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Towards a marine strategy for the deep Mediterranean Sea: Analysis of current ecological status

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Abstract :

The Marine Strategy Framework Directive (MSFD), introduced in June 2008, was adopted to achieve a Good Environmental Status (GES) in the EU's marine waters and to protect resources of socio-economic interest. The MSFD extends to the marine area over which a Member State exercises jurisdictional rights in accordance with the United Nations Convention on the Law of the Sea (UNCLOS), including the deep-sea waters, seafloor and sub-seafloor of the Exclusive Economic Zones (EEZ). However, currently the MSFD focuses on coastal habitats and the shallow-water seafloor to the detriment of the deeper habitats. Despite the huge dimension of the deep sea (below 200 m of depth) covering more than 65% of the Earth's surface and including >95% of the global biosphere, the relevance of the dark portion of the seas and oceans is still almost completely neglected. Given the important bi-directional links between shallow and deep ecosystems, there is a clear need for extending the implementation of the MSFD into the deep sea, to define a sound ecosystem-based approach for the management and protection of deep-sea ecosystems and attain GES. We assembled data on drivers, anthropogenic pressures and impacts concerning the MSFD descriptors pertaining to the Mediterranean deep sea. We list deep-sea monitoring activities and the main sources providing benchmark conditions, and discuss knowledge and geographic coverage gaps. MSFD descriptors apply to the deep sea as to coastal waters, and ought to be monitored contemporaneously. We provide recommendations for guidelines for future deep-sea monitoring in the Mediterranean Sea.

Highlights

► MSFD fails to cover the huge dimension of deep-sea environments and important bi-directional link with shallow ones. ► Extending MSFD to the deep sea and defining an ecosystem-based approach for its management and protection is urgently needed. ► Data on drivers, anthropogenic pressures and impacts regarding the MSFD descriptors for deep-sea Mediterranean were reviewed. ► Deep-sea monitoring activities were discussed and knowledge and geographic coverage gaps evidenced. ► Recommendations for guidelines for future deep-sea monitoring were provided.

Keywords : Marine strategy framework directive, Deep-sea ecosystems, Mediterranean basin

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6 **List of acronyms and abbreviations**

- 7 ABNJ: Areas Beyond National Jurisdiction
- 8 ACCOBAMS: Agreement on the Conservation of Cetaceans in the Black Sea Mediterranean Sea and
- 9 Contiguous Atlantic Area
- 10 AUV: Autonomous Underwater Vehicle
- 11 CBD: Convention on Biological Diversity
- 12 CFP: Common Fisheries Policy
- 13 CWC: Cold-Water Corals
- 14 DCF: Data Collection Framework
- 15 DSF: Deep-Sea Fisheries
- 16 DSWC: Dense Shelf Water Cascading
- 17 EEZ: Exclusive Economic Zone
- 18 EFH: Essential Fish Habitats
- 19 EIA: Environmental Impact Assessment
- 20 EMT: Eastern Mediterranean Transient
- 21 EwE: Ecopath with Ecosim
- 22 FAO: Food and Agricultural Organization
- 23 FRA: Fishery Restricted Areas
- 24 GFCM: General Fisheries Commission for the Mediterranean
- 25 GSA: Geographical Sub Area
- 26 ICCAT: International Commission for the Conservation of Atlantic Tunas
- 27 LIW: Levantine Intermediate Water
- 28 MBES: Multibeam Echosounder
- 29 MEDIAS: Mediterranean International Acoustic Survey
- 30 MEDITS: Mediterranean International Trawl Survey
- 31 MS: Member States
- 32 MSFD: Marine Strategy Framework Directive
- 33 MSY: Maximum Sustainable Yield
- 34 NIS: Non-Indigenous Species
- 35 OMZ: Oxygen Minimum Zones
- 36 PAH: Polycyclic Aromatic Hydrocarbons
- 37 POM: Particulate Organic Matter
- 38 POP: Persistent Organic Pollutants
- 39 ROV: Remotely Operated Vehicle
- 40 SAC: Scientific Advisory Committee
- 41 SCA: Stomach Content Analysis
- 42 SSB: Spawning Stock Biomass
- 43 SIA: Stable Isotope Analysis
- 44 SSS: Side-Scan Sonar
- 45 STECF: Scientific, Technical and Economic Committee for Fisheries
- 46 VME: Vulnerable Marine Ecosystem
- 47 UNCLOS: United Nations Convention on the Law of the Sea
- 48 UNGA: United Nations General Assembly
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71 **1. Introduction**

72 **1.1 The Mediterranean Sea**

73 The Mediterranean is a semi-enclosed basin between the European and African coasts with
74 the narrow and shallow Strait of Gibraltar connecting its waters and life to the Atlantic Ocean. The
75 Suez Canal creates a man-made connection to the Red Sea, recently doubled, which allows the
76 penetration of tropical Indo-pacific species (Longhurst, 2017). Concomitantly, the Mediterranean
77 Basin is experiencing major climatic-related changes that are strongly influencing its oceanography
78 in terms of water mass characteristics (e.g., temperature, salinity, dissolved oxygen), currents,
79 nutrients and relative sea levels. The interplay of these factors has, since historical times, strongly
80 influenced the diversity and colonization of the Mediterranean Sea (Taviani, 2002; Danovaro et al.,
81 2010).

82 Unique hydrology characterizes the present-day Mediterranean, including microtidal regime,
83 oligotrophy, high salinity (37.5-39.5 psu), homoeothermic temperatures from 300–500 m to the
84 bottom, with values at the seafloor ranging from ca 13-13.5 °C in the western basin to 13.5-15.5 °C
85 in the eastern basin, and the almost complete lack of thermal boundaries (Emig and Geistdoerfer,
86 2005). These features uniquely make the Mediterranean one of the “warmest” deep-sea basins of
87 the world. Strong energy gradients also characterize the Mediterranean, with primary production
88 and food supply to the deep decreasing from the western to the eastern region of the basin and
89 from shallower to deeper waters (Danovaro et al. 1999).

90 These historical, topographic and environmental characteristics complicate deep-sea
91 biodiversity patterns of the Mediterranean Sea but raise intriguing questions. Numerous studies
92 document that the Mediterranean Sea, although modest in size (0.82% and 0.32% of the global
93 ocean surface and volume, respectively; Bianchi and Morri, 2000), is a biodiversity hot spot with
94 overall ca 17000 species, which represent 7.5% of the species richness of the oceans (Danovaro
95 and Pusceddu, 2007; Coll et al., 2010; Lejeusne et al., 2010). However, although data on the
96 species richness of its deeper habitats are incomplete (two thirds of the deep species – excluding
97 prokaryotes – have not been censused yet; Ramirez-Llodra et al., 2009; Coll et al., 2010, Danovaro
98 et al., 2010), it appears that the biodiversity of the deep Mediterranean basin is lower than that of
99 other oceans (Danovaro et al. 2010).

100 The biodiversity of the deep Mediterranean Sea depends largely from the heterogeneity of
101 habitats, which include submarine canyons and seamounts, continental rise deposits, mud
102 volcanoes and extreme environments such as hydrothermal vents, cold seeps and deep-

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239 103 hypersaline anoxic basins (Olu-Le Roy et al., 2004; Danovaro et al., 2010; Taviani, 2011, 2014;
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241 104 [Fernandez-Arcaya et al., 2017](#)). Even seemingly “featureless” soft bottom habitats host unique and
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243 105 vulnerable species and habitats (e.g. sponge fields, gorgonian and pennatulacean meadows)
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245 106 (Danovaro et al., 2010).

246 107 The Mediterranean basin is threatened by multiple stressors associated with the rapid
247
248 108 expansion of coastal populations, urbanization, changes in agricultural, industrial and shipping
249
250 109 patterns, overfishing and exploration and extraction of offshore minerals and hydrocarbons, which
251
252 110 exert increasing pressures through habitat destruction, chemical pollution, and dumping of waste
253
254 111 and litter ([EEA, 1999](#); [Danovaro et al., 1993](#)). In concert with climate change, these stressors may
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256 112 act synergistically to affect the dynamics, and potentially the resilience, of fragile deep ecosystems
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258 113 (WWF/IUCN, 2004; UNEP/MAP, 2012). Direct stressors and processes also occur on the adjacent
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260 114 shelf and in the epi-mesopelagic zones, including Dense Shelf Water Cascading (DSWC) events
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262 115 down the continental slope, open-sea convection and severe coastal storms, which may transport
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264 116 sediments and organic matter to the continental slope and beyond, influencing deep-sea
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266 117 biodiversity and ecosystem functioning (Canals et al., 2006; Ulses et al., 2008; Sanchez-Vidal et al.,
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268 118 2012; Durrieu de Madron et al., 2013; Taviani et al., 2016). In particular, bottom-contacting
269
270 119 fisheries, specifically bottom-trawling and longlines, represent the most significant anthropogenic
271
272 120 threats to deep-water biota, severely impacting sensitive habitats and species such as cold-water
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274 121 corals (CWCs) and/or sponge gardens ([Rogers, 1999](#); [Koslow et al., 2000](#)). Additional evidence
275
276 122 attributes a significant proportion of deep-sea litter to the fishing industry (Bo et al., 2014; Tubau
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278 123 et al., 2015; D'Onghia et al., 2017; [Mecho et al. 2017](#)), along with land- and ship-based sources
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280 124 (Ryan et al. 2009).

276 125 Given the increasing pressures on deep-sea habitats, scientists and managers are becoming
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278 126 conscious of the need to develop standardised tools [and harmonized observation systems](#) for
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280 127 long-term biological monitoring, in order to enable [the collection of scientifically-validated data](#)
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282 128 [and a better understanding of the consequences of the present and future anthropogenic impacts](#)
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284 129 (Danovaro et al., 2017, [Aguzzi et al., 2019](#); [Danovaro et al., 2019](#)).

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286 131 **1.2 Implementing the Marine Strategy Framework Directive in the deep Mediterranean Sea**

288 132 The Marine Strategy Framework Directive (MSFD 2008/56/EC) represents the EU's
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290 133 Integrated Maritime Policy tool to achieve Good Environmental Status (GES) of marine waters,
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292 134 with an initial target for 2020. The MSFD applies to the area of marine waters over which a

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298 135 Member State exercises jurisdictional rights in accordance with the UNCLOS (see Figure 1, for the
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300 136 definition of territorial waters and EEZs in the Mediterranean). These include also deep-sea
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302 137 waters, seabed and sub-seafloor. At present, MSFD implementation focuses mostly on coastal
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304 138 habitats or those impacted by commercial fisheries (Raicevich et al., 2017). However, over long-
305
306 139 time scales, global nutrient and carbon cycles depend on a functioning deep sea (e.g. Snelgrove et
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308 140 al., 2018). Moreover, the life-cycle stages of some coastal species use offshore environments, thus
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310 141 achieving GES for marine ecosystems associated with continental shelves, must link to the
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312 142 achievement of GES for deep Mediterranean environments and Areas Beyond National Jurisdiction
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314 143 (ABNJ or “High Seas”). Otherwise, the MSFD will largely disregard the precautionary principle and
315
316 144 undermine an ecosystem-based approach to marine management.

315 145 An effective governance and management of the Mediterranean Sea requires consideration
316
317 146 of the complexity of these environmental issues, and meaningful international cooperation (de
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319 147 Vivero and Rodriguez Mateos, 2015). Given the transboundary nature of most of the deep waters,
320
321 148 their inclusion in MSFD complicates the requirement for each Member State to apply the Directive
322
323 149 to areas within its national jurisdiction. This emphasizes the need for Member States (MS) to
324
325 150 cooperate in order to ensure coordinated and harmonized development of marine strategies at
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327 151 the scale of region/sub-region in the Mediterranean Basin, where EU MS and developing countries
328
329 152 co-exist.

