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1 **Benthic effects of offshore renewables: identification of knowledge**
2 **gaps and urgently needed research.**

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49 **Abstract**

50 The EU's renewable energy is projected to grow to a share of 20% by 2020. Therefore,
51 many European countries with marine borders have set targets to increase the use of
52 marine renewable energy from wind, wave and tidal energy resources. This study i)
53 summarises knowledge on how renewable energy devices affect benthic
54 environments, ii) explains how these effects could cascade and alter the ecosystem
55 processes that are considered societally relevant issues because they are at the basis
56 of major ecosystem services and iii) provides a conceptual tool to determine the most
57 urgent research needs for effect assessment.

58 Causal networks were set up to structure hypothesised cause-effect relationships
59 (hCER) into pathways based on state-of-the-art knowledge from a literature review of
60 233 published studies. The hCER were classified into pressure groups. Next, each
61 hCER was scored by i) the temporal and spatial scale of the effect; ii) benthic sensitivity
62 to these effects; iii) the effect consistency (i.e. applicability to all habitats and biological
63 components) and iv) the confidence of the scoring based on the knowledge available.
64 The hCERs were triple ranked (highest total score, lowest confidence, highest
65 consistency) to identify knowledge gaps on ecological processes and to prioritise
66 hypothesis-driven research needs related to benthic ecology.

67 This combined approach of causal networks and scoring process identified some most
68 pressing knowledge gaps in the following areas: (a) hydrodynamic changes that could
69 result in altered primary production with potential consequences for filter feeders, (b)
70 the introduction and range expansions of non-native species through the stepping
71 stone effect and (c) the effects of noise and vibration on benthic invertebrates. Our
72 results also provide evidence that benthic sensitivity to offshore renewable effects is
73 higher than previously indicated. The knowledge on changes of ecological functioning

74 through cascading effects is limited and requires distinct targeted research in
75 combination with integrative ecological modelling.

76 **Keywords**

77 Renewable energy, offshore wind farms, environmental impact, marine ecology,
78 benthos, knowledge gaps

79 **1. Introduction**

80 Climate change effects are altering species occurrence, habitats and processes
81 causing severe repercussions for the marine environment (Birchenough et al., 2015).
82 In the attempt to combat climate change, the global demand for renewable energy has
83 increased rapidly, thereby accelerating the installation of renewable energy devices at
84 sea. In 2017, the global capacity of offshore wind generated energy was around 19
85 GW. The majority (84%) thereof is generated by European offshore wind farms (4149
86 turbines in 92 wind farms in 11 countries); another 16% is generated by offshore wind
87 farms in China, Vietnam, Japan, South Korea, the United States and Taiwan (GWEC,
88 2018; WindEurope, 2018). In Europe, offshore wind energy is projected to grow to an
89 installed capacity of 25 GW (WindEurope, 2018) by 2020 through the implementation
90 of the 2015 United Nations Paris agreement to halt climate change. Growth of the
91 renewable energy sector can be expected worldwide over the next decades, even
92 though planned constructions are delayed in some countries (e.g. France, Poland; see
93 e.g. Pezy et al., in press).

94 Marine renewable energy devices (MREDs) include wind turbines, wave, tidal stream
95 and ocean thermal energy converters, which derive energy from salinity gradients
96 (Magagna et al., 2016). Hitherto, wind turbines, arranged in offshore wind farms,
97 generate the bulk of the marine renewable energy. The introduction of MREDs induces

98 changes to the marine environment (Lindeboom et al., 2011; Gill et al., 2018). MREDs
99 generally consist of (artificial) hard substrates typically introduced in an exclusively
100 soft-bottom environment. Further, they can span the entire depth of the water column
101 thereby introducing intertidal environments where they often have not been present
102 before.

103 In this study, we focus on the benthos, the assemblages of organisms living in, on or
104 near the seabed. The benthos is composed of a diverse set of taxa characterised by a
105 wide range of size and shapes. Benthic organisms affect the environment through their
106 activities directly contributing to ecosystem processes (Snelgrove et al., 2018), and
107 indirectly the provisioning of ecosystem services (Duncan et al., 2015). These
108 ecosystem processes that support ecosystem services are here termed as societally
109 relevant issues of biodiversity, biogeochemistry and food resources.

110 Changes to the benthos associated with MREDs can be direct or indirect, occurring
111 during the construction phase, the operational phase or the decommissioning phase,
112 and are generally related to the pressure groups (i) mechanical sea-floor disturbance,
113 (ii) the artificial reef effect, (iii) the input of additional energy (sound, other energy) and
114 (iv) fishery cessation and displacement (see Bergström et al., 2014). Construction
115 effects, such as mechanical disturbance can lead to changes in the physical
116 environment (Van den Eynde et al., 2013) and the associated macrobenthos (Coates
117 et al., 2015) while noise (energy emitted) from piling activities results in the relocation
118 of fish species and marine mammals distribution, such as harbour porpoises (Brandt
119 et al., 2018; Neo et al. 2014). Once installed, the artificial reef effect is observed
120 through the rapid and extensive colonisation of offshore energy devices with sessile
121 fauna, *inter alia* non-native species (Krone et al., 2013b; De Mesel et al., 2015; Nall et
122 al., 2017), the attraction of pelagic and demersal fish (Wilhelmsson et al., 2006;

123 Reubens et al., 2014b) to the devices and increased densities of large decapods at the
124 scour protection (Krone et al., 2013a; Reubens et al., 2014b; Krone et al., 2017; van
125 Hal et al., 2017). Further, the presence of a structure stretching through the entire water
126 column results in hydrographic changes such as the decrease or even disappearance
127 of stratification due to local turbulences (Floeter et al., 2017), possibly resulting in
128 upward transport of nutrients and, concurrent affecting local primary production and
129 carbon flow to the benthos. The emission of electromagnetic fields (EMFs) from sub-
130 sea power cables may cause attraction of the commercially important crustacean (e.g.
131 *Cancer pagurus*; Scott et al., 2018), there is also the possibility that EMFs may trigger
132 developmental, physiological and/or behavioural responses in sensitive fish and
133 invertebrate species (see Hutchison et al., 2018).

134 Indirect effects on macrobenthos include changes in community composition and/or
135 increased abundance and size of, for example, lobsters as a consequence of the
136 cessation of fishing activity during the construction and/or operation of offshore
137 windfarms (Coates et al., 2016; Roach et al., 2018). The local recovery of benthic
138 assemblages within arrays (Lindeboom et al., 2011) however, may coincide with an
139 increasing fishing pressure elsewhere because of redistribution of fishing effort
140 (Berkenhagen et al., 2010; Stelzenmüller et al., 2011). Very close to the turbine
141 increased densities and diversity of macrofauna seems to be related to organic
142 enrichment of the sediment through the deposition of organic material originating from
143 the fauna colonising the turbine (Coates et al., 2014).

