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Contribution to the Themed Section: '*Decommissioned offshore man-made installations*'

Review Article

Benthic effects of offshore renewables: identification of knowledge gaps and urgently needed research

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As the EU's commitment to renewable energy is projected to grow to 20% of energy generation by 2020, the use of marine renewable energy from wind, wave and tidal resources is increasing. This literature review (233 studies) (i) summarizes knowledge on how marine renewable energy devices affect benthic environments, (ii) explains how these effects could alter ecosystem processes that support major ecosystem services and (iii) provides an approach to determine urgent research needs. Conceptual diagrams were set up to structure hypothesized cause-effect relationships (i.e. paths). Paths were scored for (i) temporal and spatial scale of the effect, (ii) benthic sensitivity to these effects, (iii) the effect consistency and iv) scoring confidence, and consecutively ranked. This approach identified prominent knowledge gaps and research needs about (a) hydrodynamic changes possibly resulting in altered primary production with potential consequences for filter feeders, (b) the introduction and range expansion of non-native species (through stepping stone effects) and, (c) noise and vibration effects on benthic organisms. Our results further provide evidence that benthic sensitivity to offshore renewable effects is higher than previously indicated. Knowledge on changes of ecological functioning through cascading effects is limited and requires distinct hypothesis-driven research combined with integrative ecological modelling.

Keywords: benthos, environmental impact, knowledge gaps, marine ecology, offshore wind farms, renewable energy.

Introduction

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

Marine renewable energy devices (MREDs) include wind turbines, wave, tidal stream, and ocean thermal energy converters, which derive energy from salinity gradients (Magagna *et al.*, 2016). Hitherto, wind turbines, arranged in offshore wind farms, generate the bulk of the marine renewable energy. The introduction of MREDs induces changes to the marine environment (Lindeboom *et al.*, 2011; Gill *et al.*, 2018). MREDs generally consist of (artificial) hard substrates typically introduced in an exclusively soft-bottom environment. Furthermore, they can span the entire depth of the water column thereby introducing intertidal environments where they often have not been present before.

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

Changes to the benthos associated with MREDs can be direct or indirect, occurring during the construction phase, the operational phase, or the decommissioning phase, and are generally related to the pressure groups (i) mechanical sea-floor disturbance, (ii) the artificial reef effect, (iii) the input of additional energy (sound, other energy), and (iv) fishery cessation and displacement (Bergström *et al.*, 2014). Construction effects, such as mechanical disturbance can lead to changes in the physical environment (Van den Eynde *et al.*, 2013) and the associated macrobenthos (Coates *et al.*, 2015) while noise (energy emitted) from piling activities results in the relocation of fish species and marine mammals distribution, such as harbour porpoises (Neo *et al.*, 2014; Brandt *et al.*, 2018). Once installed, the artificial reef effect is observed through the rapid and extensive colonization of offshore energy devices with sessile fauna, *inter alia* non-native species (Krone, Gutow, Joschko, *et al.*, 2013; De Mesel *et al.*, 2015; Nall *et al.*, 2017), the attraction of pelagic and demersal fish (Wilhelmsson *et al.*, 2006; Reubens, Degraer, et al., 2014) to the devices and increased densities of large decapods at the scour protection (Krone, Gutow, Brey, et al., 2013; Reubens, Degraer, et al., 2014; Krone *et al.*, 2017; van Hal *et al.*, 2017). Furthermore, the presence of a structure stretching through the entire water column results in hydrographic changes such as the decrease or even disappearance of stratification due to local turbulences (Floeter *et al.*, 2017), possibly resulting in upward transport of nutrients and, concurrently affecting local primary production and carbon flow to the benthos. The emission of electromagnetic fields (EMFs) from sub-sea power cables may cause attraction of commercially important Crustacea (e.g. *Cancer pagurus*; Scott *et al.*, 2018), there is also the possibility that EMFs may trigger developmental, physiological, and/or behavioural responses in sensitive fish and invertebrate species (Hutchison *et al.*, 2018).

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

Knowledge on the effect of the introduction of MREDs on the benthic ecosystem is derived from scattered monitoring programmes, executed at arbitrary spatial scales, mainly focusing on very descriptive structural aspects of soft sediment and fouling communities (density, diversity, percentage cover; Wilding *et al.*, 2017). These monitoring programmes have the general purpose to investigate whether aspects of the local environment have changed but do not contribute to our understanding of cause–effect relationships behind such changes (Lindeboom *et al.*, 2015). However, the understanding of these cause–effect relationships is urgently needed. Identification of cause–effect relationships will inform the design and execution of more strategic and cost-effective monitoring programmes (Lindeboom *et al.*, 2015), the evidence-based development of environment-friendly MREDs, and performing hypothesis-driven experiments that provide valuable data to support the understanding how the introduction of MREDs interact with marine ecosystem functioning, and thus provisioning of marine ecosystem services to society (Wilding *et al.*, 2017; Causon and Gill, 2018). Such information is urgently needed, as improved understanding of the economic and societal impacts of the sector is necessary to support energy policy developments and planning decisions and potential effective mitigation actions (Hooper *et al.*, 2017). This becomes even more important as there is an increasing demand to co-locate MREDs with emerging sustainable seafood (seaweed, fish, and shellfish farms) production facilities (Holm *et al.*, 2017) and the need to increase marine protected areas in the Natura 2000 network.

