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

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2

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

5

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40

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 sea¹⁻³, 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 ecosystems⁴⁻⁷. In particular,
71 species loss and deep-sea habitat destruction produce severe alteration of ecosystem
72 functioning and reduce overall ecosystem goods and services^{2,8,9}. In addition,
73 cumulative marine impacts act synergistically with climate-induced changes in deep-
74 ocean properties and processes, degrading environmental quality¹⁰⁻¹².

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^{8,13}. Furthermore, high biodiversity levels increase
78 ecosystem resilience to perturbations^{14,15}, elevating the importance of maintaining
79 biodiversity as an important management objective in the pursuit of sustainable use of
80 resources^{16,17}. 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^{6,18}. Bi-directional exchange of materials, nutrients, contaminants, and
84 organisms between shallow and deep-sea ecosystems occurs widely in all oceans¹⁹⁻²³
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 Qualtrics²⁴ (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 19th 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 depths²⁵ 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 years²⁶ 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 bacterial²⁷), meiofaunal and macrofaunal biodiversity,
135 which contributes to regulate deep-sea ecosystem functioning²⁸⁻³¹. 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 environments³²⁻³⁴.

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 composition³⁵), with consequent substantial
153 organic carbon burial³⁶⁻³⁹. 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 depth⁴⁰⁻⁴².

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^{43,44}. Morpho-functional traits represent
163 a key indicator for ecosystem functioning⁴⁴, 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 Directive⁴⁵, through the descriptors
168 of Good Environmental Status and the Essential Biodiversity Variables (EBV⁴⁶), 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^{47,48}. 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 loss⁴⁹. 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 resilience⁵⁰, 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 sea⁵¹⁻⁵³. 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 depth⁵⁴, 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 gradients⁵⁵⁻⁵⁷. 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°C⁴.

211 The rapid rates of ongoing changes in the deep sea⁵⁸⁻⁵⁹ require that organisms
212 adapt locally to changing conditions or migrate to more suitable environments⁶⁰. 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 Mediterranean⁶¹ relates to the high sensitivity of deep-sea species to changing
219 temperature and limited thermal tolerance^{12,62,63}, potentially leading to local

220 extinctions⁶⁴. Deep-water warming could also facilitate penetration of alien species
221 pre-adapted to such conditions⁶³ and recent studies reported the presence of alien
222 species even in the deep sea⁶⁵. 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 zone⁶⁶⁻⁶⁸. 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 adaptation⁶⁹. At low oxygen
229 concentrations, eukaryotic biodiversity and biomass decrease, whereas microbes play
230 an increasingly important role⁷⁰. 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^{59,71,72}, 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)¹¹. 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 protection⁷³⁻⁷⁷.

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 disturbance⁷⁸⁻⁸¹). 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 important⁸²⁻⁸⁴.

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 activities⁸⁵; 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 event⁸⁶. 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^{87,88}. Habitat and species diversity are intrinsically linked⁸⁹, so that
298 identification of priority areas must include the mapping of deep-sea biodiversity
299 ‘hotspots’^{90,91}. 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^{92,93}, 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 cameras⁹⁴).
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 ecosystems⁹⁵. 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 richness⁶⁰, with rovers and crawlers expanding local data acquisition to greater
333 distances (several tens of m²)^{23,94,96}. Benthic landers⁹⁷ or AUVs and gliders could
334 expand this observation capability across even wider spatial scales (several km²)⁹⁸.
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 program⁹⁹).

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^{98,100}). 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^{101,102}. 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 System¹⁰³, 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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746 *the guidelines may be practically implemented* (IUCN, Switzerland, 2008).

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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.

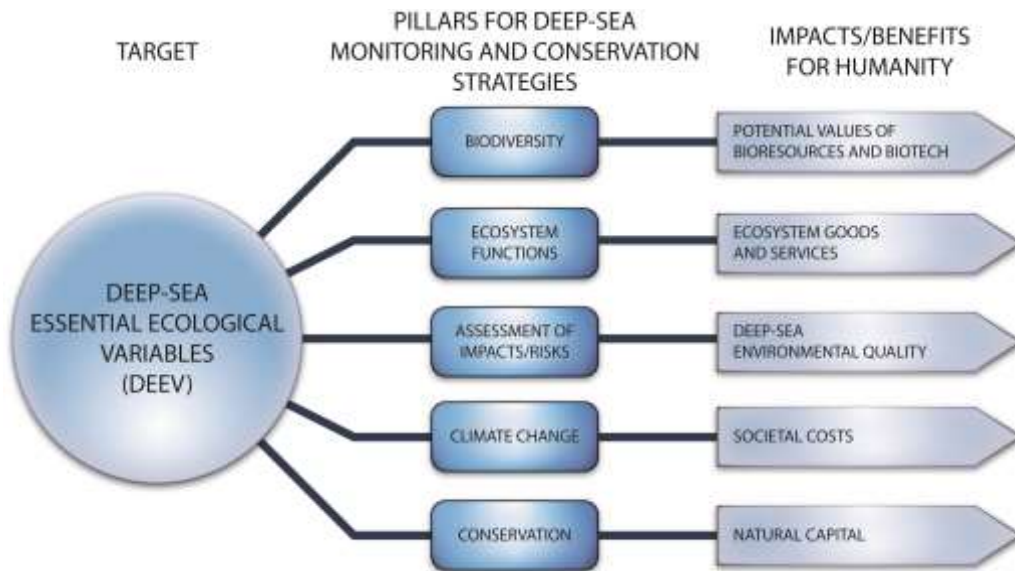
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766 **Competing interests**

