Debris.** Growing human population has led to increased inputs of  
884 pollutants and debris, including plastic, into the ocean, where they are transferred  
885 through passive sinking or trophic transfer into the deep sea. Both macro-plastic and  
886 organic contaminants are common in sediments and organisms all the way to the  
887 deepest waters including the Mariana Trench<sup>53,124</sup>. Microplastics are pervasive in deep-  
888 sea sediments where they make their way into the food web<sup>125</sup>. Deep-water oil spills,  
889 cargo spillage, intentional waste disposal, pharmaceuticals and other organic  
890 contaminants threaten the integrity of deep-sea populations, but the sources,  
891 pathways, fates and ultimate consequences are poorly known<sup>1</sup>.

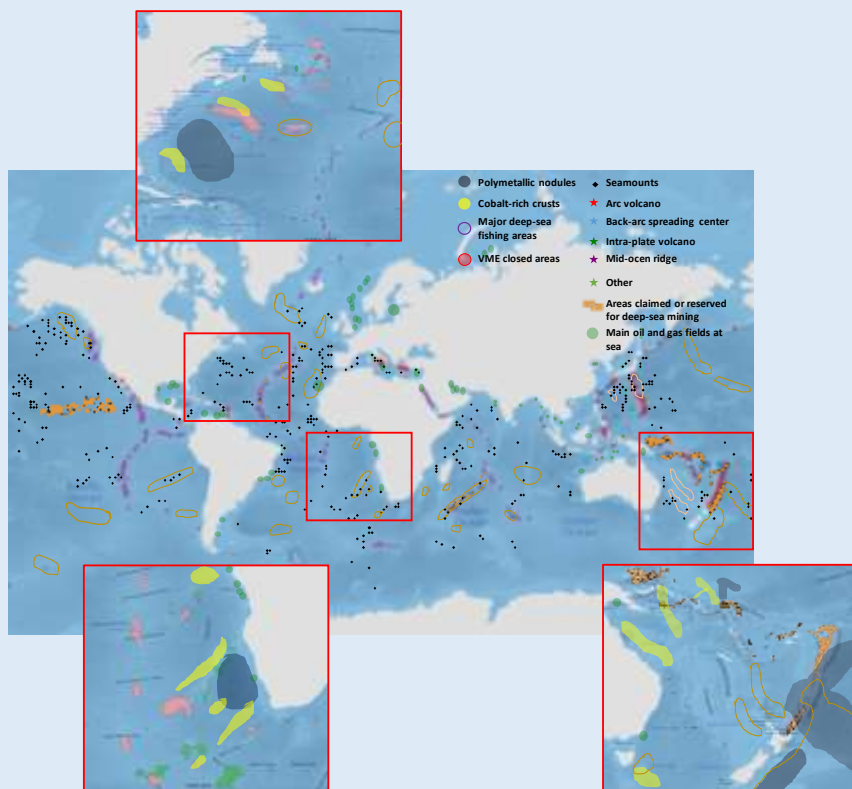
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## 895 **Box 2. Current monitoring initiatives**