144 Knowledge on the effect of the introduction of MREDs on the benthic ecosystem is
145 derived from scattered monitoring programmes, executed at arbitrary spatial scales,
146 mainly focusing on very descriptive structural aspects of soft sediment and fouling
147 communities (density, diversity, percentage cover; Wilding et al., 2017). These

148 monitoring programmes have the general purpose to investigate whether aspects of
149 the local environment have changed but do not contribute to our understanding of
150 cause-effect relationships behind such changes (Lindeboom et al., 2015). However,
151 the understanding of these cause-effect relationships is urgently needed. Identification
152 of cause-effect relationships will inform the design and execution of more strategic and
153 cost-effective monitoring programmes (Lindeboom et al., 2015), the evidence-based
154 development of environment-friendly MREDs, and performing hypothesis-driven
155 experiments that provide valuable data to support the understanding how the
156 introduction of marine renewable energy devices interact with marine ecosystem
157 functioning, and thus provisioning of marine ecosystem services to society (Wilding et
158 al., 2017; Causon and Gill, 2018). Such information is urgently needed, as improved
159 understanding of the economic and societal impacts of the sector is necessary to
160 support energy policy developments and planning decisions and potential effective
161 mitigation actions (Hooper et al., 2017). This becomes even more important as there
162 is an increasing demand to co-locate MREDs with emerging sustainable seafood
163 (seaweed, fish and shellfish farms) production facilities (Holm et al., 2017) and the
164 need to increase marine protected areas in the Natura 2000 network.

165 This paper defines a set of scientifically argued hypothesised cause-effect
166 relationships (hCERs) describing interactions between MREDs and the benthos.
167 Whilst we acknowledge that the marine ecosystem has several ecological components
168 and receptors (Willsteed et al., 2017), the main aim is to characterise with a conceptual
169 approach the hCERs over benthos as one important ecological component of the
170 marine system. We provide a conceptual approach to score the hCERs which reveals
171 knowledge gaps and serves as a robust base to prioritise the most urgent research
172 areas regarding the impact of MREDs on the benthic ecology.

173 We reviewed 233 publications to group the hCERs and set up causal networks, linking
174 the introduction of MREDs to societally relevant issues. This conceptualised
175 knowledge base provides the backbone of highlighting knowledge gaps and with the
176 identification of benthic priority research. As such, this paper provides a
177 comprehensive basis for furthering hypothesis-driven research that will contribute to
178 evidence-based planning and policy decisions with regards to the future of MREDs.

179 **2. Outline**

180 We reviewed 233 published studies to group several hCERs into causal networks,
181 linking the introduction of MREDs with the societal important issues. We took a
182 stepwise approach (a) to build a conceptualised knowledge base which enabled us (b)
183 to prioritise the current scientific knowledge gaps associated with the benthos and
184 identify research needs.

185 **(a) Conceptualised knowledge base**

186 While descriptive literature on the observed impacts of offshore renewables is plentiful,
187 there is limited knowledge that contributes to a systematic understanding of these
188 impacts (Wilding et al., 2017). As a first step, a group of experts exhaustively listed
189 hCERs unravelling the cause-effect chains between the development of MREDs and
190 their impacts on benthic biodiversity (during the ICES workshop on the Effects of
191 Offshore Wind Farms on Marine Benthos; WKEOMB; ICES, 2012). These effect chains
192 departed from the different human activities typically associated with the construction
193 and presence of the MREDs and considered the whole abiotic and biotic cause-effect
194 chain to the essential benthic ecological processes at the basis of ecosystem services.
195 To date, most information exists for the construction and operational phases, while
196 poor knowledge is poor on the effect chains during decommissioning. The latter is

197 hence not explicitly considered in this paper. The few available studies however
198 indicate that the effects of decommissioning are likely to be comparable to the
199 construction of MREDs (Bergström et al., 2014).

200 To simplify the overview of the causal network created by the hCERs, we reorganised
201 the causes and the (end) effects into two categories (abiotic, biotic) and these effects
202 were grouped into what we termed the societally relevant issues, which are the
203 essential benthic ecological processes that support the marine ecosystem services.
204 This helped structure the multitude of hCERs into a synoptic overview by allocating the
205 hCERs to these societally relevant issues and demonstrated the importance of the
206 benthic processes in these regards. This sequence also takes account of the stepwise,
207 conceptual framework considering environmental effects of marine renewable energy
208 as proposed by Boehlert and Gill (2010).

209 We classified the 'causes' of the hCER into pressure groups after Bergström et al.
210 (2014): (1) mechanical sea-floor disturbance, (2) artificial reef effect, (3) addition of
211 energy (sound, other energy) and (4) fishery cessation and displacement. Fishery
212 cessation and displacement were excluded from our analysis because evidence on
213 benthic impacts resulting from trawling activities is sufficiently documented elsewhere
214 (e.g. Jennings and Kaiser, 1998; Kaiser et al., 2006). Here, we focus on effects that
215 are not exhaustively reviewed so far, i.e. the introduction of hard substrata and
216 changes to the benthos related to the installation and operation of MREDs. After having
217 identified and structured the hCER, the ICES Working Group on Marine Benthic and
218 Renewable Energy Developments (WGMBRED;
219 <http://www.ices.dk/community/groups/Pages/WGMBRED.aspx>) screened the
220 scientific literature to validate and elaborate each of the hCERs and as such, assessed

221 the available knowledge with regards to the hCERs (see supplementary material in
222 ANNEX 1).

223 **(b) Science-based priority of benthic research needs**

224 We scored the effects based on the importance of different spatial and temporal scales,
225 the sensitivity (i.e. the extent of change), the consistency (i.e. applicability to all
226 biotopes/habitats/areas) and the level of confidence in the scoring, i.e. amount of
227 knowledge available (Table 1), following the concept of Bergström et al. (2014). The
228 scoring classes were 1-3. Sensitivity expresses the quality of the effect or the extent
229 of change (Table 1), i.e. having minor or no effects on abiotic and biotic processes
230 (low, 1), effects on abiotic and biotic processes, but no cascading effects (moderate,
231 2) or effects on abiotic and biotic processes which lead to cascading effects of the
232 structure and function of the ecosystem (high, 3), such as described by Bohnsack
233 (1989) for artificial reefs. To assess the overall effect (space – time – magnitude), we
234 ranked the hCER by their total scores (Bergström et al., 2014): a total of 3-5 indicated
235 low overall impact, i.e. low scores for temporal and spatial scale and the sensitivity. A
236 total of 6-7 represented a moderate impact, i.e. high scores for one aspect with low
237 scores on others or moderate scores throughout. A high overall impact (total sum: 8-
238 9) came from moderate to high scores for all aspects.

239 We expanded the scoring concept developed by Bergström et al. (2014) by adding
240 consistency, which reflects the differential response of benthic systems. Consistency
241 of the hCER was evaluated for different habitats (soft – hard substrate) and different
242 biological components (demersal fish, invertebrates and phyto-benthos including
243 benthic algae and microphyto-benthos). Consistency was scored as low (1) if the
244 expected effects on the benthos were applicable only to specific biotopes or ecosystem
245 components, moderate (2) if they were applicable to numerous biotopes or ecosystem

246 components and high (3) if they are applicable to all biotopes or ecosystem
247 components (Table 1). Confidence was based on the evidence ranking of the Marine
248 Life Information Network (MarLIN) (www.marlin.ac.uk/glossarydefinition/evidence
249 [ranking](#) - access date: 02.10.2018, scores between 1-4, see Table 1): very low
250 confidence (1) indicates that the scoring is based only on “informed expert judgement”
251 as there is very little or no information available on the effects. Low scoring (2) means
252 that information was derived from sources that only cover comparable general studies
253 or from a general understanding of hCER. Moderate confidence (3) means that
254 knowledge was derived from sources that consider comparable effects of the particular
255 hCER (e.g. artificial reef studies). High scoring (4) indicates that the information was
256 derived from studies that specifically deal with the hCER in an MRED context
257 (experimental or field studies).