This paper defines a set of scientifically argued hypothesized cause–effect relationships (hypothesized paths) describing interactions between MREDs and the benthos. Whilst we acknowledge that the marine ecosystem has several ecological components and receptors (Willsteed *et al.*, 2017), the main aim is to characterize with a conceptual approach the hypothesized paths over benthos as one important ecological component of the marine system. We provide a conceptual approach to score these paths which reveals knowledge gaps and serves as a robust base to prioritize the most urgent research areas regarding the impact of MREDs on the benthic ecology.

We reviewed 233 publications to group the hypothesized paths and set up conceptual path diagrams, linking the introduction of MREDs to societally relevant issues. This conceptualized knowledge base provides the backbone of highlighting knowledge gaps and with the identification of benthic priority research. As such, this paper provides a comprehensive basis for furthering hypothesis-driven research that will contribute to evidence-based planning and policy decisions with regards to the future of MREDs.

Outline

We reviewed 233 published studies to group several hypothesized paths into conceptual path diagrams, linking the introduction of MREDs with the societal important issues. We took a stepwise approach (a) to build a conceptualized knowledge base which enabled us (b) to prioritize the current scientific knowledge gaps associated with the benthos and identify research needs.

Conceptualized knowledge base

While descriptive literature on the observed impacts of offshore renewables is plentiful, there is limited knowledge that contributes to a systematic understanding of these impacts (Wilding *et al.*, 2017). As a first step, a group of experts exhaustively listed paths unravelling the cause–effect pathways between the development of MREDs and their impacts on benthic biodiversity (during the ICES workshop on the Effects of Offshore Wind Farms on Marine Benthos; WKEOMB; ICES, 2012). These effect pathways departed from the different human activities typically associated with the construction and presence of the MREDs and considered the whole abiotic and biotic cause–effect pathways to the essential benthic ecological processes at the basis of ecosystem services. To date, most information exists for the construction and operational phases, while knowledge is poor on the effect pathways during decommissioning. The latter is hence not explicitly considered in this paper. The few available studies however indicate that the effects of decommissioning are likely to be comparable to the construction of MREDs (Bergström *et al.*, 2014).

To simplify the overview of the conceptual path diagrams created by the hypothesized paths, we reorganized the causes and the (end) effects into two categories (abiotic, biotic) and these effects were grouped into what we termed the societally relevant issues, which are the essential benthic ecological processes that support the marine ecosystem services. This helped structure the multitude of paths into a synoptic overview by allocating the paths to these societally relevant issues and demonstrated the importance of the benthic processes in these regards. This sequence also takes account of the stepwise, conceptual framework considering environmental effects of marine renewable energy as proposed by Boehlert and Gill (2010).

We classified the "causes" of the hypothesized paths into pressure groups after Bergström *et al.* (2014): (1) mechanical seafloor disturbance, (2) artificial reef effect, (3) addition of energy (sound, other energy), and (4) fishery cessation and displacement. Fishery cessation and displacement were excluded from our analysis because evidence on benthic impacts resulting from altered trawling intensity is sufficiently documented elsewhere (Jennings and Kaiser, 1998; Kaiser *et al.*, 2006; De Juan *et al.*, 2007; Dannheim *et al.*, 2014; Bergman *et al.*, 2015). Here, we focus on effects that are not exhaustively reviewed so far, i.e. the introduction of hard substrata and changes to the benthos related to the installation and operation of MREDs. After having identified and structured the paths, the ICES Working Group on Marine Benthal and Renewable Energy Developments (WGMBRED; http://www.ices.dk/community/groups/Pages/WGMBRED.aspx) screened the scientific literature to validate and elaborate each of the paths and as such, assessed the available knowledge with regards to the hypothesized paths (see Supplementary Annexes S1).

Science-based priority of benthic research needs

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

We expanded the scoring concept developed by Bergström *et al.* (2014) by adding consistency, reflecting the differential response of different benthic systems relative to the same path. Context-specific responses are an important aspect of environmental impact assessments and consistency therefore provides

Table 1. Criteria for assessing the probability of impact on marine life from pressures associated with offshore renewable energy devices.

Criteria	Score			
Following (Bergström *et al.*, 2014)				
	1 (low)	**2 (moderate)**	**3 (high)**	
Spatial scale	<100 m	<1 000 m	>1 000 m	
Temporal scale	<2 years (mainly construction effect)	<30 years (operation effect)	>30 years, 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 the specific cause–effect relationship.	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 done to investigate the specific cause–effect relationship.

Each hypothesized cause-effect relationship (see supplementary material in ANNEX S2) was scored separately (1–3) for the effect size in space, time and magnitude (sensitivity), as well as consistency of the effect following (Bergström *et al.*, 2014). Confidence was scored (1–4) following the evidence ranking of Marlin.

valuable information to best interpret the local applicability and variability of the paths. Consistency of the paths was evaluated for different habitats (soft–hard substrate) and different biological components (demersal fish, invertebrates, and phytobenthos including benthic algae and microphytobenthos). Consistency was scored as low (1) if the expected effects on the benthos were applicable only to specific biotopes or ecosystem components, moderate (2) if they were applicable to numerous biotopes or ecosystem components, and high (3) if they are applicable to all biotopes or ecosystem components (Table 1). Confidence was based on the evidence ranking of the Marine Life Information Network (MarLIN) (www.marlin.ac.uk/glossarydefinition/evi dence ranking—access date: 2 October 2018, scores between 1 and 4, see Table 1): very low confidence (1) indicates that the scoring is based only on “informed expert judgement” as there is very little or no information available on the effects. Low scoring (2) means that information was derived from sources that only cover comparable general studies or from a general understanding of hypothesized path. Moderate confidence (3) means that knowledge was derived from sources that consider comparable effects of the particular path (e.g. artificial reef studies). High scoring (4) indicates that the information was derived from studies that specifically deal with the path in an MRED context (experimental or field studies).