329 153 MSFD implementation currently suffers from a lack of standardized and consistent
330
331 154 methodology for deep waters. To address this gap, we identify approaches, variables, and
332
333 155 methodologies to enable MSFD implementation in the deep Mediterranean Sea. This synthesis
334
335 156 summarises available information on MSFD descriptors for the deep Mediterranean Sea, with
336
337 157 respect to the criteria listed in the European Commission Decision (COMM/DEC/2017/848), and
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339 158 anthropogenic pressures, uses and human activities affecting the marine environment (Table 2 of
340
341 159 Annex III of COMM/DEC/2017/848).

342 161 **2. State of the knowledge of MSFD descriptors in the deep Mediterranean**

344 162 **2.1 Descriptor 1: Biological diversity**

345 163 Descriptor 1 (D1) states that *“The quality and occurrence of habitats and the distribution*
347
348 164 *and abundance of species are in line with prevailing physiographic, geographic and climatic*
349
350 165 *conditions”* (MSFD, 2008/56/EC, Annex I, summarised in Table 1). The species groups specified in
351
352 166 Part II of the Annex to COMM/DEC/2017/848, these include birds, mammals, reptiles, fish and

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356
357 167 cephalopods, some of which are present, diverse and abundant in the deep sea, such as fishes and
358
359 168 cephalopods, in addition to deep diving and feeding cetaceans. Deep-sea organisms play an
360
361 169 important role in marine food webs, either as predators or as important prey of a large set of high
362
363 170 trophic level predators, including other fishes and cephalopods and marine mammals (Fanelli et
364
365 171 al., 2012, 2013; Quetglas et al., 2013).

366 172 Data on these components from the deep Mediterranean Sea are largely included in the
367
368 173 MEDITS database, which also represent the only extensive time series available for the deep
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370 174 Mediterranean (Bertrand et al., 2002), [although with the limitation that it is a destructive sampling](#)
371
372 175 [method with discrete sampling time, which exclude the possibility to detect any displacements of](#)
373
374 176 [demersal species \(Aguzzi et al., 2009; 2013\)](#). MEDITS is funded as part of the EU Data Collection
375
376 177 multi-annual sampling program (DC-MAP), which limits the sampling frequency to yearly surveys
377
378 178 confined to the northern part of the Mediterranean Basin. MEDITS mostly targets demersal fish
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380 179 (including deep-sea sharks), but includes also commercial invertebrates and other macro and
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382 180 mega-invertebrates (as by-catch species). MEDITS provides detailed information on their
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384 181 abundance and biomass, including the population structure of several species (including length
385
386 182 frequency distributions by sex and maturity stages for different target species), which allow us to
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388 183 obtain information on the size spectra, maturity ogives, sex ratios and mortality rates. This
389
390 184 information contributes to both the census of shallow and deep marine biodiversity and stock
391
392 185 assessments carried out by the GFCM and the STECF of the European Commission (see
393
394 186 Vasilakopoulos et al., 2014; [Cardinale et al., 2017](#)) [see Descriptor 3 below]. In the case of meso-
395
396 187 and bathypelagic species (MEDIAS Handbook, 2015; i.e. Galil, 2004; Papiol et al., 2013; Fanelli et
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398 188 al., 2013, 2015; Valls et al., 2014), species of non-commercial interest, hard bottom habitats
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400 189 between 200 and 800 m depth, and in general all habitats below 800 m depth, only scattered
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402 190 information without temporal datasets exist.

403 191 Another important gap concerns the smaller size biota, such as meiofauna, which are a key
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405 192 component in the deep-sea ecosystems and are driven by water depth, regional setting and
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407 193 geomorphological characteristics of the deep Mediterranean habitats (Bianchelli and Danovaro,
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409 194 2019). Meiofauna are highly diversified (possibly hyper-diverse), and play a fundamental
410
411 195 ecological role in the biogeochemical cycles and in food webs and are sensitive to environmental
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413 196 and anthropogenic pressures ([Pusceddu et al., 2014](#)). Since this component, which increases its
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415 197 [ecological](#) relevance, in terms of abundance and functional role, with increasing water depths
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417 198 (Danovaro et al., 2015), has been recently suggested for inclusion in the D1 for the

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416 199 implementation of the MSFD (Semprucci et al., 2014; Bianchelli et al., 2016a; 2018). It is even
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418 200 more evident that it should be taken into consideration in the implementation of the MSFD in the
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420 201 deep sea.

421 202 The MSFD deep-sea habitats included in the COMM/DEC/2017/848 are: a) upper bathyal
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423 203 rocks and biogenic reefs, b) upper bathyal sediments, c) lower bathyal rock and biogenic reef, d)
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425 204 lower bathyal sediments, and e) abyssal seafloor. These include other benthic habitats such as:
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427 205 canyons (which may include rocky and sedimentary substrates), rocky bottoms with coral banks
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429 206 (including Cold-water corals) or large bivalves, different types of sedimentary bottoms in bathyal
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431 207 or abyssal plains (muds, sands or coarser sediment), chemosynthetic ecosystems (hydrothermal
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433 208 vents and mud volcanoes), and seamounts.

434 209 Previous studies on the deep Mediterranean Sea reported a west-east decreasing gradient
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436 210 of food availability (Danovaro et al., 1999; Danovaro et al., 2008), which explains the presence of a
437
438 211 significant decreasing gradient in the abundance and biomass of most deep-sea benthic
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440 212 components along that gradient, from meiofauna to megafauna (Sardá et al., 2004; Bianchelli and
441
442 213 Danovaro, 2019; Fanelli et al., 2018). The CWCs apparently follow the same gradient (Taviani et al.,
443
444 214 2017; Chimienti et al., 2019), and the presence of Levantine Intermediate Water (LIW) likely
445
446 215 strongly influences their distribution (Freiwald et al., 2009; Taviani et al., 2016, 2017).

447 216 Trawl surveys provide most of the available information on deep-sea habitats and their
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449 217 characteristics (see Table 1, Annex III, MSFD), but only for soft bottom habitats including those
450
451 218 dominated by *Isidella elongata* and *Funiculina quadrangularis* (Lauria et al., 2017; Vasilis et al.,
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453 219 2019). Oceanographic cruises using ROVs offer the possibility to conduct non-destructive image
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455 220 and sample collections able to contribute significantly to the study of deep-sea habitats. Most ROV
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457 221 surveys to date have focused on CWC habitats and coral gardens, and provide important
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459 222 information on the composition, abundance, and biomass of the communities within these
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461 223 habitats (Taviani et al., 2005, 2011, 2015, 2019; Schembri et al., 2007; Fabri et al., 2014, 2017; Bo
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463 224 et al., 2015; Evans et al., 2016; Fanelli et al., 2017; Chimienti et al., 2019; Moccia et al., 2019).
464
465 225 Most available information focuses on deep-sea canyons (Migeon et al., 2012), seamounts (Wurtz
466
467 226 and Rovere, 2015) and mud volcanoes (Masclé et al., 2014), with major data gaps for deep-sea
468
469 227 pelagic habitats, notwithstanding there is an increasing information on deep-water zooplankton
470
471 228 and micronekton (Koppelman et al., 2009; Fanelli et al. 2011, 2014; Cartes et al., 2013; Denda
472
473 229 and Christiansen, 2014; Danovaro et al., 2017; Conese et al., 2019). Descriptor 1 is directly linked
474
475 230 to D2, D3, D4 and D6 (habitats), and monitoring efforts in the deep sea can therefore gather

473
474
475 231 contextual information on all these descriptors. The ecosystem criteria listed in
476
477 232 COMM/DEC/2017/848, which link Descriptors 1 and 4, consider trophic guilds. These are highly
478
479 233 relevant to the deep sea and can therefore be immediately described, as the already available
480
481 234 data would provide the required background information.

482 235 **2.2 Descriptor 2: Non-indigenous species introduced by human activities**

483
484 236 The number of recorded [Non-Indigenous Species](#) (NIS) in the Mediterranean Sea greatly
485
486 237 exceeds that in other European seas (Galil et al., 2014; Zenetos, 2019). Their establishment alters
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488 238 biotic assemblages and ecosystem functions (Galil, 2007; Katsanevakis et al., 2007; Fanelli et al.,
489
490 239 2015; Galil et al., 2016, 2017; Goren et al., 2016; [Azzurro et al., 2019](#)). The Suez Canal is an
491
492 240 important pathway for Red Sea species, which indeed represent 2/3 of the NIS in the
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494 241 Mediterranean Sea (Galil et al., 2017). In the past, it was assumed that NIS could establish only in
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496 242 shallow waters, however, the deep sea is not immune to species invasions. NIS have been rarely
497
498 243 documented in the deep sea, a notable exception is the red king crab *Paralithodes camtschaticus*
499
500 244 in the Barents Sea (Jørgensen and Nilssen, 2011). Yet, a growing number of Erythraean species
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502 245 were reported from the deeper part of the continental shelf, beyond the shelf break and in the
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504 246 upper slope (Özcan et al., 2008; Corsini-Foka et al., 2010; Innocenti et al., 2017; Özgür Özbek et al.,
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506 247 2017). For example, the lethally poisonous silver-cheeked toadfish, *Lagocephalus sceleratus*, has
507
508 248 been collected from 350-400 m depth off Spain (Izguendo-Munoz and Izguendo-Gomez, 2014). The
509
510 249 invasive lionfish, *Pterois miles*, that was initially present only in the upper shelf has been recently
511
512 250 recorded at depths down to 110-150 m (Yağlıoğlu and Ayas, 2016; Jimenez et al., 2019). In the
513
514 251 southern Levantine Sea, three carnivorous species of Erythraean origin have been observed at 200
515
516 252 m depth: the crocodile toothfish *Champsodon nudivittis*, the burrowing goby *Trypauchen vagina*
517
518 253 and the red-eye round herring *Etrumeus golanii* (Galil et al. 2018). The presence of deeper
519
520 254 dwelling populations suggests that thermal niche assessments based only on a species' native
521
522 255 range may underestimate their ability to tolerate lower temperatures (Parravicini et al. 2015).
523
524 256 Wider thermal tolerance of some Erythraean species may facilitate their bathymetric and
525
526 257 geographic expansion to depths where unique, diverse, and fragile mesophotic 'animal forests'
527
528 258 occur. The lately observed "descent" of NIS from the upper to lower continental shelf may be an
529
530 259 indication of temperature-dependent range expansion at increasing water depths, and appears to
531
532 260 be accelerating. Therefore, even if abundances of NIS at levels of true invasions have not been
533
534 261 reported yet in the deep Mediterranean, these vulnerable environments should be monitored also
535
536 262 for D2, as they could be future targets of NIS invasions.