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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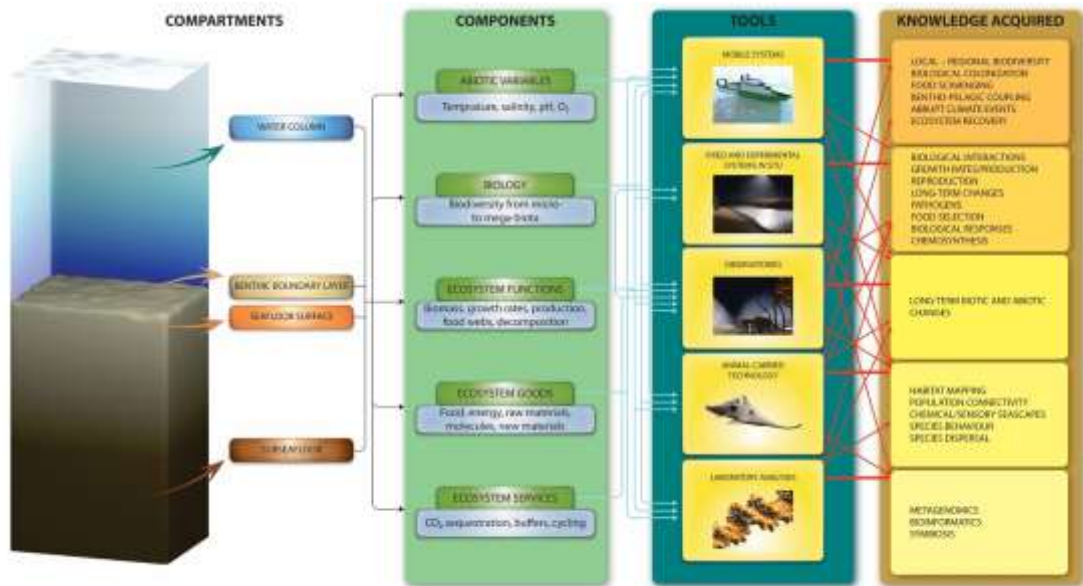
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Figure 2. An example of iconic and flag species that inhabit deep-sea ecosystems. From left to right, from the top to the bottom: *Grimpoteuthis robson* (Dumbo octopus), *Kiwa hirsuta* (Yeti crab), *Psychrolutes marcidus* (Blob fish), *Architeuthis sanctipauli* (Giant squid), *Isidella tentaculum*, *Abyssocladia polycephalus*, *Bathynomus giganteus*, *Hoplostethus atlanticus* (Orange roughy), *Harriotta raleighana*, *Beryx decadactylus*. This derivative work is made available under the terms of the Creative Commons Attribution-Non Commercial 4.0 License, <https://creativecommons.org/licenses/by-nc-sa/4.0/>

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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).

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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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<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
Endemicity	Low
Rarity	Very low
Evenness	Very low

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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
Biodiversity	Assemblage Structure	Computing species distribution and assemblage structure per sampling zone and summing up the data for the whole area
	Species Distribution	
Ecosystem functions	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)
Impact/risk assessment	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)
Adaptation & Evolution	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.
Conservation	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	

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Box 1. Main threats for deep-sea ecosystems

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

Climate change. Ocean warming is expected to reduce surface ocean production¹⁰⁴ and hence the POC flux (i.e., food supply) to the deep-sea life⁴¹, altering structural and functional variables of deep-sea assemblages¹⁰⁵⁻¹⁰⁷. Temperature changes in the deep-sea influence key life-history traits (i.e. reproductive effort, larval development^{63,108,109} longevity, and metabolic rates, and body size of deep-sea organisms¹¹⁰). Higher temperatures increase deep-sea respiration, thus exacerbating the effects of food limitation¹¹¹. Such changes are expected to select the species pre-adapted to new condition⁵⁵, thus increasing beta diversity over time¹¹². Moreover, climate change will presumably cause oxygen decline and expand OMZs⁶⁹, accelerate organic matter biogeochemical cycling, miniaturize organism size and increase mortality of deep-sea biota, potentially resulting in extinctions in species with limited dispersal capabilities, or where suitable habitats become unavailable. Also, ocean acidification reduces the calcification capacity of corals and crustaceans, alters their metabolism¹¹³, and dissolves the non-living components of coral reefs⁷².