As a final step, we used a ranking of hypothesized path by (a) highest total score, i.e. largest spatial, temporal scale, and the highest extent of change (sensitivity) and (b) lowest confidence, i.e. very little or no information is present. Consistency was not considered for the ranking, as focusing only on drivers that consistently have an important effect runs the risk of underestimating less-consistent, yet not necessarily less meaningful impacts and risks for the benthos (see Supplementary Annex S2). The ranking or ecological prioritization of hypothesized paths allowed the identification and prioritization of knowledge gaps to define urgent research needs for benthic ecosystems. The outcomes are summarized in the “Identification and science-based prioritization of knowledge gaps by assessing potential effect magnitude of marine renewable energy developments on benthos” section.

Conceptual path diagrams of hypothesized benthic changes by renewable energy devices

Hypothesized cause–effect relationships (paths) and causal pathways

Overall, 33 (hypothesized) cause–effect relationships (path) were identified (Figure 1a–c; Supplementary Annex S1: bold titles). They link human activities attributed to offshore renewable development to abiotic and biotic factors and interlink with each other by effect pathways (Table 2). The causal pathways span the gradient from unidirectional effects of the activities on the benthos, for example *path 24* (Figure 1a), to highly complicated combinations of direct and indirect effects (incl. feed-back loops) on the benthos (Table 2), causing infinite proliferation of the pathway lengths. The colonization by non-indigenous species through shipping, ballast water, and translocated equipment for instance, exemplifies a unidirectional relationship between the activity of shipping in relation to the construction and operation of offshore renewables and the biodiversity (Figure 1a, *path 3*). A more complicated pathway, which also included indirect links and feed-back loops, results from the addition of artificial hard structures changing the benthic habitats (Figure 1c, *path 9*). The initial effect will allow a specific hard bottom assemblage to colonize the area