258 As a final step, we used a triple ranking of hCER by (a) highest total score, i.e. largest
259 spatial, temporal scale and the highest extent of change (sensitivity), (b) lowest
260 confidence, i.e. very little or no information is present, and (c) highest consistency, i.e.
261 the hCER are applicable to a wide range of biotopes and ecosystem components (see
262 supplementary material in ANNEX 2). The ranking or ecological prioritisation of hCERs
263 allowed the identification and prioritisation of knowledge gaps in order to define urgent
264 research needs for benthic ecosystems. The outcomes are summarised in section 4.

265 **3. Causal network of hypothesised benthic changes by renewable** 266 **energy devices**

267 **3.1. Hypothesised cause-effect relationships (hCER) and chains**

268 Overall, 33 (hypothesised) cause-effect relationships (hCER) were identified (Figure
269 1a-c; supplementary material, see ANNEX 1: bold titles). They link human activities

270 attributed to offshore renewable development to abiotic and biotic factors and interlink
271 with each other by effect chains (Table 2). The hCER chains span the gradient from
272 unidirectional effects of the activities on the benthos, for example *hCER 24* (Figure 1a),
273 to highly complicated combinations of direct and indirect effects (incl. feed-back loops)
274 on the benthos (Table 2), causing infinite proliferation of the hCER chain lengths. The
275 colonisation by non-indigenous species through shipping, ballast water and
276 translocated equipment for instance, exemplifies a unidirectional relationship between
277 the activity of shipping in relation to the construction and operation of offshore
278 renewables and the biodiversity (Figure 1a, *hCER 3*). A more complicated effect chain,
279 which also included indirect links and feed-back loops, results from the addition of
280 artificial hard structures changing the benthic habitats (Figure 1c, *hCER 9*). The initial
281 effect will allow a specific hard bottom assemblage to colonise the area (Figure 1c,
282 *hCER 13*), which is then further enhanced by the increased structural complexity
283 caused by the fouling organisms such as mussels (Figure 1c, *hCER 15*). This
284 increased biodiversity (and productivity) finally provides foraging opportunities to
285 organisms from higher trophic levels (Figure 1c, *hCER 11*), which may positively
286 contribute to the population dynamics of commercially valuable species such as
287 Atlantic cod *Gadus morhua* (Figure 1c, *hCER C1*).

288 The hCER overviews includes two hCERs related to contaminants and how these
289 potentially affect the food resources: '*Artificial devices might release metallic*
290 *contaminants and biocides from anti-fouling paintings*' (Figure 1c, *hCER 32*) and '*Bio-*
291 *accumulation of contaminants through trophic pathways might affect performance and*
292 *survival of organisms of valuable populations*' (Figure 1c, *hCER 33*). As anti-fouling
293 paints appear not to be used, we considered the risk as being low and did not further
294 deal with bio-accumulation effects of contaminants in this review.

295 **3.2. Cause-effect allocation to societally relevant issues**

296 Three societally relevant issues that are known to be impacted by offshore renewables
297 were identified, i.e. biodiversity, biogeochemistry and food resources (see e.g. Causon
298 and Gill, 2018). Biodiversity is considered key in many present-day regulations,
299 including the Convention on Biological Diversity (United Nations, 1992) and for Europe,
300 the Marine Strategy Framework Directive (European Union, 2008). Seafood resources
301 provided or supported by the benthic biodiversity are manifold, e.g. commercial fish
302 and crayfish, and are a major driver for marine management worldwide (Botsford et
303 al., 1997; Worm et al., 2009). Although less known, marine biogeochemistry in which
304 the benthos plays a most prominent role (Snelgrove et al., 2018) has direct links to
305 marine ecosystem services in the form of e.g. organic matter mineralisation for
306 phytoplankton dynamics or carbon dioxide uptake in coastal waters (Braeckman et al.,
307 2014; Carstensen et al., 2014).

308 Aside from its focus on society, the organisation of available knowledge in causal
309 networks based on the societally relevant issues allowed clarity in the enormous
310 amount of information available. The causal networks summarise available evidence
311 on how the chains of hCERs may ultimately feed into changes of societally relevant
312 issues.

313 In general, the increased habitat complexity caused by physical structures influences
314 biodiversity of biota (Figure 1a, *hCER A1*). Further, the colonization by non-indigenous
315 species of the different structures and the potential stepping-stone effect via structure
316 arrays being connected might change the survival and spatial distribution of the
317 indigenous and non-indigenous species (Figure 1a, *hCER A2*). This in turn might
318 produce new source population/species pools with potential spill-over effects from the
319 artificial hard substrates to the soft bottoms which ultimately change biodiversity

320 (Figure 1a, *hCER A3*). As for biogeochemistry, important benthic functions such as
321 bioturbation and decomposition may be affected if there is an altered benthic
322 assemblage structure (Figure 1b, *hCER B1*). The result could be modified rates of
323 primary production, which may affect biogeochemical turnover rates of benthic species
324 (Figure 1b, *hCER B2*) and the addition of 'new players' (i.e. colonising community on
325 artificial hard substrates) and their specific metabolic activities (Figure 1b, *hCER B3*)
326 substantially affecting biogeochemical processes crucial to the functioning of the local
327 marine ecosystem. Food resources might be affected by an altered structure and
328 distribution of local benthic populations in the natural and new artificial habitat as these
329 can directly affect the performance and survival of organisms of valuable populations
330 through trophic and competitive interactions (Figure 1c, *hCER C1*).

331 Hence, not all hCERs are equally important to all three societally relevant issues: only
332 4 hCER were contained in all three, whilst 16 hCER were unique to only one societally
333 relevant issue (Figure 1). Each of the societally relevant issues were influenced by a
334 different set of hCERs, pinpointing the differential importance of cause-effect chains
335 for the societally relevant issues.

336 **3.3. Hypothesised cause-effect relationships: knowledge base**

337 Of the 233 scientific publications 36 % were directly and 64 % indirectly relevant to the
338 hCERs identified and reviewed (see supplementary material in Annex 1: plain
339 paragraphs). Directly relevant papers dealt with studies that explicitly addressed the
340 hCER in an offshore renewable energy context. Indirect relevant papers that
341 addressed research of closely allied subjects as a proxy for the offshore renewables'
342 effects, e.g. studies from dedicated artificial reefs, were also included. This literature
343 base demonstrated the diversity of scientific knowledge available, but also the
344 fragmented nature of that knowledge: all papers only covered one (or few) selected

345 issues, e.g. attraction of fish (Reubens et al., 2011; Reubens et al., 2013), colonisation
346 by non-indigenous species (De Mesel et al., 2015), mussel productivity (Krone et al.,
347 2013b) and therefore only dealt with a small number of aspects of the cause-effect
348 chain from activities to the societally relevant issues.

349 There was a high variation in confidence gained from the knowledge base with regards
350 to the hCERs. While some relationships have been explicitly investigated in relation to
351 MREDs, others are inferred from related studies (see an example in text box 1). Within
352 the available literature, support for the hCERs ranged from a rich knowledge base and
353 well-defined relationships to poorly understood relationships (text box 2).