Oil/gas extraction and mining. The substantial development of methane hydrate extraction and deep-sea mining is exacerbating conservation concerns despite the absence of baseline ecological knowledge³⁷. The impact of proposed large-scale deep-sea mining and oil and gas drilling offshore activities can potentially transform deep-sea ecosystem structure and functions irreversibly^{114,115}, removing most life locally, possibly leading to “desertification” of the ocean⁹. Such environmental degradation associated with exploitation has well-known parallels on land, where poor environmental practices have promoted land degradation and eventual desertification in many terrestrial ecosystems^{98,116-118}. The potential consequences of this degradation can add tensions between the pressure to develop industrial exploitation rapidly and the desire to establish robust and quantitative baseline knowledge on the status of deep-sea ecosystem goods and services^{3,119}.

Deep-sea fishery. Historically established deep-sea fisheries have a proven capacity to remove slow-growing, long-lived species¹²⁰ and many habitat-forming organisms from the seafloor¹²¹, greatly altering habitat properties (e.g. removal and resuspension of bottom sediment¹²²). Further, many deep-sea commercial species congregate in large numbers around seamounts to feed and spawn, making them extremely vulnerable to overfishing (the case of Patagonian toothfish and orange roughy fished to commercial extinction in just a few years). Presently, most deep-water species are likely to be over-exploited, as ca. 40% of the world’s fishing grounds are now in waters deeper than 200 m¹²³.

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^{53,124}. Microplastics are pervasive in deep-
888 sea sediments where they make their way into the food web¹²⁵. 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 known¹.

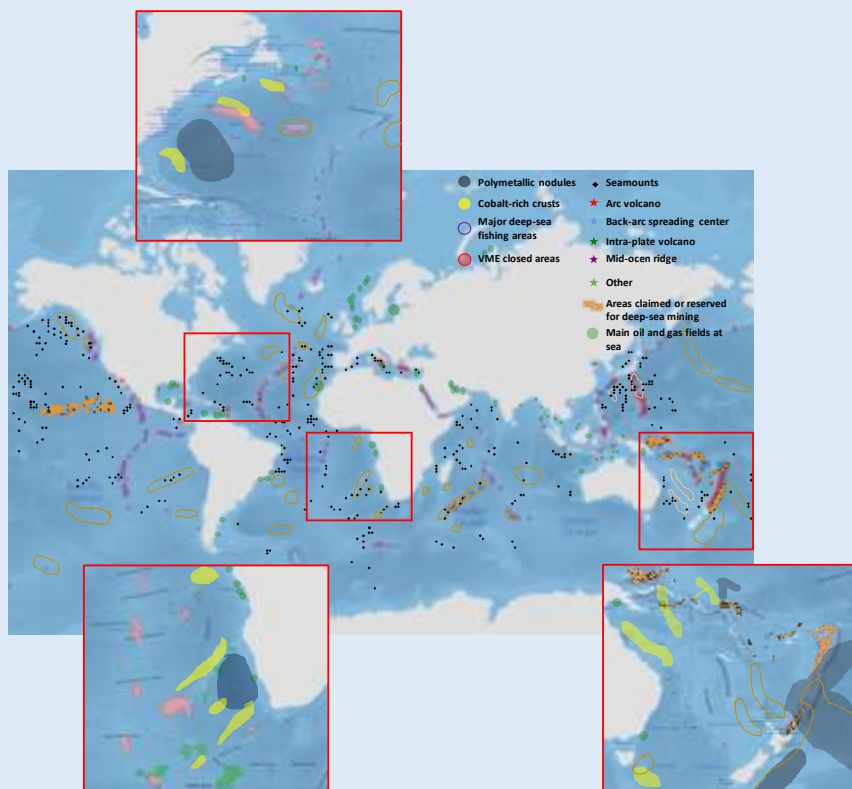
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895 **Box 2. Current monitoring initiatives**

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 Variables¹²⁶, but lack of adequate
 903 biological/ecological approach^{119,127}. 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 (CoML¹²⁸) 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^{129,130}. 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 corals¹³¹). Carbon limitation
 919 may push deep-sea organisms to increase the efficiency of resources' exploitation¹³².
 920 Potential indicators of ecosystem efficiency⁸ 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 disturbances¹. 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^{133,134}). The indicators of **climate**
 933 **change impacts** consider shifts in deep-sea species spatial distribution¹³⁵, 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 biodiversity¹³⁶. 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^{137, 138}. New

939 ecosystems and habitat types are continuously discovered at depths below 200 m^{49,139},
 940 and most of these represent hotspots of key processes or endemic species^{19, 140,141},
 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 place¹⁴² (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 scales¹⁴³. 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^{76,77}. 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.



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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)¹⁴⁴;
972 main deep-sea fishing areas and major fisheries on seamounts and ridges (purple
973 lines)¹⁴⁵.

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