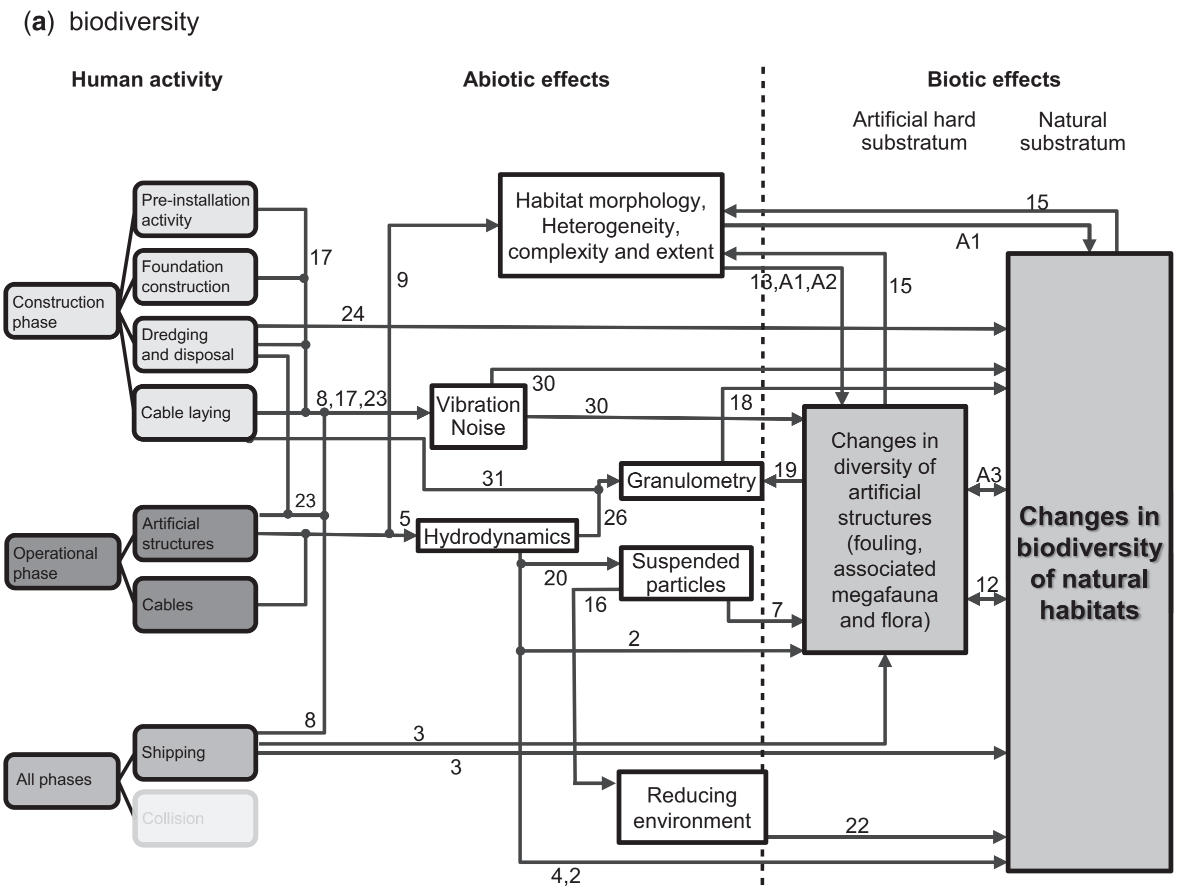

Figure 1. Conceptual path diagrams of the abiotic and biotic processes linked to (a) biodiversity importance, (b) biogeochemical importance, and (c) food resources-importance of the benthos, altered by human activities and the resulting activity pressures during the construction and operational phase of offshore renewable energy devices. Hypothesized cause–effect relationships (paths) are numbered (see Supplementary Annexes S1 and S2). Dashed line divides abiotic (left) from biotic (right) effects. Note: Cause–effect relationships linked to cessation and displacement of fisheries are not considered here. ©ICES WGMBRED.

(Figure 1c, *path 13*), which is then further enhanced by the increased structural complexity caused by the fouling organisms such as mussels (Figure 1c, *path 15*). This increased biodiversity (and productivity) finally provides foraging opportunities to organisms from higher trophic levels (Figure 1c, *path 11*), which may positively contribute to the population dynamics of commercially valuable species such as Atlantic cod *Gadus morhua* (Figure 1c, *path C1*).

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

Cause–effect allocation to societally relevant issues

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

Aside from its focus on society, the organization of available knowledge of conceptual path diagrams based on the societally relevant issues allowed clarity in the enormous amount of information available. The conceptual path diagrams summarize available evidence on how the ways of hypothesized paths may ultimately feed into changes of societally relevant issues.

In general, the increased habitat complexity caused by physical structures influences biodiversity of biota (Figure 1a, *path A1*). Furthermore, the colonization by non-indigenous species of the different structures and the potential stepping-stone effect via structure arrays being connected might change the survival and

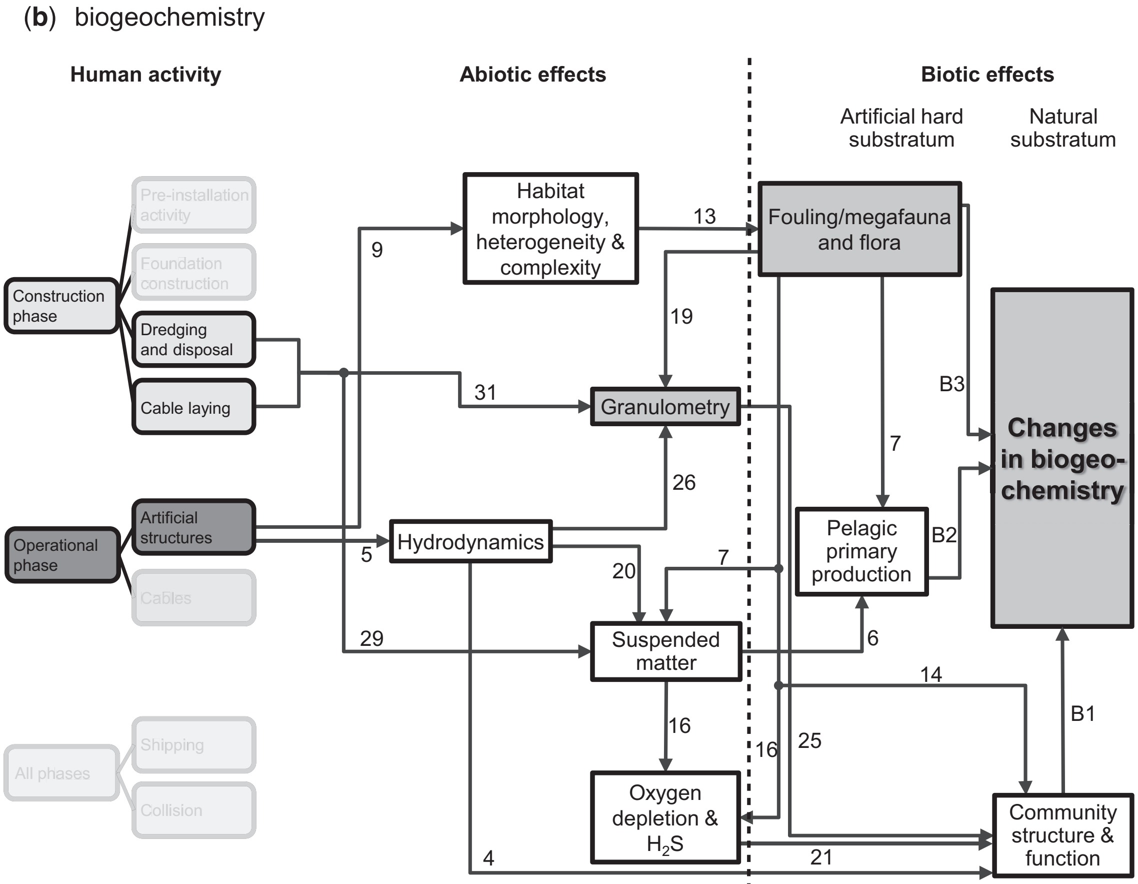

Figure 1. Continued.