TEXT BOX 1. Example of the knowledge base inferred from related studies.

Organisms from higher trophic levels (e.g. fish) are attracted/aggregated to/at the physical artificial structures for shelter (Figure 1c, *hCER 10*)

Due to confounding factors, this hypothesis is difficult to verify experimentally in offshore wind farms. Support for the hypothesis may be inferred from the fact that fish aggregate at the turbine foundations a short time after the construction of the wind farm (Wilhelmsson et al., 2006; Reubens et al., 2011; Bergström et al., 2013; Reubens et al., 2013), at a time when the colonisation of potential prey species is likely to not have been fully developed yet. Similar observations have also been made for other types of artificial reefs (Bohnsack et al., 1994; Leitão et al., 2008). However, in most cases, the colonisation of potential prey species has been very rapid, so the predators could also be aggregating there in food search (Reubens et al., 2011; Reubens et al., 2013). According to studies at artificial reefs, the level of aggregation is seen to increase with increased habitat complexity, implying that the species benefit from the increased amount and diversity of shelter provided (Hixon and Beets, 1989; Bohnsack et al., 1994; Danner et al., 1994). In addition to finding shelter from predators, organisms from higher trophic levels may also aggregate at the artificial reefs because these provide shelter to ambush prey. This kind of behaviour has been observed, for example in cod and horse mackerel (Reubens, pers. obs.).

354 By detailing the level of understanding of hCER chains, the knowledge base promoted
355 the importance of ecological processes with respect to the direction and multitude of
356 the effects of MREDs onto the benthos and societally relevant issues. Moreover, it also
357 highlighted the knowledge gaps with regards to ecological processes deemed
358 important in assessing the impacts of MREDs. Such knowledge gap analysis shows
359 where additional understanding is needed through dedicated research. Rather than
360 setting up a monitoring program for observing changes, the result from such research
361 allows a science-based design and management, as well as support of cost-effective
362 practices of future MREDs.

TEXT BOX 2. Example of the knowledge base with regards to a cause-effect relationship that is poorly understood so far.

Altered water flow and/or stratification influences benthic anoxia, hypoxia and the presence of H₂S (Figure 1b, *hCER 16*)

The hydrographic interactions between artificial structures (of whatever type) and the receiving water body may result in the acceleration or baffling of flow around the structures, the formation of various types of vortices and the generation of turbulence and wave breaking (Sumer et al., 2001; Al-Bouraei, 2013). Such hydrographic interactions potentially affect both the particulate transport around reefs and the associated epifaunal and infaunal assemblages. Research into the broader effects of artificial reefs on their surrounding sediment is limited and contradictory. Around the edges of reefs scour can increase and fine material can be reduced (Davis et al., 1982; Ambrose and Anderson, 1990; Barros et al., 2001), or increased (Guiral et al., 1996; Fabi et al., 2002; Wilding, 2006). In terms of organic enrichment the spatial scale has been shown to be limited, occurring within circa 1 m from the reef edge, with the subsequent impact being more severe during the summer and autumn (Wilding, 2014). There is no reason to expect that the magnitude and extent of change will be any greater around offshore wind-farms and the effects are only likely to be detrimental in oxygen-deficient sediments, and on sites that are not well-flushed (Wilding, 2014).

363 Combining the hCER chains and the knowledge base, an in-depth view on the direct
364 and indirect scientific knowledge at the basis of the processes behind the effects of
365 MREDs onto marine benthos has been achieved. This can be considered a first step
366 towards knowledge gap identification with regards to the understanding of MRED
367 effects. An example for evidence-based cause-effect chains (Figure 1c, chain of
368 *hCERs 9 – 13 – 15 – 13 – 11 – C1*) is presented in text box 3.

369

TEXT BOX 3. An example from evidence based cause-effect chains of offshore wind farms

Worked example of chain *hCERs 9 – 13 – 15 – 13 – 11 – C1* (Figure 1c)

Wind turbines provide hard substrata in regions and at depths often dominated by soft bottom habitats (Figure 1c, *hCER 9*). They introduce atypical, and initially unutilised, substrate types in terms of structure and inclination, and often offer a range of depths and environments for marine organisms, including shallow/littoral habitats in otherwise deeper water (Wilhelmsson and Langhamer, 2014). While the structural complexity and the diversity of microhabitats (apart from the depth gradient) generally are lower on wind turbine foundations compared to the surrounding seabed (Wilhelmsson and Malm, 2008), the turbines predominantly increase the habitat complexity at the scale of the wind farm areas. The main effect from offshore wind farms is to transform soft-bottom to hard bottom due to the installation of foundations and piles. This creates an artificial reef with associated biodiversity that can be considered as a positive effect (Vaissière et al., 2014), but it can also introduce non-native species which can be considered a negative effect (De Mesel et al., 2015; Coolen et al., 2018). Moreover, there is a risk of scouring around the base of the foundations due to local hydrodynamic changes which depends on the current velocities in the zone of implementation of turbines; to prevent such scouring gravel beds and boulders are placed around each foundation which increases the reef effect (Vaissière et al., 2014).

TEXT BOX 3. continued

After construction, a specific hard bottom assemblage (fouling and mobile megafauna) consisting of primary and secondary consumers will colonise the new artificial habitat (Wilhelmsson and Malm, 2008; Kerckhof et al., 2010; Lindeboom et al., 2011; Langhamer, 2012; Krone et al., 2013b) (Figure 1c, *hCER 13*). In the North Sea, this community follows a clear vertical zonation: the intertidal zone is dominated by barnacles and mussels and the subtidal zone is dominated by tubicolous amphipods, hydroids and anemones (Andersson and Öhman, 2010; Krone et al., 2013b; van der Stap et al., 2016).

In soft sediment environments, the added hard substrate structures increase the habitat available for a wide range of species (Andersson and Öhman, 2010; Langhamer, 2012). The effect is most notable on the scour protection which has a higher habitat complexity than the foundations and is a suitable habitat for mobile demersal megafauna species such as lobsters and crabs (Jensen et al., 2000; Langhamer and Wilhelmsson, 2009; Krone et al., 2013a). From offshore oil and gas platforms it is known that the community changes over time, where initial colonisers (e.g. tubeworms and hydroids) are replaced by secondary colonisers such as anemones after 2-4 years which stay dominant up to 11 years after construction (Whomersley and Picken, 2003).

Typical “pier piling assemblages” (Davis et al., 1982), dominated by filter feeding invertebrate organisms generally develop on wind turbines (Figure 1c, *hCER 15*). In post construction surveys of wind turbines two principal assemblages have been observed; either dominance by barnacles and blue mussels (*Mytilus edulis*), in true marine areas together with predatory starfish, or dominance by anemones, hydroids and solitary sea squirts (Dong Energy et al., 2006; Wilhelmsson et al., 2006; Linley et al., 2007; Maar et al., 2009; Krone et al., 2013b). Wind turbines may offer a particularly favourable substrate for blue mussels (Wilhelmsson and Malm, 2008; Maar et al., 2009). The mussel matrices on the turbines provide habitat for small crustaceans such as amphipods, and increase biodiversity of macroinvertebrates on the turbines (Ragnarsson and Raffaelli, 1999; Norling and Kautsky, 2007; Norling and Kautsky, 2008; Wilhelmsson and Malm, 2008).