896 The Deep-Ocean Stewardship Initiative (DOSI), the International Network for Scientific  
 897 Investigation of Deep-Sea Ecosystems (INDEEP), the Group on Earth Observation –  
 898 Biodiversity Observing Network (GEO-BON) aim at providing scientific advice to  
 899 support the United Nations Sustainable Development Goal SDG 14 (i.e. conservation  
 900 and sustainable use of the ocean and its resources). The Global Ocean Observing  
 901 System (GOOS), and the Deep Ocean Observation System (DOOS) are attempting to  
 902 define strategies for identifying Essential Ocean Variables<sup>126</sup>, but lack of adequate  
 903 biological/ecological approach<sup>119,127</sup>. The INDEEP has developed A World Register of  
 904 Deep-Sea Species (WoRDSS) based on the World Register of Marine Species (WoRMS).  
 905 The Census of Marine Life (CoML<sup>128</sup>) has contributed to the census of deep-sea species,  
 906 which however remains far from being complete as 50% of macro-megafaunal and  
 907 likely more than 80-90% of meiofaunal species remain undiscovered<sup>129,130</sup>. These  
 908 monitoring initiatives supported the characterization of a set of variables described  
 909 according to the scientific pillars identified. Existing approaches, protocols and  
 910 technologies focused on deep-sea pelagic and benthic ecosystems processes include  
 911 the following indicators of **ecosystem functioning**: i) microbial heterotrophic  
 912 production and microbial chemoautotrophic production (i.e., the ability to transfer  
 913 energy to higher trophic levels); iii) size-specific biomass and production in prokaryotes  
 914 and eukaryotes (including uni- and multicellular organisms) as a measure of the  
 915 production of renewable resources by ecosystems; iv) predator-prey relationships,  
 916 food-web structure, and energy flows; v) rates of organic matter respiration,  
 917 decomposition, and recycling; and vi) habitat provisioning (numbers and composition  
 918 of fauna utilizing biological structures such as deep-water corals<sup>131</sup>). Carbon limitation  
 919 may push deep-sea organisms to increase the efficiency of resources' exploitation<sup>132</sup>.  
 920 Potential indicators of ecosystem efficiency<sup>8</sup> include: i) the ratio of benthic faunal  
 921 biomass or production to organic C input; ii) the ratio of prokaryote C production to  
 922 organic C flux; iii) the ratio of benthic faunal biomass to available food in sediments.  
 923 The identification of the indicators of **ecological impacts** requires a holistic approach.  
 924 Environmental risk assessments rely on understanding the intensity and frequency of  
 925 disturbance created by an activity and the sensitivity of the target ecosystem to those  
 926 disturbances<sup>1</sup>. Current monitoring initiatives consider the needs of baseline studies to  
 927 analyze baseline conditions, thus facilitating routine monitoring of environmental  
 928 impacts of human activities (and natural events) to gauge ocean health within the  
 929 context of natural variation. The ideal set of indicators should combine broad  
 930 spectrum and specific indicators, able to provide high sensitivity in detecting a wide  
 931 range of impacts (i.e., degradation or loss of habitat, sediment resuspension, light and  
 932 noise footprints, the introduction of toxic materials<sup>133,134</sup>). The indicators of **climate**  
 933 **change impacts** consider shifts in deep-sea species spatial distribution<sup>135</sup>, as a measure  
 934 of the capacity of organisms to adapt to changing conditions or the preference to  
 935 migrate to more favorable conditions, and loss of marine biodiversity<sup>136</sup>. Species-  
 936 specific traits (i.e. body size, reproduction mode, feeding behavior, etc.) allow  
 937 quantification of how species respond to global change including climate change,  
 938 biological invasions, overexploitation and habitat fragmentation<sup>137, 138</sup>. New

939 ecosystems and habitat types are continuously discovered at depths below 200 m<sup>49,139</sup>,  
 940 and most of these represent hotspots of key processes or endemic species<sup>19, 140,141</sup>,  
 941 which require conservation strategies. Currently, **deep-sea conservation initiatives**  
 942 include off-shore MPAs (i.e. Special Areas of Conservation) and Other Effective Area-  
 943 Based Conservation Measures, including Area-Based Fisheries Management, the  
 944 designation of Vulnerable Marine Ecosystems (VME), or Areas of Particular  
 945 Environmental Interests –APEIs- which are a form of MPA where no mining will be  
 946 authorized to take place<sup>142</sup> (see also **Supplementary Table 5**). However, these  
 947 conservation measures ensure the effective protection of very few specific habitat-  
 948 types and species assemblages or even unique species and over very limited spatial  
 949 scales<sup>143</sup>. Additionally, the Convention on Biological Diversity (CBD) has begun the  
 950 effort of deep-sea conservation by designating Ecologically and Biologically Significant  
 951 Areas (EBSAs), based on several criteria: i) uniqueness or rarity; ii) special importance  
 952 for life history of species; iii) importance for threatened, endangered or declining  
 953 species, and/or habitats; iv) vulnerability, fragility, sensitivity, slow recovery; v)  
 954 biological productivity; vi) biological diversity; and vii) naturalness. These criteria  
 955 should be weighted according to the connectivity of the areas, their  
 956 representativeness, and their extension. There is therefore an urgent need to identify  
 957 priority areas for protection at a global scale, starting from Areas Beyond National  
 958 Jurisdiction and the High Seas. Conservation efforts should also consider the need to  
 959 protect the full range of habitats within an ecoregion, at spatial scales and spacing  
 960 sufficient to sustain populations<sup>76,77</sup>. Deep-sea conservation should target three-  
 961 dimensional representative habitats, areas with high topographic complexity and  
 962 habitat heterogeneity, and biodiversity hot-spots with high levels of endemism.



963

964 **Figure Box 2.** Global map of deep-sea areas that according to international standards  
965 have been identified as priority target for protection. Source: VME closed areas,  
966 seamounts, arc volcanoes, back arc spreading centers, intra-plate volcanoes, mid-  
967 ocean ridges and other similar features and bottom fishing areas (green blocks in inset  
968 figure off SW Africa, SEAFO area) from the FAO VME database (accessed March 2018);  
969 areas claimed or reserved for deep-sea mining from International Seabed Authority,  
970 Flanders Marine Institute, Nautilus Mineral (orange areas); marine mineral deposits  
971 (i.e. polymetallic nodules (blue) and cobalt-rich ferromanganese crusts (light green)<sup>144</sup>;  
972 main deep-sea fishing areas and major fisheries on seamounts and ridges (purple  
973 lines)<sup>145</sup>.

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975