spatial distribution of the indigenous and non-indigenous species (Figure 1a, *path A2*). This in turn might produce new source population/species pools with potential spill-over effects from the artificial hard substrates to the soft bottoms which ultimately change biodiversity (Figure 1a, *path A3*). As for biogeochemistry, important benthic functions such as bioturbation and decomposition may be affected if there is an altered benthic assemblage structure (Figure 1b, *path B1*). The result could be modified rates of primary production, which may affect biogeochemical turnover rates of benthic species (Figure 1b, *path B2*) and the addition of "new players" (i.e. colonizing community on artificial hard substrates) and their specific metabolic activities (Figure 1b, *path B3*) substantially affecting biogeochemical processes crucial to the functioning of the local marine ecosystem. Food resources might be affected by an altered structure and distribution of local benthic populations in the natural and new artificial habitat as these can directly affect the performance and survival of organisms of valuable populations through trophic and competitive interactions (Figure 1c, *path C1*).

Hypothesized cause–effect relationships: knowledge base

Of the 233 scientific publications 36% were directly and 64% indirectly relevant to the hypothesized paths identified and reviewed (see Supplementary Annex S1: plain paragraphs). These publications, and all citations of this publication, are summarized in a publically available library at www.mendeley.com/community/benthic-effects-of-offshore-renewables—access date: 15 January 2019). Directly relevant papers dealt with studies that explicitly addressed the path in an offshore renewable energy context. Indirect relevant papers that addressed research of closely allied subjects as a proxy for the offshore renewables' effects, e.g. studies from dedicated artificial reefs, were also included. This literature base demonstrated the diversity of scientific knowledge available, and also the fragmented nature of that knowledge: all papers only covered one (or few) selected issues, e.g. attraction of fish (Reubens *et al.*, 2011, 2013), colonization by non-indigenous species (De Mesel *et al.*, 2015), mussel productivity (Krone, Gutow, Joschko, *et al.*, 2013), and therefore only dealt with a small number of aspects of the cause–effect pathways from activities to the societally relevant issues.

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

By detailing the level of understanding of pathways, the knowledge base promoted the importance of ecological processes with respect to the direction and multitude of the effects of MREDs onto the benthos and societally relevant issues. Moreover, it also highlighted the knowledge gaps with regards to ecological processes deemed important in assessing the impacts of MREDs. Such knowledge gap analysis shows where additional

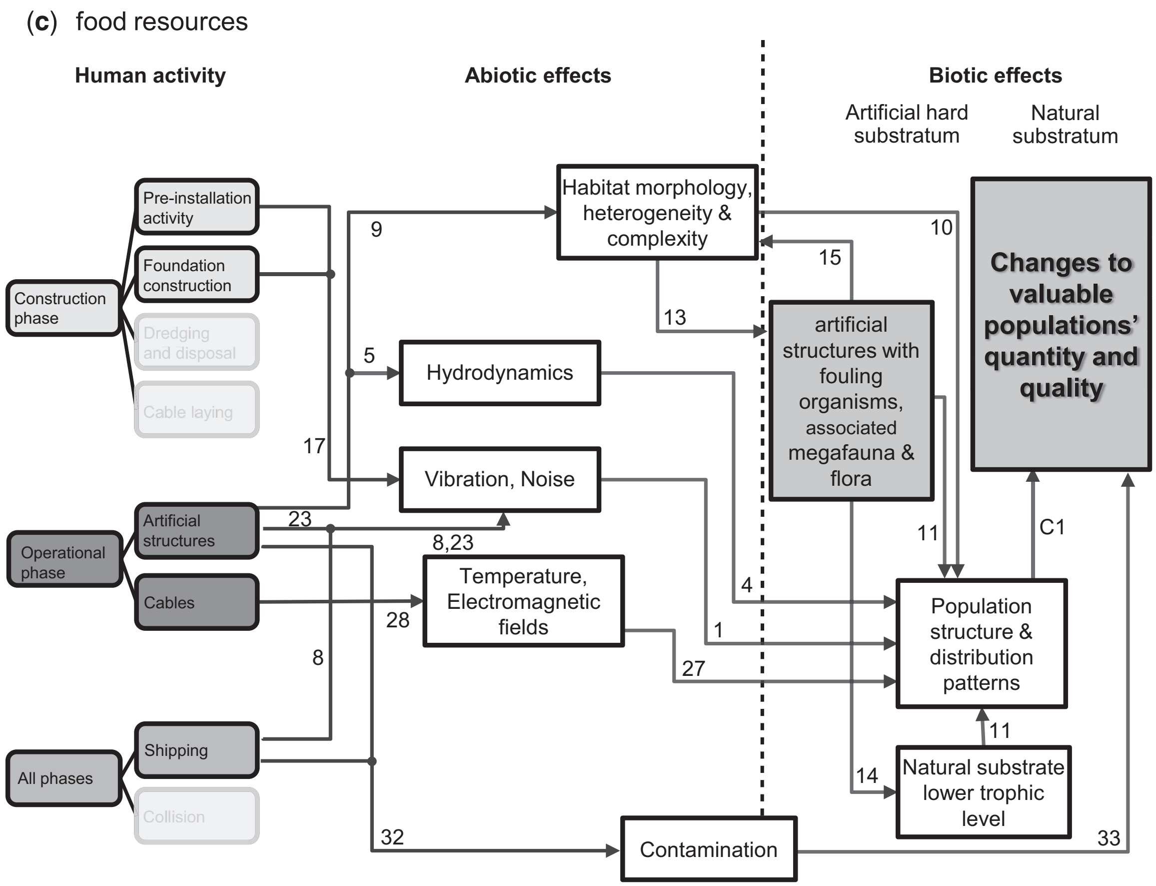

Figure 1. Continued.