TEXT BOX 3. continued

Further, the blue mussels on the seabed favour the local biomass of small crustaceans, such as amphipod species of the genus *Jassa* (Wilhelmsson and Malm, 2008), as the blue mussel shells form a new three-dimensional habitat.

Species may be attracted to the offshore wind farm structures since organisms from higher trophic levels may benefit from foraging on the assemblages on the artificial structures, and in the surrounding natural habitats (Figure 1c, *hCER 11*). Studies in other types of artificial reefs indicate that these created habitats are used as foraging areas by fish and marine mammals (Hixon and Beets, 1989; Bohnsack et al., 1994; Mikkelsen et al. 2013). Studies in OWFs have shown that both fish and marine mammals forage close to the turbines (Reubens et al., 2011; Reubens et al., 2013; Reubens et al., 2014a; De Troch et al., 2013; Russell et al., 2014). The increased food abundance or increased food availability provided at the artificial structure may have a positive effect on the fitness of the predating species (fish, marine mammals) and potentially for improved productivity. The enrichment of the macrofauna community around the foundation can serve as an additional food source for higher trophic levels (Schückel et al., 2011). However, a feedback effect on the abundance of prey species can be assumed (Hixon and Beets, 1989; Leitão et al., 2008; Russell et al., 2014).

372

373 **4. Identification and science-based prioritisation of knowledge**374 **gaps by assessing potential effect magnitude of marine**375 **renewable energy developments on benthos**

376 We formulated a total of 31 hCERs of which eleven were linked to abiotic effects
 377 exclusively and 20 to both abiotic and biotic effects (see Figure 1). Because our
 378 objective was to prioritise research needs regarding the impact of MREDs on the
 379 benthic ecology, we scored all hCERs but analysed only the latter 20 hCERs from a

380 benthic perspective. These comprised 13 hCERs related to artificial reef effects, four
381 hCERs related to mechanical sea-floor disturbance and three hCERs related to the
382 introduction of energy effects (see supplementary material in ANNEX 2). In the first
383 section here, we consider the scales of effects in space and time, and their magnitude
384 (sensitivity), as well as the knowledge available. As such, it forms the scientific basis
385 to structure and scientifically prioritise the hCER for our main objective, i.e. the
386 identification of knowledge gaps and benthic research priorities, which is subject of the
387 second part of this section.

388 **4.1. Scoring the scale and magnitude of the effects**

389 In general, hCERs linked to the artificial reef effect had the highest scores on temporal
390 and spatial scale, as well as the highest magnitude of the effect (sensitivity) (Figure
391 2a). Therefore, the artificial reef effect in general scored higher (6.7 ± 0.7 standard
392 deviation, SD) in total, i.e. sum of temporal and spatial scales and sensitivity, than
393 mechanical sea-floor disturbance (6.3 ± 1.0) and the introduction of energy effects (6.2
394 ± 2.5). Bergström et al. (2014) scored comparable effect sizes for fish and benthos
395 during construction and operation phase: moderate effects for the introduction of
396 energy effects (4-6; acoustic disturbance/pile driving), for mechanical sea floor
397 disturbances during the construction phase (4; sediment dispersal) and artificial reef
398 effects (5-6; habitat gain).

399 Further, scoring of the consistency was also highest for artificial reef effects (2.4 ± 0.8 ,
400 see Figure 2b) compared to the other pressure groups (mechanical sea-floor
401 disturbance: 1.5 ± 1.0 ; introduction of energy effects: 1.7 ± 0.6). For both latter issues,
402 the knowledge base for the effect assessment is not generally applicable, but rather
403 refers to selected biotopes, ecosystem components and effect sizes. Lowest
404 confidence scoring of 2.5 ± 0.5 was found for the introduction of energy effects,

405 implying that information on the effects was mainly derived from sources that only
406 cover related studies or from a general expert judgement on the hCERs. Similarly, also
407 Bergström et al. (2014) scored low confidence for benthic hCERs regarding acoustic
408 disturbance and high confidence for sediment dispersal effects. Both assessments
409 hence conclude that research regarding the introduction of energy effects (in all forms)
410 are largely lacking.

411 Most of the hCERs (9 hCERs) were rated as occurring only at a local scale (<100 m,
412 see Figure 3a), while five hCERs were rated as acting on larger scales (>1000 m). This
413 is in line with the current research showing that most effects act on a local scale (e.g.
414 Lindeboom et al., 2011; Coates et al., 2014; Degraer et al., 2018). However, newer
415 studies documented larger scale effects, i.e. by investigating the effects of devices
416 acting as stepping stones for spatial distribution of hard substrate species (Kerckhof et
417 al., 2016; Coolen, 2017). On a temporal scale, most hCERs are relevant for the
418 duration of the operational phase of MREDs (9 hCERs) or beyond the lifetime of the
419 devices (8 hCERs), i.e. being permanent (Figure 3a). Lindeboom et al. (2011) also
420 stated that no meaningful short-term effects, i.e. during the construction phase only,
421 were observed for the benthos. In summary, most hCERs relate to a local scale and
422 long-term local effects and were all related to the artificial reef effect on the benthic
423 system.

424 The main finding of our scoring was that 17 hCERs constitute effects on abiotic and
425 biotic processes with knock-on effects onto the benthic system (see sensitivity scoring,
426 Figure 3a). Only one hCER was scored as having minor or no effects on abiotic and
427 biotic processes, while two will have an effect on such processes but lack any further
428 cascading of the effects. Consistency scoring varied randomly implying that some
429 hCERs are applicable to specific (6 hCERs), numerous (6 hCERs) or all (8 hCERs)

430 biotopes/ecosystem components (Figure 3b). Most of the hCERs (12 hCERs) were
431 scored high regarding the confidence (Figure 3b). Therefore, this information has been
432 derived from sources that consider comparable effects of this particular hCER in
433 studies derived from artificial reef studies. For five hCERs there is specific information
434 from MREDs by experimental or field studies (scoring = 4, Figure 3b) and only for three
435 hCERs there was no or little information available.

436 **4.2. Knowledge gaps: science-based prioritisation of hypothesised** 437 **cause-effect relationships**

438 We ranked the hCERs according to (a) the highest total score, (b) the lowest
439 confidence and (c) the highest consistency (Figure 4, see supplementary material in
440 ANNEX 2). The science-based prioritisation of the hCERs by the largest spatio-
441 temporal scale and magnitude of the effect and only little or no scientific knowledge
442 available (confidence) and the consistency enabled us to identify knowledge gaps and
443 to give recommendation on for which hCERs specific research is needed.