264 2.3 Descriptor 3: Populations of commercially exploited fish and shellfish

265 Descriptor 3 determines that Member States should maintain commercially exploited stocks
266 of fish and shellfish in a healthy state. This descriptor implies sustainable exploitation that does
267 not exceed the Maximum Sustainable Yield (MSY), i.e. the maximum yield catch that can be taken
268 annually without reducing the fish stock productivity. Heavy fishing pressures, such as
269 overexploitation or overfishing, produce negative environmental and socio-economic impacts,
270 ranging from loss of significant potential yield of targeted stocks to severe stock depletion and
271 fisheries collapse (Gascuel et al., 2016). Overfishing can also reduce fish stocks dramatically to the
272 point where they lose internal genetic diversity and, with it, their capacity to adapt to
273 environmental change (Pinsky and Palumbi, 2014; Allendorf et al., 2014). Fish communities may
274 also change, such as altered size structures, when fisheries target or discard particular-sized
275 individuals of a species, may potentially affect predator and prey dynamics (Fanelli et al., 2010),
276 i.e. Descriptor 4 addresses the question of trophic relationships and marine food webs. The MSFD
277 builds on existing EU legislation such as the Common Fishery Policy (CFP), and the criteria
278 describing stock status follow internationally acknowledged best practices. The SAC of the GFCM,
279 the STECF of the European Commission and the ICCAT (for highly migratory species, such as tunas
280 or swordfishes, which account for more than 10 % of the value of the total catches in the
281 Mediterranean) collectively monitor exploitation of fisheries resources in the Mediterranean
282 marine sub-regions. The FAO and GFCM oversee collection of fisheries monitoring data in the
283 Mediterranean Sea within GSAs (Geographical Sub Areas management divisions, according to
284 resolution GFCM/33/2009/2, www.gfcm.org, for the correspondence between GSA numbers and
285 their names Fig. 2), often assessing stocks over one or several GSAs. However, the MSFD sub-
286 regions do not match with the GSAs. Furthermore, when we focus our attention on depths >200
287 m, the distinction between shallow and deep-water species is often irrelevant because
288 distribution, exploitation and assessment of many stocks often cover wide depth ranges.

289 Descriptor 3 stipulates the need for fishery-induced mortality, yielding (but not exceeding)
290 MSY (D3C1), and that populations of all commercially exploited species should remain within safe
291 biological limits (D3C2), with a population age and size distribution (D3C3) indicative of a healthy
292 stock. Fulfilling D3 criteria for deep-sea stocks requires: (1) sustainable exploitation consistent
293 with high long-term yields, (2) maintaining full reproductive capacity in order to maintain stock
294 biomass, and (3) maintaining or increasing the proportion of older and larger fish/shellfish, an

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593 295 indicator of a healthy stock. Achieving GES also for a deep-sea stock requires fulfilling all three of
594 296 these attributes and, for the reasons highlighted above, D3 indicators require trans-national
595 297 cooperation at the level of each MFSD sub-region.

598 298 In the Mediterranean Sea, the enforcement of the CFP and, more recently, of the MSFD,
599 299 continues to fall far short of achieving its objectives for exploited living marine resources (e.g.,
600 300 Colloca et al., 2013; Vasilakopoulos et al., 2014). Notwithstanding the enforcement of the EU-Data
601 301 Collection Regulation (EU, 2000) in the early 2000s by all EU Member States, and the rapid
602 302 increase in the number of assessed stocks by the GFCM and the STECF, industries continue to
603 303 exploit Mediterranean Sea marine resources above MSY levels, with few signs of population
604 304 recovery (Vasilakopoulos et al., 2014; Cardinale et al., 2017; Colloca et al., 2017).

610 305 Management practices of DSF and VMEs in the Mediterranean were reviewed in 2016 and
611 306 2017 (FAO, 2016 and GFCM, 2017). UNGA Resolutions 51/2006 and the FAO International
612 307 Guidelines for the Management of Deep-sea Fisheries in the High Seas (FAO, 2009), identify DSF in
613 308 the Mediterranean Sea, as those: a) using bottom-contact gears or b) using deep-pelagic trawls
614 309 and c) targeting species associated with the sea floor between 300/400 m and 1000 m depth (FAO,
615 310 2016 and GFCM, 2017). This grouping considers shallower fisheries that extend below 400 m.
616 311 These reports identify deep-water red shrimps (*Aristaeomorpha foliacea* and *Aristeus antennatus*)
617 312 as the primary DSF targets in the Mediterranean deep-sea habitats, which are harvested mostly at
618 313 300/400–800 m depths, along with European hake (*Merluccius merluccius*), Norway lobster
619 314 (*Nephrops norvegicus*) and deep-water rose shrimp (*Parapenaeus longirostris*). In addition, gillnet
620 315 fisheries and demersal long-liners target both *M. merluccius* and the blackspot seabream (*Pagellus*
621 316 *bogaraveo*). Also in Spain, deep-sea fisheries target *Plesionika* shrimps below 300 m depth (see
622 317 also IDEM 2018a). GFCM banned the use of towed dredges and trawl nets at depths beyond 1,000
623 318 m in 2005 (Recommendation GFCM/29/2005/1), protecting over ca. 1,700,000 km² of
624 319 Mediterranean Sea seafloor habitats (about 59% of the GFCM area of application) (FAO, 2018).

635 320 To date, the GFCM has established a number of Fishery Restricted Areas (FRAs) to protect
636 321 Essential Fish Habitats (EFHs) or/and VMEs from excessive fishing mortality or the significant
637 322 adverse impact of fishing activities through bottom-contact fishing gears, respectively. The FRAs
638 323 encompass a total marine area of ca. 22,500 km² (FAO, 2018). Four of the FRAs were declared
639 324 within a multiannual management plan for deep-sea fisheries, in order to protect EFHs for
640 325 spawners of several species that are heavily exploited, to maintain habitat of the continental slope
641 326 (canyons and submarine canyons), and to preserve all the species of the area (commercially

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652 327 exploited or not), i.e., one in the Gulf of Lion in France (Le Corre and Farrugio, 2011), one in the
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654 328 Jabuka-Pomo Pit (Elahi et al., 2018) and two FRAs south of Sicily. The existence of management
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656 329 plans, however, does not necessarily imply regular completion of accurate stock evaluation.
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658 330 Moreover, the existence of the FRA does not necessarily imply banning bottom trawling and may
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660 331 simply represent an effort management tool (to prevent further effort increase as seen in freezing
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662 332 fishing effort in the Gulf of Lion FRA).

662 333 Member States shall establish a list of commercially exploited species to which the criteria
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664 334 apply in each assessment area through regional or sub-regional cooperation, and update that list
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666 335 for each six-year evaluation period, taking into account Council Regulations (EU) 1251/2016,
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668 336 1380/2013, 1343/2011, and 1967/2006, in accordance with article 43 (3) of the Treaty on the
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670 337 Functioning of the European Union, article 9 of Regulation (EU) No 1380/2013 and article 19 of
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672 338 Regulation (EC) No 1967/2006.

672 339 The MSFD criteria available for coastal environments cannot often be directly utilised for
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674 340 deep-sea species. This is because stock assessments are limited and not sufficiently monitored,
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676 341 hampering the assessment of stock exploitation at MSY (Criterion D3C1). The available
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678 342 information decreases eastwards and southwards. In addition, a gap of knowledge is also present
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680 343 in terms of time-series coverage of Spawning Stock Biomass (SSB) (Criterion D3C2) trend data
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682 344 hampering the possibility to define appropriate reference points.

682 345 The third criterion, i.e. "Healthy age and size structure" (criterion D3C3), assumes that a
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684 346 stock with sufficient large, and therefore old, fish corresponds to a healthy stock, thus reflecting
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686 347 good status. The larger and older fish stocks indicate healthier conditions, but this criterion has
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688 348 not been developed because GES lacks accepted thresholds (European Environment Agency,
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690 349 2018).

690 350 This gap suggests a need to identify and test suitable indicators, metrics, and thresholds for
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692 351 populations and age size distributions for each deep-sea stock (ICES, 2016, 2017). In conclusion,
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694 352 our analysis points out that there is a potential to inform D3 criteria, but more data need to be
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696 353 collected in the future to propose sound stocks analyses and reference conditions, likely though
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698 354 the extension of the EU Data Collection Multiannual Programme (DC-MAP, EU Regulation
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700 355 2016/1701) to include more deep-sea species.

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703 357 2.4 Descriptor 4: Marine food webs

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711 358 Descriptor 4 addresses the functional aspects of marine food webs, especially the rates of
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713 359 energy transfer within the system and levels of productivity in key components. In the context of
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715 360 the MSFD, this descriptor reaches GES when “All elements of the marine food webs, to the extent
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717 361 that they are known, occur at normal abundance and diversity and population levels capable of
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719 362 ensuring the long-term abundance of the species and the retention of their full reproductive
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721 363 capacity” (MSFD, 2008/56/EC, Annex I).

721 364 Deep-sea food webs critically depend on input of organic carbon from the photic zone
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723 365 (Thomsen et al., 2017). The microbial loop and viral infections can play an important role in the
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725 366 functioning of deep-sea food webs both in the water column and in sediments, and in the control
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727 367 of the biogeochemical cycles (Danovaro et al., 2008). At the same time, deep-sea meiofauna
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729 368 represents a potential basic linkage in energy transfer from the benthic detritus and microbes to
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731 369 the macro- megafauna and demersal fishes (Van Oevelen et al., 2011; Gambi et al., 2014).

731 370 D4 is one of the most controversial MSFD Descriptors in terms of protocols, criteria, and
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733 371 thresholds (ICES, Report 2015). D4 is generally investigated along with Descriptors D1 and D6 or
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735 372 D3. Studies of food web properties typically utilize two different approaches: a) Stomach Contents'
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737 373 Analyses (SCA) and b) Stable Isotope Analyses (SIA), and fatty acid trophic markers. Modelling
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739 374 techniques, in contrast, can provide insights regarding the potential structure of food webs
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741 375 (Rombouts et al., 2013). SIA identified three trophic levels among deep-sea supra-benthos (Fanelli
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743 376 et al., 2009) and four levels within macrozoobenthos (Iken et al., 2001; Fanelli et al., 2011a) and
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745 377 macrozooplankton/micronekton (Fanelli et al., 2011b). Fishes, decapods, and cephalopods
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747 378 dominate higher trophic levels in deep-sea demersal communities. Despite the availability of a
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749 379 large dataset for the deep Mediterranean Sea (MEDITS, 2002), this dataset includes few
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751 380 commercial species from bathyal depths: the European hake *Merluccius merluccius* and the
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753 381 greater forkbeard *Phycis blennoides*, some sharks (mostly *Etmopterus spinax* and *Galeus*
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755 382 *melastomus*), decapods (the red shrimps *Aristaeus antennatus* and *Aristaeomorpha foliacea*, the
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757 383 rose shrimp *Parapenaeus longirostris* and the Norway lobster *Nephrops norvegicus*). We lack
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759 384 sufficient data on other dominant deep-sea species, such as macrourids, or key predators such as
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761 385 deep-sea sharks (e.g., *Centroscymus coelolepis*; Stefanescu et al., 1994; Massutí et al., 2004;
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763 386 Anastosopoulou et al., 2016).

760 387 Most studies on trophic functional groups have focused on macro- and megafauna (i.e. fish,
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762 388 decapods, cephalopods and echinoderms), whereas few studies are available on other biotic
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764 389 compartments such as meiofauna or mesozooplankton (Danovaro et al., 2010). The northwestern

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770 390 Mediterranean portion is better studied (Fanelli et al., 2009, 2011a, b, 2013, 2015, 2016; Papiol et
771 al., 2013; Cresson et al., 2014), whereas the Ionian and Aegean seas have been much less
772 391 investigated (Carlier et al., 2009; Koppelman et al., 2009; Tecchio et al., 2013; Cartes et al., 2014;
773 392 Naumann et al., 2015). On the other hand, these types of studies rarely consider some key
774 393 species/taxa, such as mesopelagic fishes or megazooplankton (Fanelli et al., 2014; Valls et al.,
775 394 2014).

780 396 COMM/DEC/848/2017 sets criteria and methodological standards for monitoring and
781 397 assessment of GES within the theme “Ecosystems”. For example, selection criteria require that at
782 398 least one of the three trophic guilds monitored should focus on primary producers. This criterion is
783 399 the major drawback for this descriptor given that, aside from the few, very localized ecosystems
784 400 that depend on chemosynthesis (hydrothermal vents, cold seeps, or wood and whale falls; Luna et
785 401 al., 2012; Molari et al., 2013), the vast majority of the deep sea lacks primary production. The data
786 402 gap between experimental and functional data adds further complication.