Table 2. (a) Number of hypothesized cause–effect relationships (paths), (b) number of paths classified according to their path character, i.e. if a path links an activity to an abiotic factor, biotic factor, an abiotic factor to an abiotic or biotic component, or a biotic component to another biotic component, (c) number of loops formed by paths, and (d) pathway length formed by several paths.

Parameter	All paths	Paths related to biodiversity	Paths related to biogeochemistry	Paths related to food resources
(a) Number of paths	31	21	15	14
Thereof unique paths	16	7	4	5
(b) Character of path				
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 path loops	5	4	–	1
(d) Pathway length				
Mean	inf.	inf.	4.3	4 (inf.)
Minimum	1	1	3	3
Maximum	inf.	inf.	6	7 (inf.)

Numbers are given for all schematics (see Figure 1), as well as the specific societally relevant issues (see Figure 1a–c). inf., infinite number of path combinations.

understanding is needed through dedicated research. Rather than setting up a monitoring programme for observing changes, the result from such research allows a science-based design and management, as well as support of cost-effective practices of future MREDs.

Combining the pathways and the knowledge base, an in-depth view on the direct and indirect scientific knowledge at the basis of the processes behind the effects of MREDs onto marine benthos has been achieved. This can be considered a first step towards knowledge gap identification with regards to the understanding

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, *path 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, 2013; Bergström *et al.*, 2013), at a time when the colonization 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 colonization of potential prey species has been very rapid, so the predators could also be aggregating there in food search (Reubens *et al.*, 2011, 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 (J. T. Reubens, pers. obs.).

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 H_2S (Figure 1b, *path 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-Bouraee, 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).

of MRED effects. An example for evidence-based cause–effect pathway (Figure 1c, pathway of *paths 9–13–15–13–11–C1*) is presented in Text Box 3.

Identification and science-based prioritization of knowledge gaps by assessing potential effect magnitude of marine renewable energy developments on benthos

We formulated a total of 31 paths of which eleven were linked to abiotic effects exclusively and 20 to both abiotic and biotic effects (see Figure 1). Because our objective was to prioritize research needs regarding the impact of MREDs on the benthic ecology, we scored all paths but analysed only the latter 20 paths from a benthic perspective. These comprised 13 paths related to artificial reef effects, four paths related to mechanical sea-floor disturbance, and three paths related to the introduction of energy effects (see Supplementary Annex S2). In the first section here, we consider the scales of effects in space and time, and their magnitude (sensitivity), as well as the knowledge available. As such, it forms the scientific basis to structure and scientifically prioritize the paths for our main objective, i.e. the identification of knowledge gaps and benthic research priorities, which is subject of the second part of this section.

Scoring the scale and magnitude of the effects

In general, paths linked to the artificial reef effect had the highest scores on temporal and spatial scale, as well as the highest magnitude of the effect (sensitivity) (Figure 2a). Therefore, the artificial reef effect in general scored higher (6.7 ± 0.7 standard deviation, *SD*) in total, i.e. sum of temporal and spatial scales and sensitivity, than mechanical sea-floor disturbance (6.3 ± 1.0) and the introduction of energy effects (6.2 ± 2.5). Bergström *et al.* (2014) scored comparable effect sizes for fish and benthos during

Text Box 3. An example from evidence-based cause–effect pathway of offshore wind farms

Worked example of pathway *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, *path 9*). They introduce atypical, and initially unutilized, 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).

After construction, a specific hard bottom assemblage (fouling and mobile megafauna) consisting of primary and secondary consumers will colonize the new artificial habitat (Wilhelmsson and Malm, 2008; Kerckhof *et al*., 2010; Lindeboom *et al*., 2011; Langhamer, 2012; Krone, Gutow, Joschko, *et al*., 2013) (Figure 1c, *path 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, Gutow, Joschko, *et al*., 2013; 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, Gutow, Brey, et al., 2013). From offshore oil and gas platforms it is known that the community changes over time, where initial colonizers (e.g. tubeworms and hydroids) are replaced by secondary colonizers 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, *path 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, Gutow, Joschko, *et al*., 2013). 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, 2008; Wilhelmsson and Malm, 2008).

Furthermore, 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, *path 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, 2013; De Troch *et al*., 2013; Reubens, De Rijcke, et al., 2014; 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).

Improved survival and feeding conditions may positively contribute to the population dynamics of the species concerned, some of which may be commercially important (Figure 1c, *path C1*).