444 For the artificial reef effects (the physical presence of the foundations), three hCERs
445 (and one abiotic hCER) were identified as potentially important, achieving total scores
446 between maximum 8 and 9 (hCER 4, 2 and 3; Figure 4, see supplementary material in
447 ANNEX 2). These effects cover changing hydrodynamic conditions, increased food
448 availability to filter-feeders and the colonization by non-indigenous species through
449 new shipping activities related to MREDs. These three hCERs related to artificial reef
450 effects have a spatial scale reaching beyond 1000 m. The expected effects last at least
451 as long as the device/array is present and the artificial reef effect hCERs lead to
452 cascading processes starting once the artificial structure is installed. Limited scientific
453 documentation describing the effects of modified hydrodynamics on the settlement and
454 occurrence of benthic species in the surrounding natural substrates is available (but

455 see Coates et al., 2014; Floeter et al., 2017). Simultaneously, these effects are
456 applicable to all biotopes. Thus, especially the modification of currents and
457 hydrodynamic conditions is identified as a field of research that should be investigated
458 in more depth. Moreover, the long-term reef effects on the ecosystem and its
459 functioning are not yet fully understood and remain important to be further investigated.

460 For the hCERs related to mechanical sea floor disturbance (see supplementary
461 material in ANNEX 2), the reduction of the phytoplankton primary production generated
462 by an increase in turbidity was scored high (hCER 6, see Figure 4). In fact, this effect
463 could have a high spatial scale (beyond 1000 m) and a moderate temporal scale (up
464 to 30 years). Sensitivity was scored low as this hCER seems to be responsible for
465 minor or no effects on further abiotic and biotic processes, i.e. it lacks further cascading
466 of the effects. It is expected that this reduction of the phytoplankton's primary
467 production could be observed in specific ecosystems or some components as it
468 received a low score for the consistency. However, as there is little information on this
469 effect, further studies are required.

470 For the hCERs related to the introduction of energy one hCER (*hCER 1*; and one
471 abiotic hCER) was scored high based on our criteria (see Figure 4 and supplementary
472 material in ANNEX 2). With a total maximum score of nine, shipping noise and vibration
473 and noise scored 8 and 9, respectively. The effects of noise and vibration from
474 construction/operation have been shown to extend beyond local scales and can be
475 observed many kilometres from the source. In addition, exposure to noise and vibration
476 and noise from operation is likely to be long lasting given the expected lifespan of
477 installations. Therefore, the hCERs received high scores for spatial scale and temporal
478 scale of the effects. Sensitivity, i.e. the magnitude of the effect, scored high for this
479 hCER as cascading effects are likely to result from it.

480 It is considered that noise and vibration effects as an abiotic factor (*hCER 8*; see
481 supplementary material in ANNEX 2) could be experienced across all biotopes and
482 could impact other ecosystem components. As such, this *hCER* received a high score
483 for consistency. In general, vibration and noise effects could be experienced across
484 numerous biotopes and ecosystem components. However, it is not likely to affect all
485 biotopes and as such the biotic *hCER* (*hCER 1*; see Figure 4 and supplementary
486 material in ANNEX 2) received a moderate score for consistency. Confidence was
487 moderate for shipping noise effects (*hCER 8*) and moderate to high for vibration and
488 noise effects on the biological system (*hCER 1*). Therefore, the information available
489 has indicated that further studies are required to better understand their influence on
490 benthic ecosystems.

491 **5. Benthic research priorities and recommendations**

492 The combination of a causal network to structure and disentangle the hypothesised
493 cause-effect relationships (*hCER*) and the approach to apply scores to the *hCERs* with
494 regards to their spatio-temporal scale, magnitude, consistency and confidence
495 demonstrated to be a scientifically sound tool to highlight priority areas for future
496 research relating to the benthos. These issues are considered as '*known unknowns*',
497 and to support informed decisions on environment-friendly MREDs. However, our
498 approach also identified potential effects which will have to be considered to improve
499 our current state of knowledge, i.e. the high sensitivity pointing towards unforeseen
500 cascading effects in the benthic system. These knowledge gaps are defined as
501 '*unknown unknowns*'. Both knowledge gaps, either known or unknown, call for a
502 scientific discussion, helping to target and improve future monitoring and benthic
503 research and to improve our current, potentially incomplete, understanding of the

504 footprint of offshore renewables. This information is of importance as the development
505 of offshore renewables is planned to be expanded (WindEurope, 2018).

506 ***“The known unknowns”***

507 We identified five priority research areas associated with the benthos. These relate to:
508 i) artificial reef effects, ii) the introduction of sound and energy, and iii) mechanical sea-
509 floor disturbance. Following the methodology applied in the present study, future
510 research could therefore target the following research hCERs:

- 511 - The introduction of three-dimensional artificial structures will modify the
512 hydrodynamic conditions. These newly added structures will determine
513 settlement success and species occurrences in the natural surrounding habitats
514 (*hCER 4*)
- 515 - Changed hydrodynamic conditions by MREDS potentially change the food
516 availability to filter-feeders (*hCER 2*)
- 517 - Phytoplankton primary production may be reduced due to an increase in
518 turbidity reducing light penetration into the water column (*hCER 6*)
- 519 - Artificial structures could influence the colonization by non-indigenous species
520 through new shipping activities related to MREDS (*hCER 3*)
- 521 - The effects of shipping noise and vibration and the noise of construction and
522 operation of MREDS might induce avoidance behaviour and reduce fitness of
523 sound-sensitive organisms, thereby potentially changing population structure
524 and distribution patterns (*hCER 1*)

525 All these cause-effect relationships have the potential to change the benthic system
526 over large spatial scales and for a long-term. An increase of phytoplankton’s primary
527 production by increased vertical mixing due to MREDS (reduced stratification during

528 summer), and subsequent nutrient transport throughout the water column, was
529 recently demonstrated by Floeter et al. (2017). Concurrently, local hydrographic
530 turbulences by MREDs increase particulate matter that increases the attenuation of
531 light (Devlin et al., 2008, Baeye and Fettweis, 2015) affecting primary production of
532 phytoplankton. Slavik et al. (2018) demonstrated that an increase of MREDs and the
533 attached periphyton by mainly filter feeders in the North Sea, might lead to lower
534 phytoplankton production. Water filtering by these species might lead to changes in
535 clearance rates of the water (Newell, 2004; Gallardi, 2014), i.e. reducing phytoplankton
536 bloom and larvae affecting larval settlement success. Further, these changes may
537 have measurable effects on the composition of the benthic assemblages close to
538 MREDs (Coates et al., 2014). However, all the interactions between water stratification
539 and turbidity within the nutrient and light-limitation context, as well as the effect of filter-
540 feeders on phytoplankton and larval settlement success have yet not been investigated
541 effectively. These interactions may lead to changes in the zooplankton as well as in
542 the benthos, affecting higher trophic levels in food webs and thus food provisioning of
543 commercially important species.

544 MREDs may offer new pathways of invasion or range expansion by using the artificial
545 hard substrate as stepping stones (Miller et al., 2013). Species that are restricted in
546 their distribution range to genuine clear water rock (stacks) and rocky coasts, such as
547 in the English Channel (e.g. Brittany) and Northern North Sea (e.g. Norwegian and
548 Scottish coastlines), or rare stones in mostly soft bottom habitats, such as in the
549 southern Baltic Sea, might use MREDs as stepping stones for their spread. First
550 evidence of invasion and range expansion by MREDs is proven (De Mesel et al., 2015;
551 Coolen et al., 2016; 2018) but suggest that range expansion in the subtidal will be
552 marginal due to the species already known to inhabit existing habitats. However, the

553 expansion of intertidal (invasive) species will be more pronounced as this represents
554 a new habitat offshore (Kerckhof et al., 2016) and future modelling and field studies
555 are needed to identify the risk of invasions by MREDs.