792 403 Stable isotope analysis may comply with the primary criterion D4C1 (diversity of trophic
793 404 guilds) and the secondary criterion D4C3 (distribution of individuals across the trophic guild).
794 405 Moreover, in combination with abundance, biomass, and other biological data available from
795 406 MEDITS data, it may offer inputs into ecosystem models that could generate useful outputs, such
796 407 as identification of unrecognized keystone species, a gap not presently considered. Italy addresses
797 408 D4 under its fishery monitoring program (i.e. D3) and specifically with three subprograms aimed
798 409 at: i) defining, testing, and applying ecosystem indicators through models (essentially EwE,
799 410 <http://www.ecopath.org>); ii) identifying functional groups through the application of stable
800 411 isotope analysis of monitored species within the DCF; and iii) integrating analysis of commercial
801 412 species with those for benthos, zooplankton and Particulate Organic Matter (POM) samples every
802 413 three years. Spain and France recently introduced SIA and SCA of species collected during MEDITS
803 414 or MEDIAS surveys for use in D4.

812 415 In conclusion, the analysis of D4 can be realistically initiated for the deep Mediterranean,
813 416 using the available technologies, protocols and monitoring programs and adapting the criteria, by
814 417 neglecting the relevance of primary production, which could be replaced by the analysis of the
815 418 inputs of primary organic matter and/or by starting from primary consumers and/or including the
816 419 chemosynthetic primary production.

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823 421 **2.5 Descriptor 5: Human-induced eutrophication**

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829 422 Eutrophication refers to “a process driven by enrichment of water by nutrients, especially
830 423 compounds of nitrogen and/or phosphorus, leading to increased primary production and biomass
831 424 of algae, changes in the balance of organisms, and water quality degradation” (Ferreira et al.,
832 425 2010). According to the MSFD, GES is achieved with respect to eutrophication when “Human-
833 426 induced eutrophication is minimised, especially adverse effects thereof, such as losses in
834 427 biodiversity, ecosystem degradation, harmful algae blooms and oxygen deficiency in bottom
835 428 waters” (MSFD, 2008/56/EC, Annex I).

841 429 In coastal environments, eutrophication means the increase of primary production generally
842 430 monitored through the chlorophyll-*a* (Chl *a*) content and/or macroalgal biomass (Ferreira et al.,
843 431 2007; Xiao et al., 2007; Borja et al., 2008; Bricker et al., 2008; Nixon, 2009). The effects of
844 432 eutrophication are the lowering of oxygen concentrations, losses of submerged aquatic
845 433 vegetation, and mass mortalities especially at the sediment water interface (Claussen et al., 2009;
846 434 Ferreira et al., 2011). The global occurrence and expansion of hypoxic/anoxic events at bathyal
847 435 depths worldwide point to the need for better understanding and monitoring of the effects of
848 436 such phenomena on deep-sea benthic communities (Doya et al., 2015; Breitburg et al., 2018).
849 437 Recent models foresee an oxygen decline from 1 to 7% in the next 100 years (Keeling et al., 2010)
850 438 with an increase in the extension of Oxygen Minimum Zones (OMZs) (Stramma et al., 2008).
851 439 Farther, OMZs, with their naturally occurring low pH and oxygen, offer some hints as to the
852 440 structure of deep-sea ecosystems affected by eutrophication (Levin, 2003; Moffit et al., 2015).

861 441 Deep-sea ecosystems have been historically considered as a food-poor environment, and
862 442 this is typically true for the deep Mediterranean Sea, especially in its eastern basin, but some areas
863 443 may experience symptoms of eutrophication and oxygen depletion (Danovaro et al., 2014). For
864 444 instance, it has been reported that massive phytodetritus exports from highly productive coastal
865 445 waters to the deep-sea floor (Billet et al., 1983). Excessive C inputs in combination with the high
866 446 bottom temperatures can cause episodic oxygen depletion in the deep sea (Ferreira et al., 2011;
867 447 Danovaro et al., 2014). Recent studies highlighted that deep-sea trophic status can be also
868 448 affected by climate change, as the Western basin is expected to become more oligotrophic and
869 449 the Eastern basin more eutrophic (Piroddi et al., 2017). In addition, predicted increasing surface
870 450 temperatures may affect water mass stratification and the formation of cold oxygenated deep
871 451 water, modifying global ocean circulation and the dissolved oxygen availability in deep-water
872 452 masses (Ramirez-Llodra et al., 2011). Local scale eutrophication could affect deep-sea sediments
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888 453 facing highly productive areas of the Mediterranean Sea, such as the Gulf of Lions, the northern
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890 454 Aegean Sea and the Ionian Sea receiving inputs from the Adriatic Sea.

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892 455 However, the MSFD, in relation to the qualitative Descriptor 5, calls for an assessment of
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894 456 nutrients and organic matter inputs (Annex III of Directive 2017/845) and the use of the following
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896 457 criteria (Directive 2017/848): i) nutrient concentrations in the water column, ii) chlorophyll a in the
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898 458 water column, iii) harmful algal blooms, iv) photic limit, v) dissolved oxygen at the bottom of the
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900 459 water column, vi) opportunistic macroalgae, vii) macrophyte communities and viii) macrofaunal
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902 460 communities. These criteria can only be partially applied to the deep sea. Firstly, primary
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904 461 producers (e.g., macrophyte, macroalgae, harmful algal bloom) must be excluded, and the
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906 462 assessment of trophic status using variables measured in the water column can lead to misleading
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908 463 classifications (Dell'Anno et al., 2002, see also Fabri et al., 2018). Considering that oxygen
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910 464 depletion is one of the main causes of benthic faunal mortality, it is important to measure
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912 465 physical-chemical parameters and indicators also in the sediments (Mercado et al., 2015). In
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914 466 addition, the concentration of organic matter accumulated in surface sediments can provide a
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916 467 good indication of the eutrophication process occurring on the seafloor (Dell'Anno et al., 2002;
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918 468 Pusceddu et al., 2009). The current conceptual framework suggests the need to introduce new
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920 469 criteria and indicators, related to benthic ecosystems and, particularly, to the deep sea.

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922 470 A group of core indicators is already utilised to monitor eutrophication in open waters,
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924 471 including: i) nutrients (nitrate, ammonium, phosphate), ii) dissolved oxygen and iii) phytoplankton
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926 472 (chlorophyll a, dominance). Zooplankton biomass is considered a potential, though not fully
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928 473 mature indicator (UNEP(DEPI)/MED, 2007 and references therein) because of incomplete
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930 474 knowledge of its relationship to eutrophication. The monitoring of benthic ecosystems should
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932 475 include i) quantity and quality of sedimentary organic matter, and ii) biodiversity and taxonomic
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934 476 composition of benthic invertebrates (Dell'Anno et al., 2002; Pusceddu et al., 2009, 2011, 2014;
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936 477 Bianchelli et al., 2016a). Among indicators recently proposed to assess benthic trophic status of
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938 478 marine ecosystems, the quantity and biochemical composition of sedimentary organic matter has
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940 479 received the widest application, both in coastal and deep-sea ecosystems (Pusceddu et al., 2009;
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942 480 see also Fabri et al., 2018). The concentrations of biopolymeric C (defined as the sum of C deriving
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944 481 from proteins, carbohydrates and lipids) and its algal fraction have been used to assess impacts of
482 humans on benthic trophic status in different oceanic and coastal regions and varying water
483 depths, within the Mediterranean basin (Dell'Anno et al., 2002; Pusceddu et al., 2009, 2011, 2014;
484 Bianchelli et al., 2016b). Changes in the quantity and quality of organic matter in the deep sea

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947 485 lead to responses from all benthic components, from prokaryotes to foraminifera, and from
948 486 meiofauna to macrofauna (Danovaro et al., 1999). Also the functional traits of macrofauna have
949 487 been widely used as indicators of alteration and for measure the health status of marine benthic
950 488 ecosystems (Borja et al., 2008). Further, meiofauna could be considered a good indicator as it is
951 489 highly sensitive to environmental changes, and particularly to organic enrichment due to
952 490 eutrophication (Pusceddu et al., 2011). For these reasons, meiofauna have been recently proposed
953 491 for the monitoring of eutrophication effects and for assessing the environmental quality of both
954 492 coastal and deep-sea ecosystems (Bianchelli et al., 2016a; Pusceddu et al., 2016).
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962 494 **2.6 Descriptor 6: Sea floor integrity**

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964 495 Descriptor 6 requires that seafloor integrity is “*at a level that ensures that the structure and*
965 496 *functions of the ecosystems are safeguarded and benthic ecosystems, in particular, are not*
966 497 *adversely affected*” (Commission Decision 2010/477/EU). This involves addressing “*physical*
967 498 *damage, having regard to substrate characteristics*”, and the “*condition of benthic community*”,
969 499 the latter being directly related to Descriptor 1. The relevant pressures identified in the
970 500 Commission Decision (EU) 2017/848 generically refer to “physical loss (due to permanent change
971 501 of seabed substrate or morphology and to extraction of seabed substrate)” and to “physical
972 502 disturbance to seabed (temporary or reversible)”. Four primary criteria address these points, three
973 503 of which (D6C1 to D6C3) are specific for Descriptor 6, while two are also relevant for Descriptor 1
974 504 (D6C4 and D6C5).
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981 505 The deep Mediterranean seafloor experiences two dominant physical disturbances
982 506 associated with human activities: i) bottom-contact fisheries and ii) oil and gas activities (Boschen
983 507 et al., 2013; D’Onghia et al., 2017; Lauria et al., 2016; Holler et al., 2017). Fisheries using bottom-
984 508 contacting gear lead to direct alteration of seafloor morphology at large, medium and small scales
985 509 (Puig et al., 2012; Martin et al., 2014). Bottom trawling is a key driver for large-scale seascape
986 510 change as it smoothens the natural topography (Puig et al., 2012). Direct and indirect biological
987 511 effects of bottom trawling have been demonstrated in terms of biogeochemical changes (e.g. less
988 512 total amino acid concentration in sediments) and faunal desertification (Pusceddu et al., 2014).
989 513 The Mediterranean Sea shows the highest fisheries footprint per unit landings in Europe (Eigaard
990 514 et al., 2017), with peak intensities in the Tyrrhenian and the Adriatic Sea. In the Catalan margin,
991 515 trawling impact is major down to 800 m depth (Puig et al., 2012). Sediment resuspension from
992 516 fishing grounds can propagate to wider and deeper areas eventually leading to suffocation and
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1006 517 burial of VME (Martin et al., 2008). Downslope moving gravity-driven resuspension flows enhance
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1008 518 sedimentation rates far beyond fishing grounds, such as in canyon axes. Other types of fishing gear
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1010 519 such as bottom touching longlines and gillnets could also have a significant adverse impact on
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1012 520 vulnerable benthic communities and organisms such as black corals, gorgonians, scleractinians and
1013 521 many other habitat-forming species (GFCM, 2017), because of breaking while pulling, ghost fishing
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1015 522 or entanglement.