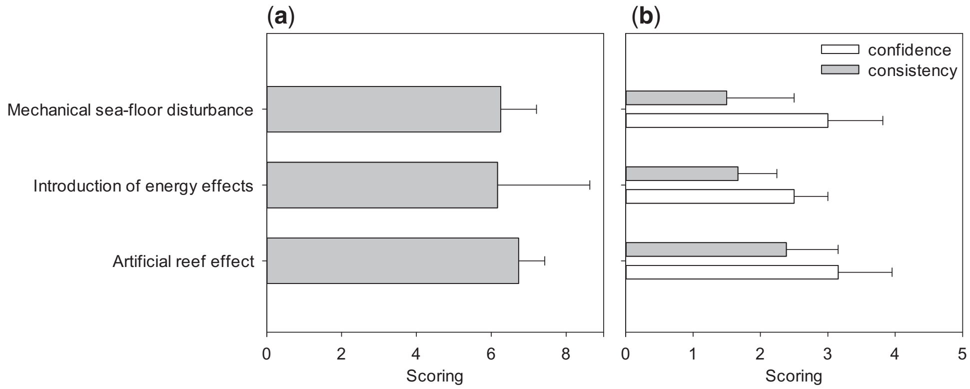

Figure 2. (a) Mean total scoring of hypothesized paths (± *SD*), i.e. the sum of the magnitude of the effect in time, space, and quantity, and (b) mean confidence and consistency (± *SD*) between different effect-groups (overarching topics).

construction and operation phase: moderate effects for the introduction of energy effects (4–6; acoustic disturbance/pile driving), for mechanical sea floor disturbances during the construction phase (4; sediment dispersal), and artificial reef effects (5–6; habitat gain).

Furthermore, scoring of the consistency was also highest for artificial reef effects (2.4 ± 0.8, see Figure 2b) compared to the other pressure groups (mechanical sea-floor disturbance: 1.5 ± 1.0; introduction of energy effects: 1.7 ± 0.6). For both latter issues, the knowledge base for the effect assessment is not generally applicable, but rather refers to selected biotopes, ecosystem components, and effect sizes. Lowest confidence scoring of 2.5 ± 0.5 was found for the introduction of energy effects, implying that information on the effects was mainly derived from sources that only cover related studies or from a general expert judgement on the hypothesized paths. Similarly, also Bergström *et al.* (2014) scored low confidence for benthic paths regarding acoustic disturbance and high confidence for sediment dispersal effects. Both assessments hence conclude that research regarding the introduction of energy effects (in all forms) are largely lacking.

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

The main finding of our scoring was that 17 paths constitute effects on abiotic and biotic processes with knock-on effects onto the benthic system (see sensitivity scoring, Figure 3a). Only one path was scored as having minor or no effects on abiotic and biotic processes, while two will have an effect on such processes but lack any further cascading of the effects. Consistency scoring varied randomly implying that some paths are applicable to specific (6 paths), numerous (6 paths), or all (8 paths) biotopes/ecosystem components (Figure 3b). Most of the paths (12 paths) were scored high regarding the confidence (Figure 3b). Therefore, this information has been derived from sources that consider comparable effects of this particular path in studies derived from artificial reef studies. For five paths there is specific information from MREDs by experimental or field studies (scoring = 4, Figure 3b) and only for three paths there was no or little information available.

Knowledge gaps: science-based prioritization of hypothesized cause–effect relationships

We ranked the hypothesized paths according to (a) the highest total score and (b) the lowest confidence (Figure 4, see Supplementary Annex S2). The science-based prioritization of the paths by the largest spatio-temporal scale and magnitude of the effect and only little or no scientific knowledge available (confidence) enabled us to identify knowledge gaps and to give recommendation on for which hypothesized paths specific research is needed.

For the artificial reef effects (the physical presence of the foundations), three paths (and one abiotic path) were identified as potentially important, achieving total scores between maximum 7.5 and 9 (*path 4*, *2*, and *3*; Figure 4, see Supplementary Annex S2). These effects cover changing hydrodynamic conditions, increased food availability to filter-feeders and the colonization by non-indigenous species through new shipping activities related to MREDs. These three paths related to artificial reef effects have a spatial scale reaching beyond 1000 m. The expected effects last at least as long as the device/array is present and the artificial reef effect paths lead to cascading processes starting once the artificial structure is installed. Limited scientific documentation describing the effects of modified hydrodynamics on the settlement and occurrence of benthic species in the surrounding natural substrates is available (Coates *et al.*, 2014; Floeter *et al.*, 2017). Simultaneously, these effects are applicable to all biotopes. Thus, especially the modification of currents and hydrodynamic conditions is identified as a field of research that should be investigated in more depth. Moreover, the long-term reef effects on the