556 Energy emissions, principally noise or vibration might affect local populations of fish
557 (Gill et al., 2012; De Backer and Hostens, 2017) or as indicated in noise experimental
558 studies fitness and bioturbation by noise pollution may be affected (Pratt et al., 2014;
559 Debrusschere et al., 2016). Knowledge on the impact of sound on epibenthos,
560 particularly invertebrates remains poor and is generally lacking on the impact of
561 impulsive sound (Edmonds et al., 2016; Roberts and Elliott, 2017). Recent studies
562 have shown cephalopod sensitivity to noise (Solé et al., 2017) or changing behaviour
563 affecting e.g. bioirrigation and associated ecological processes as demonstrated for
564 *Nephrops norvegicus* (Solan et al., 2016). However, many invertebrates are not able
565 to escape and may experience a higher risk of direct damage from sound exposure.
566 Hitherto, we are still lacking an understanding of the causal underwater sound
567 parameters (namely particle motion and sound pressure) and their effect on marine
568 fauna, which hampers the establishment of mitigation measures and sound criteria.

569 All these aspects are considered to be fundamental ecological changes to protect
570 ecological functioning and thus benthic system stability, to ensure the benthos
571 continues to support a healthy system.

572 ***“The unknown unknowns”***

573 This study highlighted that the sensitivity of the benthos to the effects of MREDs was
574 significantly higher than shown in previous studies (Bergström et al., 2014). Available
575 knowledge on the effects of artificial hard substrates on benthos has increased
576 continuously during the last decades. Studies on oil and gas rigs, platforms or other

577 devices (incl. artificial reefs) (e.g. Wolfson et al., 1979; Bohnsack, 1989) and more
578 recently also on MREDs (Degraer et al., 2016; Coolen et al., 2018) have provided
579 further insights into the ecological changes to the benthos by such structures and thus
580 delivered basic knowledge on the potential changes. However, we still miss a full
581 understanding of the ecological processes that might change the ecological
582 functioning, as studying biodiversity related to ecological functioning is still in its
583 infancy. For example, cascading effects on the benthic system by the presence of
584 artificial hard substrates are more than likely (see e.g. feedback loops and hCERs
585 linking biotic to biotic compartments, Figure 1 and Table 2), but might not be foreseen
586 due to our current lack of knowledge. Understanding the ecological processes has
587 therefore been identified as the '*unknown unknowns*'. Many studies targeted benthic
588 recovery after trawling cessation and recently also in offshore wind farm context.
589 However, even after several years, such studies were unable to demonstrate a
590 significant benthic recovery (e.g. Duineveld et al., 2007; Bergman et al., 2015). This
591 aspect raises general important considerations in terms of the scale over which impact
592 studies are operating are missing important ecological processes for e.g. benthic
593 recovery. To identify the '*unknown unknowns*', examination of causal network models
594 (such as Figure 1) help to identify current knowledge gaps, as they form the scientific
595 base to differentiate hCERs on how a mechanism should theoretically act. hCERs can
596 be tested through the validation of quantitative mechanistic models with field data.
597 Results can point to gaps in knowledge and factors not yet considered effectively (such
598 as the energy emissions of electromagnetic fields or heat from MRED cables), leading
599 to hypothesis- driven and basic research (i.e. environmentally and biologically
600 focussed).

601 Species populations with their biological characteristic are the basic units of an
602 ecosystem. The level of organisation and operation of benthic systems varies over a
603 series of scales (Hall, 1994). Removal or addition of a single or multiple species from
604 or to a system by biological or environmental interactions will undoubtedly influence
605 the ecological way this system is working. There is evidence that species interactions,
606 particularly indirect interspecific interactions, can disturb populations and that non-
607 equilibrium dynamics such as in food webs can affect ecological functioning (Wootton,
608 2002; Benincà et al., 2008). Ecological dynamics are the result of a network of internal
609 feedback processes yet little understood (Wootton, 2002). With the increase in MRED
610 deployment (WindEurope, 2018) the introduction of these structures will have the
611 ability to affect trophic food webs and energy flow (Raoux et al., 2017; 2018; Pezy et
612 al., 2018), with repercussions for the wider benthic system. Some studies have
613 demonstrated wider benthic system effects in areas impacted by trawling activities
614 (e.g. Hiddink et al., 2006; Queirós et al., 2006; Dannheim et al., 2014).

615 The turbines themselves might serve as stepping stones for the introduction of non-
616 indigenous species or for range expansion of species (Coolen, 2017). Ricciardi and
617 Rasmussen, (1998) stated that particularly strong dispersal pathways, such as
618 MREDs, between the donor and target regions might lead to a relatively high probability
619 of future invasions.

620 Effects of noise or sediment changes such as coarsening of the sediment might affect
621 biogeochemical processes such as long-term carbon storage (Pratt et al., 2014; Solan
622 et al., 2016). For example, the common heart urchin *Echinocardium cordatum* has
623 been shown to be the most important bioturbator in the German part of the North Sea
624 (Wrede et al., 2017) and this species prefers organically enriched fine sediments

625 (Wieking and Kröncke, 2003; Kröncke et al., 2004). Sediment coarsening thus might
626 lead in turn to a lower bioturbation activity of the species.

627 Despite the high sensitivity of the benthos to MREDs, knowledge, particularly on long-
628 term changes and large-scale effects related to artificial structures is lacking, as they
629 are yet not understood enough for us to make reliable assessments of effects to be
630 able to predict changes. Consequently, this lack of knowledge hinders our ability to
631 make informed decisions.

632 **Recommendations for future research**

633 The systematic approach on hypothesised cause-effect relationships (hCERs) and the
634 drawing together of expert opinion here has provided the opportunity to undertake a
635 detailed review and documentation of current information and provide an authoritative
636 assessment with regards to the effects of MREDs on the benthic ecosystem. Clear
637 changes are apparent in the benthos affected by MREDs even with the limited
638 knowledge available, hence there is the potential to significantly change benthic
639 ecological functioning and thus ecosystem services provided. Therefore, we
640 recommend to structure offshore renewable impact research on benthos by:

- 641 - Including more hypothesis-driven questions, e.g. by targeted field studies or
642 experiments, to support the current monitoring programs to further our
643 understanding of ecological patterns and processes on local scales;
- 644 - Defining relevant ecological scales and in particular looking at large scale
645 effects, supported by the hypothesis-driven research at smaller scales (i.e.
646 local effects) complemented by modelling approaches in order to upscale
647 potential ecological changes (Wilding et al., 2017);

- 648 - Combining benthic research into ecosystem-based management approaches
649 to ensure long-term sustainability of benthic systems and safeguard key
650 processes of societal and ecological relevance (i.e. food webs,
651 biogeochemical changes, biodiversity) under future marine development;
- 652 - Detailed knowledge of the natural variability of the benthic system in space
653 and time is a prerequisite to distinguish potential changes induced by MREDs
654 from the natural variability, to better understand the structure and dynamics of
655 benthic ecosystems. Cooperation between studies groups and locations could
656 enhance our ability to determine the factors affecting variability;
- 657 - Modelling approaches might also help to assess the likelihood of effects. Such
658 detailed knowledge is the base to developing ecologically meaningful
659 management approaches and, to understanding and potentially predicting
660 ecological cascading effects which might lead to as yet unknown changes.