1016 523 Activities undertaken by the offshore oil and gas industry may cause physical loss of the
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1018 524 natural deep seabed. Physical (and chemical) impacts on the seafloor and subseafloor range from
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1020 525 the installation of drilling rigs, wellheads and other structures on the seabed to the accumulation
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1022 526 of litter including lost or abandoned equipment, consumables and other materials. Today's deep-
1023 527 water (>200 m) oil and gas production in the Mediterranean Sea, or advanced prospects for it,
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1025 528 takes place essentially offshore Egypt, Israel, Lebanon, Syria and Cyprus (The Petroleum Economist
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1027 529 Ltd, 2013; Galil and Herut, 2011). The environmental approach for the hydrocarbon industry in the
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1029 530 Mediterranean Sea is developed in the Offshore Protocol of the Barcelona Convention, adopted in
1030 531 October 1994, which obliges countries to perform comprehensive EIAs after entering into force in
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1032 532 December 2012. The EU adopted the Directive on Safety of Offshore Oil and Gas Prospection,
1033 533 Exploration and Production Activities in July 2013, which provides a blueprint of the best
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1035 534 international practice also for non-EU countries in the Eastern Mediterranean that are new to the
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1037 535 energy industry (Livnat, 2014). Further disturbance occurs in case of cable deployment, for not the
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1039 536 cables and pipelines per se, rather for the impact of the anchoring of the supply vessel during the
1040 537 deployment of the cable.

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1042 538 Dumping of industrial waste in the deep Mediterranean Sea is a matter of concern for
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1044 539 habitat integrity. Submarine canyons with heads close to the coast are favoured sites for direct
1045 540 deep-sea disposal (Ramirez-Llodra et al., 2015). Two aluminium-processing plants have discharged
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1047 541 red mud waste in the deep Mediterranean Sea: one in France (Cassidaigne Canyon, Gulf of Lion)
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1049 542 (Dauvin, 2010; Fontanier et al., 2012, 2014; see also Fabri et al., 2018) and one in Greece (Gulf of
1050 543 Corinth, Antikyra Bay) (Varnavas et al., 1986; Varnavas and Archilleopoulos, 1995; Poulos et al.,
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1052 544 1996). Since 1988, Coal Fly-Ash (CFA) from the Hadera power plant, in Israel, has been dumped
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1054 545 into a 16 km² disposal site some 70 km offshore, at a water depth of 1400 m, where a 0.5-1.0 cm
1055 546 thick ash layer has been noticed (Kress et al., 1996, 1998) together with severe impoverishment of
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1057 547 benthic fauna. Israel allowed also long-term disposal of dredged sediments and industrial waste
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1065 548 (1,900,000 m³) polluted with Hg, Cd, Pb, tributyltin and organotins, and PCBs at a site 1300 m deep
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1067 549 (Herut et al., 2010).

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1069 550 Different proved tools is currently available to assess seafloor integrity. High-resolution
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1071 551 maps of benthic substrata and habitats are increasingly required both to underpin environmental
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1073 552 and socioeconomic impact assessments and to help in developing effective management
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1075 553 measures (Kenny et al., 2003; Brown et al., 2011; Stephens and Diesing, 2014; Holler et al., 2017;
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1077 554 Fabri et al., 2018). Multibeam Echo-Sounders (MBES) and side scan sonars (SSS), map seabed areas
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1079 555 with 100% spatial coverage at a resolution finer than 1 m², depending on the depth of data
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1081 556 collection and on distance-to-bottom of the sensors (Kenny et al., 2003). Ground-truthing
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1083 557 methods, [such as the use of remotely operated vehicles \(ROVs\) and autonomous underwater](#)
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1085 558 [vehicles \(AUVs\) \(Fabri et al., 2014; Lastras et al., 2016\)](#), are widely available and could be applied
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1087 559 according to the size and the nature of the area of interest (Kenny et al., 2003; Brown and Blondel,
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1089 560 2009; Brown et al., 2011; Holler et al., 2017). Habitat suitability models try to predict the
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1091 561 distribution of some habitats such as CWCs (Lo Iacono et al., 2012; Bargain et al., 2017, 2018; Fabri
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1093 562 et al., 2017; Angeletti et al., 2019; Lo Iacono et al., 2018; Giusti et al., 2014, 2017; Lauria et al.,
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1095 563 2017). However, because such models often include a large degree of uncertainty, decisions based
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1097 564 entirely on modelling approaches may involve significant risk.

1094 565 The revision of the MSFD ([through the COMM. DEC. 2017/848/EU](#)) emphasised that
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1096 566 “Physical loss shall be understood as a permanent change to the seabed which has lasted or is
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1098 567 expected to last for a period of two reporting cycles (12 years) or more”, but for this to be
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1100 568 implemented, a very long time perspective is needed. All impacts described in this section have
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1102 569 immediate effects (and sometimes also delayed effects) on seafloor communities, which in most
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1104 570 cases could represent either a tipping point (e.g. large-scale seascape change) or require long time
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1106 571 before any significant recovery could take place. A time-span of 12 years is possibly too short and
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1108 572 it is urgent to proceed with a sound extensive evaluation of the current status of the deep benthic
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1110 573 habitats in the Mediterranean Sea before human impact severely modifies or erases them from
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1112 574 the face of our planet.

1111 575 1112 1113 576 **Descriptor 7: Permanent alteration of hydrographical conditions**

1114 577 Descriptor 7 is geared towards addressing the problem of the permanent alteration of
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1116 578 hydrographical conditions. These conditions are often affected by the presence of coastal
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1118 579 infrastructure and other man-made activities (ports, artificial reefs, etc.). However, in most cases

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1124 580 these structures impact coastal areas and only rarely can reach higher depths. Conversely, global
1125
1126 581 climate change, combined with episodic climate-driven events, can alter the “hydrographical
1127
1128 582 conditions” also at depths. In recent decades, deep Mediterranean waters have experienced
1129
1130 583 drastic changes resulting in an alteration of the stratification associated to temperature increases
1131
1132 584 and salinity shifts (Schroeder et al., 2009, 2016). At the end of the 1980s, climate change, changing
1133
1134 585 hydrographic properties, surface circulation, and deep-water convection caused a ‘regime shift’ on
1135
1136 586 a global scale (Reid et al., 2016) and throughout the Mediterranean basin (Conversi et al., 2010).
1137
1138 587 During that period, the main site of deep-water formation shifted from the southern Adriatic to
1139
1140 588 the Aegean sub-basins. This “Eastern Mediterranean Transient” (EMT; 1987-1994) event resulted
1141
1142 589 in increased oxygen consumption (Roether and Well, 2001; Klein et al., 2003) and, in the eastern
1143
1144 590 Ionian, in a nutricline shoaling by about 150 m (Klein et al., 1999). Other rapid hydrological
1145
1146 591 changes have also occurred in the Western Mediterranean Sea. The “Western Mediterranean
1147
1148 592 Transient” (WMT; 2004/05 and 2005/06) was characterised by the formation of warmer and
1149
1150 593 denser new deep waters over the continental shelf as a result of cooling and evaporation of the
1151
1152 594 surface layer and downslope cascading (Canals et al., 2006; Palanques et al., 2006; Schroeder et
1153
1154 595 al., 2009). The high volumes of newly formed deep waters generated during intense cascading and
1155
1156 596 convection events dramatically altered the hydrological structure of the basin, completely de-
1157
1158 597 stratifying the water column and transferring massive heat and salt to the deep layers (Canals et
1159
1160 598 al., 2006; Schroeder et al., 2009; Martin et al., 2010). The 2004/05 event was the first of a series of
1161
1162 599 similar events in the last decade that greatly altered the structure of the intermediate and,
1163
1164 600 especially, the deep layers of the Western Basin (Durrieu de Madron et al., 2013). Cascading
1165
1166 601 events transport huge amounts of nutrients and organic matter, to bathyal depths (Canals et al.,
1167
1168 602 2006; Sanchez-Vidal et al., 2008; Danovaro et al., 1999; Company et al., 2008). Hydrographic
1169
1170 603 preconditioning (heat and salt content and structure of the water column before the onset of
1171
1172 604 convection), and atmospheric forcing (heat, freshwater and buoyancy fluxes) triggered deep-water
1173
1174 605 formation (Fabri et al., 2018). Moreover, progressive increase in heat and salt content in the
1175
1176 606 intermediate layer, advected from east to west, favoured new dense water formation in the
1177
1178 607 North-Western Mediterranean basin. Multiple heat and saline anomalies characterised the
1179
1180 608 Mediterranean Sea from 1950 to 2000 (Rixen et al., 2005; Kress et al., 2014) and although these
1173
1174 609 alterations cannot be considered permanent, all of these changes have long-term effects.

1175 610 The multidisciplinary Mediterranean Targeted Projects MTP-I and MTP-II/MATER (1993-
1176
1177 611 2000; Monaco and Peruzzi, 2002), the MEDAR/MEDATLAS database (Fichaut et al., 2003), the

1181
1182
1183 612 SeaDataNet (i.e., <https://www.seadatanet.org/>) and EMODnet (<http://www.emodnet-physics.eu>)
1184
1185 613 infrastructures created datasets on temperature, salinity oxygen, silicate, nitrates and phosphates,
1186
1187 614 but in some cases with insufficient coverage in the eastern region (including Tunisia, Libya, Croatia
1188
1189 615 and Turkey; Simoncelli et al., 2015).

1190 616 Since the 2000's, national and international programmes (e.g. EU-PERSEUS and MedSeA, IT-
1191
1192 617 VECTOR, FR-MERMEX, E-RADMED) produced hydrological data on the whole Mediterranean Basin.
1193
1194 618 Regular cruises, mooring lines, and deployment of new instruments and infrastructure (Argo
1195
1196 619 floats, gliders) now support intensive collection of *in situ* observations in the North-Western
1197
1198 620 Mediterranean Sea. Argo floats, autonomous profiling floats, drift at a given depth for a given time
1199
1200 621 period. After drifting for a set time, they sink to 2000 m and profile temperature and salinity
1201
1202 622 during the upcast. These data proven useful in describing deep-water formation (Smith et al.,
1203
1204 623 2008). Moreover, in the last decade, glider technology mainly in the North-Western
1205
1206 624 Mediterranean Sea has enabled repeated cross-basin transects at depths from the surface to 1000
1207
1208 625 m. In addition, numerical models implemented at regional or local scales use these data to
1209
1210 626 elucidate water mass formation and spreading, and basin-scale hydrological dynamics (Bonaldo et
1211
1212 627 al., 2015; Estournel et al., 2005).

1210 628 Long-term monitoring of basic hydrological parameters (temperature and salinity), collected
1211
1212 629 as time series with appropriate temporal resolution (i.e. sampling intervals that resolve all relevant
1213
1214 630 timescales) represent a science priority in the context of climate change study for key locations in
1215
1216 631 the Mediterranean Sea (e.g. straits and channels, zones of dense water formation and spreading,
1217
1218 632 deep basins) (Schroeder et al., 2013; Aguzzi et al., 2019). The HYDROCHANGES network aims to
1219
1220 633 address this need by deploying moorings fitted with Conductivity, Temperature, Depth sensors
1221
1222 634 (CTDs) at key locations for monitoring temperature and salinity (Schroeder et al., 2013). The FixO3
1223
1224 635 (Fixed point Open Ocean Observatory network, <http://earthvo.fixo3.eu/>) programmes and the
1225
1226 636 EMSO (European Multidisciplinary Seafloor and water column Observatories, <http://emso.eu/>) EU
1227
1228 637 Infrastructure provide additional near-bottom data from fixed-point observations. For example,
1229
1230 638 DYFAMED and LION deep-water stations, and ANTARES neutrino telescope in the North-Western
1231
1232 639 Mediterranean or the KM3NET in the Ionian Sea (Tamburini et al., 2013; Aguzzi et al., 2018),
1233
1234 640 continuously monitor sets of specific parameters. Long time series provided by these mooring
1235
1236 641 stations have contributed pivotal findings on the deep dynamics of the Mediterranean Sea in last
1237
1238 642 years. In order to partially interpolate data within homogeneous habitats, scientists have
1239
1240 643 generated gridded products through objective analysis of available observations (such as

1240
1241
1242 644 numerical models with data assimilation delivered by Copernicus downstream services
1243
1244 645 (<http://marine.copernicus.eu/services-portfolio/access-to-products/>).