661 The linkages between environmental patterns, MREDs, other anthropogenic effects
662 and ecological processes will be the major challenge in future marine research (e.g.
663 Duffy et al., 2007, Wilding et al., 2017; Wilsteed et al., 2017). This type of work is
664 essential to undertake ecosystem-based approaches for the sustainable use of
665 offshore renewable energy, and to move beyond the case-by-case approach, i.e. the
666 focusing on the most recent population changes by offshore renewables, rather than
667 on understanding the intrinsic mechanisms (e.g. Jackson et al., 2001; Elliott, 2002;
668 Causon and Gill, 2018). Understanding ecological processes and patterns to maintain
669 ecological and societal relevant services supported by the benthos calls for a holistic
670 management, as n-order effects do not only affect the benthos but potentially change
671 other ecosystem functions and ecological receptors. We hence plea to integrate
672 benthic research in an MRED impact assessment context into scientific approaches at

673 the ecosystem level, studied across ecosystems and ecosystem components (see e.g.
674 Atkins et al., 2011; Wilding et al., 2017; Wilsteed et al., 2017).

675 In the light of the fast and large-scale development of MREDs in our continental shelf
676 seas, it is time to speed up dedicated research on benthos preferably co-ordinated
677 across state boundaries and to integrate research findings into ecosystem-based
678 management approaches. Such an approach is the most efficient and feasible way to
679 a fully understanding of the potential changes, the benthos might undergo in relation
680 to the development of offshore renewables and to develop scientifically-sound adaptive
681 changes or mitigation actions where needed. Our tool for the disentanglement of
682 specifically hCERs could serve as a robust base to conceptually improve monitoring
683 and scientifically prioritise urgent research needs, not only for the effects of offshore
684 renewables, but could also be applied to the unravelling of other human impacts. Some
685 of the uncertainties regarding offshore renewable development on benthos and our
686 prevailing lack of the details of ecological functioning suggest that further research is
687 needed to ensure that coastal ecosystems are understood and to promote the
688 sustainable use of the marine environment under a growing blue growth economy.

689 **6. Supplementary material**

690 The following supplementary material is available at ICESJMS online and contains
691 two Annex: ANNEX 1 contains the complete review on current knowledge on the
692 main pressures of offshore wind farms on benthos for each hypothesised cause-
693 effect relationship (hCER) based on the 233 publications reviewed. ANNEX 2
694 summarises the scoring of each hypothesised cause-effect relationships (hCER)
695 according to its spatial and temporal scale, its sensitivity, the confidence of
696 knowledge available and the consistency of the effect.

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1133 **9. Tables**

1134 Table 1: Criteria for assessing the probability of impact on marine life from pressures
 1135 associated with offshore wind farms. The evaluation was made separately for each
 1136 hypothesised cause-effect relationship (see supplementary material in ANNEX 2)
 1137 and scored (1-3) for the effect size in space, time and magnitude (sensitivity), as well
 1138 as consistency of the effect following (Bergström et al., 2014). Confidence was
 1139 scored (1-4) following the evidence ranking of Marlin.

Criteria	Score			
Following (Bergström et al., 2014)				
	1 (low)	2 (moderate)	3 (high)	
Spatial scale	<100 m	<1000 m	>1000 m	
Temporal scale	<2 y (mainly construction effect)	<30 y (operation effect)	>30 y, beyond MRED life time (permanent)	
Sensitivity = quality of impact, extent of change	Minor or no effects on abiotic and biotic processes	Effects on abiotic and biotic processes, no cascading effects	Effects on abiotic and biotic processes, cascading effects	
Consistency	Applicable to specific biotope/ecosystem components/effect size	Applicable to numerous biotopes/ecosystem components/effect size	Applicable to all biotopes/ecosystem components/effect size	
Following the evidence ranking of Marlin (www.marlin.ac.uk/evidenceranking.php)				
	1 (very low)	2 (low)	3 (moderate)	4 (high)
Confidence	information by “informed judgement” where very little or no information is present at all on the species	information has been derived from sources that only cover comparable studies or effects or from a general understanding of the cause-effect relationship. No information is present regarding	information has been derived from sources that consider comparable effects of a particular cause-effect relationship (e.g. such as artificial reef studies)	information has been derived from sources that specifically deal with the cause-effect relationship of MREDs. Experimental or field work has been

		the specific cause-effect relationship		done to investigate the specific cause-effect relationship
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1141 Table 2: (a) Number of hypothesised cause-effect relationship (hCER), (b) number of
 1142 hCERs classified according to their hCER character, i.e. if an hCER links an activity
 1143 to an abiotic factor, biotic factor, an abiotic factor to an abiotic or biotic component, or
 1144 a biotic component to another biotic component, (c) number of loops formed by
 1145 hCERs and (d) chain length formed by several hCERs. Numbers are given for all
 1146 schematics (see Figure 1), as well as the specific societally relevant issues (see
 1147 Figure 1a, b and c). inf. = infinite number of hCER combinations.

Parameter	All hCER	hCER related to Biodiversity	hCER related to Biogeochemistry	hCER related to Food resources
(a) Number of hCER	31	21	15	14
thereof unique hCER	16	7	4	5
(b) Character of hCER				
activity --> abiotic	8	6	4	6
abiotic--> abiotic	3	3	3	-
abiotic--> biotic	12	6	5	5
activity --> biotic	2	2	-	-
biotic --> abiotic	2	2	1	1
biotic --> biotic	4	2	2	2
(c) Number of hCER loops	5	4	-	1
(d) hCER chain length				
Mean	inf.	inf.	4.3	4 (Inf.)
minimum	1	1	3	3
maximum	inf.	inf.	6	7 (inf.)

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1149 **10. Figure legends**

1150 Figure 1: Causal network presentation of the abiotic and biotic processes linked to a)
1151 biodiversity importance, b) biogeochemical importance and c) food resources-
1152 importance of the benthos, altered by human activities and the resulting activity
1153 pressures during the construction and operational phase of offshore renewable
1154 energy devices. Hypothesised cause-effect relationships are numbered (see
1155 supplementary material in ANNEX 1 and 2). Dashed line divides abiotic (left) from
1156 biotic (right) effects. Note: Cause–effect relationships linked to cessation and
1157 displacement of fisheries are not considered here. ©ICES WGMBRED

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1159 Figure 2: a) Mean total scoring of hypothesis (\pm SD), i.e. the sum of the magnitude of
1160 the effect in time, space and quantity, and b) mean confidence and consistency (\pm
1161 SD) between different effect-groups (overarching topics).

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1163 Figure 3: Number of hypothesis which were scored (1-4) for the spatial and temporal
1164 scale of the effect, sensitivity analysis, i.e. the magnitude of the effect, the confidence
1165 and consistency.

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1167 Figure 4: Scoring of hCER according to total score (combined score from temporal,
1168 spatial scale and magnitude of effect), confidence and consistency. hCER are colour
1169 coded according to the ranking/science-based prioritisation of research: 8–9 = high
1170 (white), 5–7 = moderate (light grey), 3–5 = low (dark grey). Numbers corresponds to
1171 hCER identification numbers (see Figure 1, see supplementary material in ANNEX
1172 2).