1245 646
1247 647 **2.8 Descriptor 8: Concentrations of contaminants giving rise to pollution effects**
1248

1249 648 The input of xenobiotic substances represent one of the major threats for ocean health
1250
1251 649 (Halpern et al., 2008). Hydrophobic pollutants, such as organo-halogenates and polycyclic
1252
1253 650 aromatic hydrocarbons (PAH), enter the marine environment through effluent discharges,
1254
1255 651 atmospheric deposition, runoff and other means (Iwata et al., 1994). Once in the water column,
1256
1257 652 the adsorption onto particulate matter transfers these compounds from the surface to the deep
1258
1259 653 waters and sediments (Buessler, 1998). Particle settling is also favoured by biological processes,
1260
1261 654 and by lateral transport from continental shelves (Heussner et al., 2006; Martin et al., 2006; Zuñiga
1262
1263 655 et al., 2009). DSWC is a massive mechanism of pollutant transfer to the open deep ocean (Canals
1264
1265 656 et al., 2006). Higher fluxes of organohalogen pollutants and Polycyclic Aromatic Hydrocarbons
1266
1267 657 (PAH) occur during these cascading events (Salvadó et al., 2017). PAH settling fluxes in the north-
1268
1269 658 western Mediterranean Sea vary widely (Lipiatou et al., 1993; Raoux et al., 1999), with highest
1270
1271 659 concentrations of contaminants in the Alboran Sea (Dachs et al., 1996), and much lower values in
1272
1273 660 Sardinia and in the Southern Ionian Sea (Bouloubassi et al., 2006; Tsapakis et al., 2006). However,
1274
1275 661 these values greatly exceed atmospheric deposition of PAH in central sites of the Western
1276
1277 662 Mediterranean Sea, thus highlighting the role of river discharge (Heussner et al., 2006; Bonnin et
1278
1279 663 al., 2008; Palanques et al., 2008). Qualitative differences are also observed in relation to these
1280
1281 664 transfer processes. Sediments of coastal areas, continental shelves and slopes have higher
1282
1283 665 proportions of petrogenic PAHs whereas the deep basin of the north-western Mediterranean Sea
1284
1285 666 is characterized by high amounts of pyrogenic PAHs.

1286 667 Organochlorine compounds such as Polychlorobiphenils (PCBs) and chlorinated pesticides,
1287
1288 668 characterised a group of Persistent Organic Pollutants (POPs) of worldwide concern due to their
1289
1290 669 toxic effects (Harmon, 2015). Notwithstanding the discontinued use of these compounds in most
1291
1292 670 world areas, thanks to relevant national regulations and international agreements such as the
1293
1294 671 Stockholm Convention, their extensive occurrence is still observed, Their high lipophilicity,
1295
1296 672 hydrophobicity, chemical stability and resistance to biological degradation have led to their
1297
1298 673 accumulation in biological tissues and biomagnification through the food chain.

1299 674 Radioactive compounds in the Mediterranean Sea are derived from the fallout of nuclear
1300
1301 675 weapon testing and the Chernobyl accident. In sediments, concentrations of ^{137}Cs and $^{239+240}\text{Pu}$

1299
1300
1301 676 have been measured in various parts of the Mediterranean Sea, including deep basins. The
1302
1303 677 concentrations are generally higher in coastal ecosystems because land-based sources can exceed
1304
1305 678 atmospheric inputs (Durrieu de Madron et al., 2011; Garcia-Orellana et al., 2009). Concentrations
1306
1307 679 in biota are presently undistinguishable from those in areas without point sources. Hence, the
1308
1309 680 relevance of these contaminants lies in their usefulness as process tracers, more than on their
1310
1311 681 impact on the environment. Studies on radionuclides in marine organisms also underscore that
1312
1313 682 the radionuclide levels are constantly decreasing due to modifications of the inputs. Very little
1314
1315 683 work has been done to examine the trophic transfers of man-made radionuclides (Harmelin-Vivien
1316
1317 684 et al., 2012). Finally, neglected impacts that can be very important in several areas of world are
1318
1319 685 military activities. Information on their impacts on the environment are relatively scarce and are
1320
1321 686 often studied after several years from their production and without any baseline available
1322
1323 687 (Lawrence et al., 2015; Danovaro et al., 2019).

1322 688 Atmospheric inputs constitute one of the major sources of Trace Elements (TE) to the deep
1323
1324 689 Mediterranean Sea (Migeon et al., 2012; Guerzoni et al., 1999), where TE concentrations in waters
1325
1326 690 are typically higher than in other areas of the world ocean. In addition, Cd, Cu and Ni (as well as
1327
1328 691 Cr) are dominated by lateral advection and vertical mixing rather than by biogeochemical cycling
1329
1330 692 (Morley et al., 1997). The hydrologic regime of the Mediterranean Sea tends to transfer the
1331
1332 693 pollutants and nutrients to the Atlantic by bottom water flow transport. Our knowledge on the
1333
1334 694 concentrations, fluxes, and behaviour of trace elements, radionuclides and organic substances in
1335
1336 695 the deep waters and sediment and their toxicological impacts on habitats and organisms is scarce
1337
1338 696 (Durrieu de Madron et al., 2011). Pollutants with hydrophobic properties, e.g. PCBs and mercury,
1339
1340 697 accumulate in biota and thus in the food web. In case of chronic pollution events, the
1341
1342 698 concentration of contaminants should be analysed in sediments collected by sediment cores,
1343
1344 699 which enable the reconstruction of temporal trends. Sample collection of water at different
1345
1346 700 depths and analysis of the dissolved and particulate matter would also be important. Abundance
1347
1348 701 of populations and estimates of the extent of habitats adversely affected by chronic pollution
1349
1350 702 should be assessed concurrently.

1347 703 Nonetheless, information on pollutants in the deep sea is almost completely lacking, and
1348
1349 704 this represent the main gap in the application of the criteria needed to determine the D8.

1350 705

1352 706 **2.9 Descriptor 9: Contaminants in fish and other seafood for human consumption**

1358
1359
1360 707 Descriptor 9 focuses on the accumulation of toxic, persistent and liable substances in wild
1361
1362 708 deep-sea organisms used for human consumption (i.e., mostly teleost and decapod crustaceans)
1363
1364 709 and the contaminants considered by D9 are only part of those of interest for the D8 (cfr.
1365
1366 710 Regulation EC 1881/2006 and its amendments EC 2006, 2008). Each Member State may ignore
1367
1368 711 specific contaminants and/or include additional ones (EC 2017) (Fliedner et al., 2018). In any case
1369
1370 712 the monitoring of the contaminants accumulated in the deep-sea biota should at least consider
1371
1372 713 the following compounds for which regulatory levels have been set: i) heavy metals (lead,
1373
1374 714 cadmium and mercury); ii) PAHs; iii) dioxins (including dioxin-like PCBs). In addition, the following
1375
1376 715 contaminants of relevance should be monitored: i) non-dioxins like PCBs; ii) phthalates; iii)
1377
1378 716 organochlorine pesticides; iv) organotin compounds; v) brominated flame retardants; vi)
1379
1380 717 polyfluorinated compounds. Also, artificial radionuclides should be monitored in case of nuclear
1381
1382 718 accidents or any other radioactive emergencies that could lead to or has led to significant
1383
1384 719 radioactive contamination of food.

1382 720 Contaminants in fish and other seafood might derive from numerous anthropogenic
1383
1384 721 sources described for the D8. Chemical contamination in fish and seafood results from a complex
1385
1386 722 process that balances inputs of contaminants, mostly through diet, and their excretion (Solé et al.,
1387
1388 723 2001; Trudel and Rasmussen, 2001; Cresson et al., 2014).

1389 724 Investigating contamination levels in fish and seafood requires understanding which
1390
1391 725 contaminants exceed regulatory limits, how much they alter food webs, and what metabolic
1392
1393 726 processes are involved in detoxification. The presence of xenobiotics in the deep Mediterranean
1394
1395 727 organisms has been repeatedly documented (Galil et al., 1995; Storelli et al., 2009) with deep-sea
1396
1397 728 Mediterranean fishes tending to exhibit higher levels of metal accumulation than those of
1398
1399 729 populations inhabiting other areas such as the Atlantic Ocean (Damiano et al., 2011). Red-shrimps,
1400
1401 730 *Aristeus antennatus* and *Aristaeomorpha foliacea* may be useful indicator species of levels of
1402
1403 731 deep-sea contamination (e.g., see data on *A. antennatus*, Koenig et al., 2012). Contaminants in fish
1404
1405 732 muscle and liver have been investigated in the most abundant deep-sea megafaunal species, e.g.
1406
1407 733 *Alepocephalus rostratus*, *Coelorinchus mediterraneus*, *Coelorhynchus caelorhincus*, *Trachyrincus*
1408
1409 734 *trachyrincus* and *Nezumia sclerorhynchus*, *Chimaera monstrosa*, *Lophius budegassa*, *Lepidion*
1410
1411 735 *lepidion* (Koenig et al., 2013c), revealing mercury concentration exceeding 0.5 µg g⁻¹ muscle wet
1412
1413 736 weight in all species but one. This represents the threshold value indicated by the European
1414
1415 737 Commission as acceptable for human consumption. High mercury concentration is a distinct
1416
1417 738 feature of the Mediterranean Sea (the so-called “Mediterranean mercury anomaly”; Cossa and

1417
1418
1419 739 Coquery, 2005; Cossa et al., 2012). The Hg concentration is even higher in some deep-sea fish
1420
1421 740 species (Koenig et al., 2013c; Cresson et al., 2014; Chauvelon et al., 2018). Most deep-sea species
1422
1423 741 are long-lived and slow-growing, which favours the bioaccumulation of pollutants (Drazen and
1424
1425 742 Haedrich, 2012; Koenig et al., 2013a, b, c). Since some deep-sea species are of commercial
1426
1427 743 interest, the high contamination level poses serious risks for human health (Rotllant et al., 2006;
1428
1429 744 Carbery et al., 2018). Despite this, few studies have investigated the concentrations of
1430
1431 745 contaminants in the deep Mediterranean fauna fished for human consumption (Storelli et al.,
1432
1433 746 2004, 2007; Koenig et al., 2013c; Cresson et al., 2014). In this regard, the Gulf of Lion is the best-
1434
1435 747 investigated area, whereas the Levantine Basin (with the exception of Israel waters; Galil et al.,
1436
1437 748 1995) are the least studied. A comparison of the concentrations of xenobiotics in fish collected in
1438
1439 749 the NW Mediterranean Sea, in 1996 and 2009 (Koenig et al., 2013a; Porte et al., 2000; Solé et al.,
1440
1441 750 2001) indicate that their contamination did not change over time.

1442
1443 751 The application of the criteria of Descriptor 9 should consider the concentration, the
1444
1445 752 thresholds, and the contamination sources. Regulators should also consider the species of interest
1446
1447 753 for human diets and their ability to bioaccumulated pollutants. GES would be achieved if all
1448
1449 754 contaminants occur at levels below those established for safe human consumption.

1448 756 **2.10 Descriptor 10: Marine litter**

1450 757 Two primary and two secondary criteria are associated to Descriptor 10: i) the composition,
1451
1452 758 amount and spatial distribution of litter (D10C1) and of micro-litter (D10C2) “on the coastline, in
1453
1454 759 the surface layer of the water column, and on the seabed, are at levels that do not cause harm to
1455
1456 760 the coastal and marine environment” (primary) and ii) the amount of litter ingested by marine
1457
1458 761 animals, which should not reach a level that adversely affect the health of the species (D10C3) and
1459
1460 762 the number of individuals which are adversely affected due to litter, such as by entanglement,
1461
1462 763 other types of injury or mortality, or health effects (D10C4) (secondary). Each sub-region should
1463
1464 764 assess the outcomes for all criteria and as well as threshold values.

1465 765 Marine litter represents a threat for the health of the deep Mediterranean Sea due to its
1466
1467 766 limited exchange with other basins, dense population, touristic and industrialized coastlines, and
1468
1469 767 heavy maritime traffic (UNEP, 2015). The sources of marine litter to the deep-sea floor of the
1470
1471 768 Mediterranean Sea are either from land (river discharge, storm drains, sewage treatment plants
1472
1473 769 and industrialized areas) or marine (fishing activities, commercial and recreational shipping,
1474
1475 770 aquaculture, direct dumping), and include plastics (accounting for >70% of the total), glass, metal,

1476
1477
1478 771 clinker, cardboard and fabrics (Galgani et al., 2000; Ramirez-Llodra et al., 2013; Fabri et al., 2014;
1479
1480 772 Pham et al., 2014; Tubau et al., 2015; UNEP, 2015; [Mecho et al., 2017](#)). The quantity and
1481
1482 773 composition of marine litter differs among regions and changes with depth, probably as a result of
1483
1484 774 a complex set of interactions between hydrodynamics, geomorphology, and anthropogenic
1485
1486 775 sources (Pham et al., 2014; Tubau et al., 2015; UNEP, 2015). The abundance of marine litter items
1487
1488 776 in the deep Mediterranean Sea varies from 500 items km⁻² on the continental slopes off Malta and
1489
1490 777 Cyprus (Mifsud et al., 2013; Ioakeimidis et al., 2014), the Tyrrhenian Sea (Angiolillo et al., 2015), or
1491
1492 778 the Adriatic Sea (Galgani et al., 2000), to more than 2,000 items km⁻² in the Antalya Bay in the
1493
1494 779 Eastern Mediterranean or in the submarine canyons of the Gulf of Lion and of the Catalan Sea
1495
1496 780 (Galgani et al., 2000; Tubau et al., 2015). Astonishingly high litter abundance of up to 1.3 million of
1497
1498 781 items km⁻² were reported at 300-600 m depth in the Messina Strait canyons (Central
1499
1500 782 Mediterranean Sea) (Pierdomenico et al., 2019). Litter abundance found in submarine canyons
1501
1502 783 and depths greater than 500 m typically exceeds that at shallower depths, suggesting that
1503
1504 784 submarine canyons can act as primary conduits of litter from the coast to the deep sea (Galgani et
1505
1506 785 al., 2000; Tubau et al., 2015). Superposition of highly efficient source-to-sink sedimentary
1507
1508 786 transport (with flash-flood generated hyperpycnal flows) and strong urbanization of the coastal
1509
1510 787 area promote the occurrence of large litter hotspots in the deep sea (Pierdomenico et al., 2019). In
1511
1512 788 addition to large marine debris, concern has grown about microplastics (i.e., <1-5 mm in diameter;
1513
1514 789 Desforges et al., 2014), which can directly enter the ocean also through cosmetic abrasives (i.e.
1515
1516 790 microbeads), preproduction plastic pellets, or textile fibres known as primary plastics. Additionally,
1517
1518 791 combined mechanical, biological, photic and thermal actions can break down larger plastic objects
1519
1520 792 into numerous small fragments, which are defined as secondary microplastics. Depending on the
1521
1522 793 density of the polymer, microplastics may sink and behave as very fine-grained sediments (for
1523
1524 794 example polyester; Woodall et al., 2014), or they may float and subsequently sink following
1525
1526 795 colonization by organisms, adsorption to phytoplankton, and/or aggregation with organic debris.
1527
1528 796 Fibres appear to dominate the microplastics reported in Mediterranean deep-sea sediments (van
1529
1530 797 Cauwenberghe et al., 2013; Woodall et al., 2014; Sanchez-Vidal et al., 2018). Recent studies
1531
1532 798 indicate that the Mediterranean deep-sea floor might act as a long-term sink for microplastics
1533
1534 799 where the abundances of such particles can exceed those in surface waters (Sanchez-Vidal et al.,
800 2018). Marine litter in the Mediterranean deep sea may significantly affect different ecological
801 compartments and, consequently, human health, with potentially severe economic impacts. Biotic
802 effects of large and small items include entanglement, ingestion, colonization and rafting (Gregory,

1535
1536
1537 803 2009; Murray and Cowie, 2011; Anastasopoulou et al., 2012; Ramirez-Llodra et al., 2013; Bo et al.,
1538
1539 804 2014; Pham et al., 2014; Angiolillo et al., 2015; Tubau et al., 2015). However, information on the
1540
1541 805 actual effects of (micro)plastics on deep-sea organisms and trophic webs is still limited (Taylor et
1542
1543 806 al., 2016).

1544 807 Marine litter in deep sea produces economic impacts primarily on the fishery sector,
1545
1546 808 damaging vessels and fishing equipment due to entanglement of catch, loss of target species
1547
1548 809 through ghost fishing, or reduced reproductive capacity of benthic organisms consuming
1549
1550 810 microplastics (Newman et al., 2015). Furthermore, marine litter may contain pollutants (hazardous
1551
1552 811 plastic additives, POPs) that exert toxic and endocrine disruptive effects on marine organisms that
1553
1554 812 ingest plastics (Oehlmann et al., 2009).

1554 813

1556 814 **2.11 Descriptor 11: Introduction of energy including underwater noise**

1557
1558 815 Descriptor 11 deals with introduction of energy into the marine environment. Underwater
1559
1560 816 noise can be pulsed or continuous. MSFD currently focuses on two criteria: anthropogenic pulsed
1561
1562 817 (D11C1) and continuous low-frequency (D11C2) sounds in water. D11C1 addresses the space-time
1563
1564 818 distribution of pulsed noise sources, whereas D11C2 addresses levels of continuous noise, using in
1565
1566 819 situ measurements and models. Pulsed noise may cause direct acute effects such as hearing loss,
1567
1568 820 tissue damage, and death of individuals of sensitive species such as cetaceans. Whereas
1569
1570 821 continuous or chronic noise exposure mainly causes stress and behavioural alterations, with
1571
1572 822 negative effects on deep-sea organisms (Nowacek et al., 2015). The proposed strategy on noise
1573
1574 823 monitoring recommends several adaptations in the case of the deep Mediterranean. Particularly,
1575
1576 824 both indicators are closely related to the acoustic biology of deep-diving marine mammal species,
1577
1578 825 such as sperm whale and Cuvier's beaked whale. Pulsed noise can be monitored by setting up a
1579
1580 826 register of anthropogenic activities, reporting on date, location, proportion of days within a given
1581
1582 827 period and over a given geographical scale in which activities generating pulsed sounds occur. [This](#)
1583
1584 828 [could be done through the deployment of hydrophones \(e.g., permanent or semi-permanent](#)
1585
1586 829 [PAM\) on new infrastructures \(or implementation of the existing infrastructures\) and their](#)
1587
1588 830 [subsequent future development into larger geographic network: Rountree et al., 2019\).](#)

1585 831 A variety of phenomena generates noise in the ocean, either from physical processes, such
1586
1587 832 as wind-generated waves, earthquakes, precipitation, or from biological phenomena such as
1588
1589 833 whale songs, dolphin clicks, and fish vocalizations (Montgomery and Radford, 2017); not all reach
1590
1591 834 the deep sea. Fish produce sounds for their navigation, habitat selection and mating, as well as to

1594
1595
1596 835 communicate (Simpson et al., 2005). Marine mammals use sound as a primary tool for underwater
1597
1598 836 communication (Wartzok and Ketten, 1999), mating and social interaction (Edds-Walton, 1997),
1599
1600 837 and for tracking the prey (Au, 1993).

1601 838 Anthropogenic noise can reach the deep sea, through commercial shipping, oil and gas
1602
1603 839 exploration, fishing, and scientific research; all of these sources currently contribute to the general
1604
1605 840 noise budget of the ocean (Montgomery and Radford, 2017). The impact of noise on marine is
1606
1607 841 being increasingly investigated (Wenz, 1962; Hildebrand, 2009). Noise sources are divided into
1608
1609 842 three frequency bands: low (10 to 500 Hz), medium (500 Hz to 25 kHz) and high (>25 kHz).
1610 843 Anthropogenic sources dominate the low-frequency band, and include commercial shipping and
1611
1612 844 seismic emissions for hydrocarbon exploration. Minimal attenuation of low-frequency sound
1613
1614 845 allows long-distance propagation. Sea-surface agitation (breaking waves, spray, bubble formation
1615
1616 846 and collapse, and rainfall) and various sonars (e.g. military and multibeam seabed mapping), as
1617
1618 847 well as small vessels produce most medium frequency sound. Greater attenuation limits
1619
1620 848 propagation of noise in the mid-frequency band over long distances, and only local or regional
1621
1622 849 (10s of km distant) sound sources contribute to this ambient noise field. At high frequencies,
1623
1624 850 extreme acoustic attenuation confines all noise sources to the area close to the receiver.

1623 851 Oil industry operations have traditionally focused on shallow, continental shelf waters, but
1624
1625 852 exploration is moving in deeper waters (>500-1000 m). Expansion of oil exploration into deeper
1626
1627 853 water has increased the potential for long-range propagation of seismic reflection signals. Indeed,
1628
1629 854 sound in deep waters can propagate greater distances than in shallow-water ecosystems, by
1630
1631 855 moving through the deep sound channel (Hildebrand, 2009). Seismic surveys currently target all
1632
1633 856 regional seas in the south-eastern Mediterranean, apart from the Aegean Sea (Maglio et al., 2016).
1634
1635 857 This expansion stresses the transboundary aspect of seismic surveys and calls for international
1636
1637 858 cooperation.

1637 859 Anthropogenic noise can cause physical and biological damage, such as behavioural changes
1638
1639 860 and stress, especially in marine mammals, sea turtles and fish (Popper et al., 2014; Peng et al.,
1640
1641 861 2015). The occurrence of low frequency noise in the deeper part of the basins is particularly
1642
1643 862 important for deep-diving marine mammals, such as toothed whales, because the ambient noise
1644
1645 863 they use as a background for echolocation decreases rapidly with depth (Foote et al., 2004; André
1646
1647 864 et al., 2011; Azzellino et al., 2011). [Indeed, small odontocetes produce high frequency sounds](#)
1648
1649 865 [\(ranging from 70 kHz to more than 150 kHz\), while sperm whales, *Physeter macrocephalus*, during](#)
1650
1651 866 [diving, make sound with frequencies ranging to more than 30 kHz which are detectable within 10-](#)
1652

1653
1654
1655 867 15 km. The fin whale *Balaenoptera physalus*, the only mysticete constantly present in the
1656
1657 868 Mediterranean Sea, emits mostly infrasonic signals (20-40 Hz), which are emitted in long
1658
1659 869 sequences and can be detected at large distances.

1660 870 Research on sea turtles in the South-Eastern Mediterranean region revealed that they can
1661
1662 871 detect low frequency sounds that overlap with seismic airgun frequencies, these are high-
1663
1664 872 intensity, low-frequency impulsive noise at regular intervals, mostly between 10 and 300 Hz
1665
1666 873 (Carroll et al., 2017; Nelms et al, 2016). Airguns can stress the sea turtles, *Caretta caretta*
1667 874 (DeRuiter et al., 2012). The impacts of anthropogenic noise on sharks and rays are poorly studied,
1668
1669 875 with most research to date focusing outside the Mediterranean region (Weilgart, 2017). Fish
1670
1671 876 sensitivity to certain frequencies varies among species (Carroll et al., 2017). Recent studies
1672 877 demonstrate negative effects of seismic survey airgun operations even in zooplankton (McCauley
1673
1674 878 et al., 2017).

1675 879 *In situ* acoustic measurements can document continuous low-frequency sound, gathering
1676
1677 880 field data on ambient noise in a given location. Understanding the large-scale influence of artificial
1678
1679 881 noise on marine organisms and ecosystems represents the main gap to the application of the D11
1680
1681 882 on the deep sea. Deep-sea observatories offer new opportunities to assess the presence and
1682
1683 883 effects of noise in on deep-sea life (Aguzzi et al., 2019). Deep-sea cabled observatories (i.e. NEMO-
1684 884 SN1 in the Western Ionian Sea, Caruso et al. 2015, Favali et al., 2013; ANTARES in the Ligurian Sea,
1685
1686 885 André et al., 2017; and PYLOS in the South Ionian Sea, <http://www.fixo3.eu/observatory/pylos/>)
1687
1688 886 are equipped with hydrophones for passive acoustic monitoring. Besides these measurements,
1689
1690 887 and especially for monitoring continuous low-frequency sound in deep sea, modelling approaches
1691 888 (both for single sources or distributed sources of noise, from the most advanced Dynamic Ambient
1692
1693 889 Noise Prediction System elaborated by the U.S. for modelling multiple sources, to the Acoustic
1694 890 Integration Model used for modelling the effects of noise on cetaceans; NRC, 2003) may reduce
1695
1696 891 the time required to establish trends and patterns.

1697 892

1699 893 3. Future implementation

1700
1701 894 In order to effectively implement the deep-sea MSFD, we need to identify the criteria to
1702
1703 895 achieve or maintain GES in open waters and deep-sea bottoms, including “spatial protection
1704
1705 896 measures, contributing to coherent and representative networks of marine protected areas,
1706 897 adequately covering the diversity of the constituent ecosystems, such as special areas of
1707
1708 898 conservation pursuant to the Habitats Directive, special protection areas pursuant to the Birds

1712
1713
1714 899 Directive, and marine protected areas as agreed by the Community or Member States concerned in
1715
1716 900 the framework of international or regional agreements to which they are parties" (MSFD,
1717
1718 901 2008/56/EC, Article 13).

1719 902 The MSFD takes an overarching and integrated approach by focusing on achieving GES and
1720
1721 903 targets, and we therefore recommend exploring and assessing synergies between the different
1722
1723 904 treaties, directives, and conventions (e.g. see Descriptor 6 section) so that, wherever possible, the
1724
1725 905 programme of measures and proposed MSFD monitoring simultaneously address the
1726 906 requirements of other legislations.

1727
1728 907 Our analysis indicates that the 11 Descriptors promulgated by the MSFD (MSFD,
1729
1730 908 2008/56/EC) can be adapted and applied to the deep sea. Several Descriptors (D1, D2, D3, D6, D8,
1731
1732 909 D10) can be readily implemented, others (D4, D9 and D11) require additional data in order to set
1733 910 up benchmark and threshold values, while two (D5, D7) require changes in the assumptions
1734
1735 911 and/or modification in the concept of "permanent".

1736 912 Priority ecological variables, spatial distribution, extent of pressures and impacts ought to
1737
1738 913 be identified and standardized in order to establish targets and indicators addressing the distinct
1739
1740 914 conditions in the deep sea. The expertise, tools and resources required for deep-sea monitoring
1741
1742 915 are not universally available to all Mediterranean Member States (MS), nor to countries in the
1743 916 southern and easternmost Mediterranean. These limitations may be overcome by initiating deep
1744
1745 917 sea MSFD-focused monitoring in already data-rich locations (presumably off MS), and pioneering
1746
1747 918 joint-effort monitoring in collaboration with non-MS, to enhance awareness, capacity building,
1748 919 and gain much needed data on scantily studied regions. Given the costs entailed by scientific and
1749
1750 920 technical expertise, tools and infrastructure required for deep-sea research and monitoring, we
1751
1752 921 advocate for EU-level financial support for MS/non-MS collaboration spanning joint fieldwork,
1753 922 training (early career research fellowships, workshops) and *public awareness* communication.

1754
1755 923 Since the millennium, increased awareness of the vulnerability of deep-sea ecosystems has
1756
1757 924 changed attitudes concerning their protection and conservation (Ramirez-Llodra et al, 2011). Yet,
1758
1759 925 for effective regulatory measures, legislators and managers require scientific evidence, which
1760
1761 926 follows from basic scientific research and monitoring. Ecosystem-based management of the
1762
1763 927 Mediterranean deep sea pressingly requires comprehensive analysis of available data, new data
1764 928 from yet unexplored regions, and impact assessment studies. Mounting evidence points to the
1765
1766 929 vulnerability of the deep biota to anthropogenic disturbance that may result in biodiversity loss,

1771
1772
1773 930 urgent implementation of the MSFD in the Mediterranean deep sea will go a long way towards
1774
1775 931 conserving its unique biodiversity and habitats.
1776
1777 932
1778
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1780
1781
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1788
1789 938 CTM2013-44598-R) and NUREIEVA (ref. CTM2016-75953-C2-1-R) on far-field and near-field
1790
1791 939 impacts of the Portman Bay, SE Spain, coastal submarine mine tailings disposal site. Generalitat de
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1793
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1795
1796 942
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Table 1. List of the descriptors, their definition if GES is achieved and if they are a state or pressure descriptors. Only D3 is both a state and pressure descriptor as it related to aspects such as the level of fishing activity (pressure) and population age, size distribution and biomass indices (state).

Descriptor	GES	State	Pressure
1	Biodiversity is maintained	X	
2	Non-indigenous species do not adversely alter the ecosystem		X
3	The population of commercial fish species is healthy	X	X
4	Elements of food webs ensure long-term abundance and reproduction	X	
5	Eutrophication is minimised		X
6	The sea floor integrity ensures functioning of the ecosystem	X	
7	Permanent alteration of hydrographical conditions does not adversely affect the ecosystem		X
8	Concentrations of contaminants give no effects		X
9	Contaminants in seafood are below safe levels		X
10	Marine litter does not cause harm		X
11	Introduction of energy (including underwater noise) does not adversely affect the ecosystem		X

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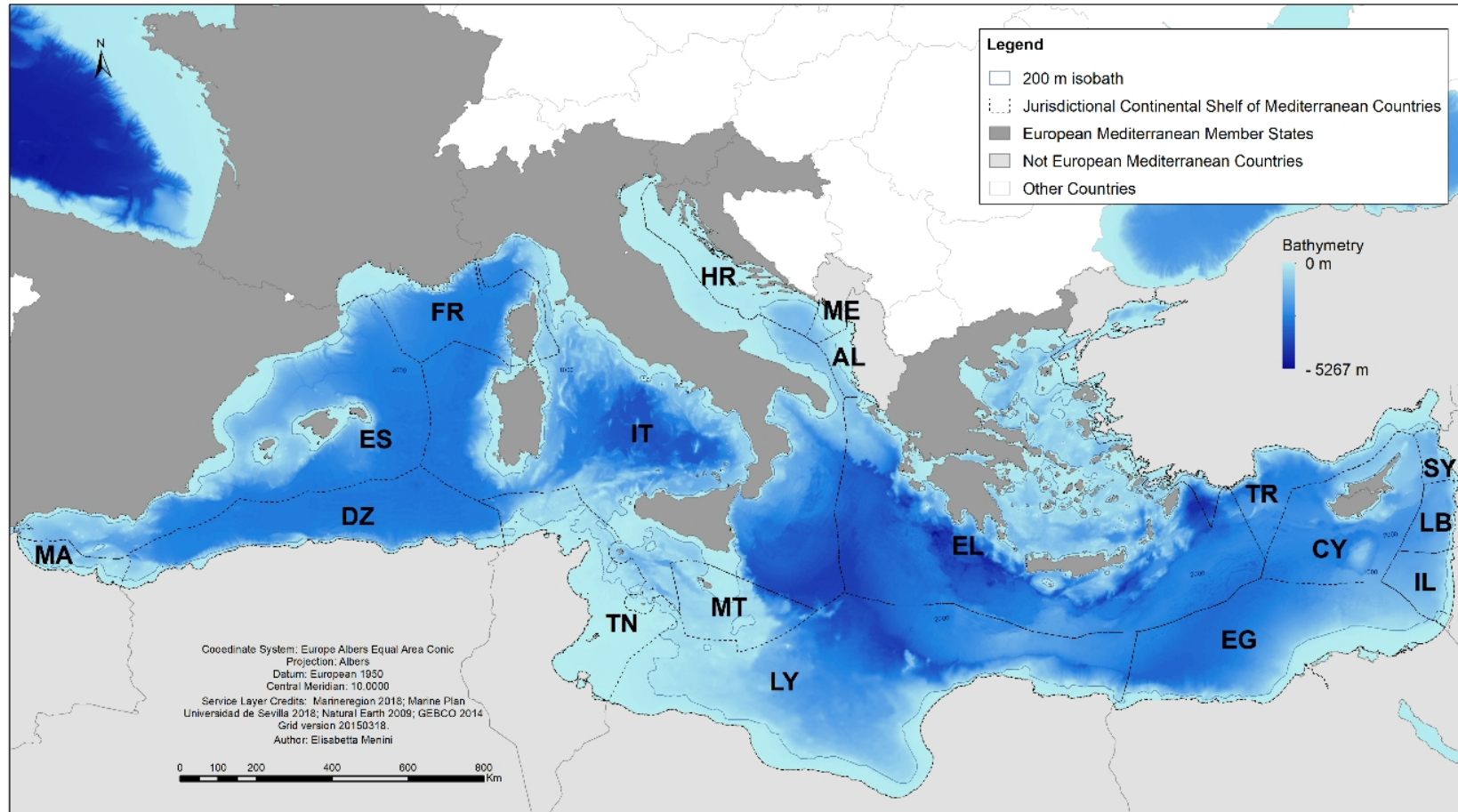
1884 Figure captions

1885
1886 Figure 1. Jurisdictional Continental Shelf and deep Mediterranean Sea, with indication of
1887 jurisdictional continental shelf per each country (including non-EU countries).

1888
1889 Figure 2. Location of GFCM Geographical Sub-Areas (GSAs) and MSFD Mediterranean national sub-
1890 regions. FAO divisions are shown in thumbnail map.

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Jurisdictional Continental Shelf and Deep Mediterranean Sea



Approximative percentages of Jurisdictional Continental Shelf per Country related to the total area of deep sea, calculated with the 200 meters isobath limit, in the Mediterranean Sea: Albania (AL): 0,3%; Algeria (DZ): 6,1%; Croatia (HR): 0,5%; Cyprus (CY): 4,8%; Egypt (EG): 7%; France (FR): 3,5%; Greece (EL): 20,6%; Israel (IL): 1,1%; Italy (IT): 21,2%; Lebanon (LB): 0,95%; Lybia (LY): 15,1%; Malta (MT): 2,3%; Montenegro (ME): 0,15%; Morocco (MA): 0,6%; Spain (ES): 11,1%; Syria (SY): 0,5%; Tunisia (TN): 1,5%; Turkey (TR): 2,5%.