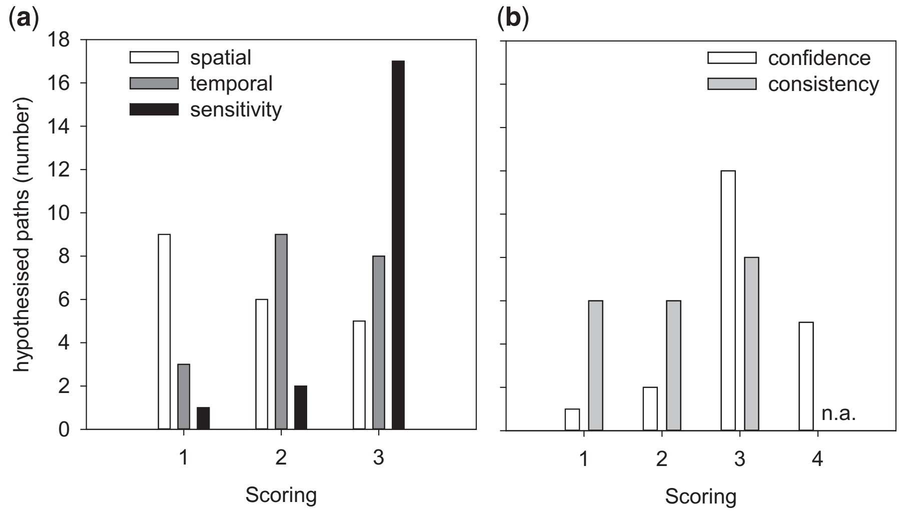

Figure 3. Number of hypothesized paths which were scored (1–4) for (a) the spatial and temporal scale of the effect and sensitivity analysis, i.e. the magnitude of the effect and (b) the confidence and consistency.

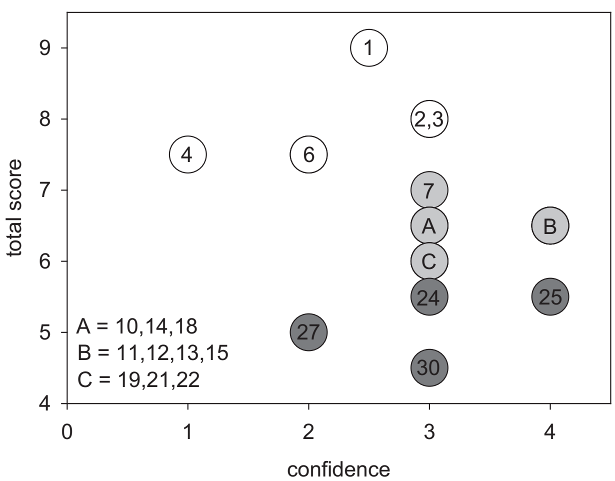

Figure 4. Scoring of hypothesized paths according to total score (combined score from temporal, spatial scale, and magnitude of effect) and confidence. Paths are colour coded according to the ranking/science-based prioritization of research of high (white), moderate (light grey), and low (dark grey) total scores; numbers correspond to path identification numbers (see Figure 1, see Supplementary Annex S2).

ecosystem and its functioning are not yet fully understood and remain important to be further investigated.

For the hypothesized paths related to mechanical sea floor disturbance (see Supplementary Annex S2), the reduction of the phytoplankton primary production generated by an increase in turbidity was scored high (*path 6*, see Figure 4). In fact, this effect could have a high spatial scale (beyond 1000 m) and a moderate temporal scale (up to 30 years). Sensitivity was scored low as this path seems to be responsible for minor or no effects on further abiotic and biotic processes, i.e. it lacks further cascading of the effects. It is expected that this reduction of the phytoplankton's primary production could be observed in specific ecosystems or some components as it received a low score for the consistency. However, as there is little information on this effect, further studies are required.

For the hypothesized paths related to the introduction of energy one path (*path 1*; and one abiotic path) was scored high based on our criteria (see Figure 4 and Supplementary Annex S2). With a total maximum score of nine, shipping noise and vibration and noise scored 8 and 9, respectively. The effects of noise and vibration from construction/operation have been shown to extend beyond local scales and can be observed many kilometres from the source. In addition, exposure to noise and vibration and noise from operation is likely to be long lasting given the expected lifespan of installations. Therefore, the paths received high scores for spatial scale and temporal scale of the effects. Sensitivity, i.e. the magnitude of the effect, scored high for this hypothesized path as cascading effects are likely to result from it.

It is considered that noise and vibration effects as an abiotic factor (*path 8*; see Supplementary Annex S2) could be experienced across all biotopes and could impact other ecosystem components. As such, this path received a high score for consistency. In general, vibration and noise effects could be experienced across numerous biotopes and ecosystem components. However, it is not likely to affect all biotopes and as such the biotic path (*path 1*; see Figure 4 and Supplementary Annex S2) received a moderate score for consistency. Confidence was moderate for shipping noise effects (*path 8*) and moderate to high for vibration and noise effects on the biological system (*path 1*). Therefore, the information available has indicated that further studies are required to better understand their influence on benthic ecosystems.

Benthic research priorities and recommendations

The combination of a conceptual path diagram to structure and disentangle the hypothesized cause–effect relationships (paths) and the approach to apply scores to the paths with regards to their spatio-temporal scale, magnitude, consistency, and confidence demonstrated to be a scientifically sound tool to highlight priority areas for future research relating to the benthos. These issues are considered as "*known unknowns*", and to support informed decisions on environment-friendly MREDs. However, our approach also identified potential effects which will have to be considered to improve our current state of knowledge, i.e. the high sensitivity pointing towards unforeseen cascading effects in the benthic system. These knowledge gaps are defined as "*unknown unknowns*". Both knowledge gaps, either known or unknown, call for a scientific discussion, helping to target and improve future monitoring and benthic research and to improve our current, potentially incomplete, understanding of the footprint of offshore renewables. This information is of importance as the development of offshore renewables is planned to be expanded (WindEurope, 2018).

"The known unknowns"

We identified five priority research areas associated with the benthos. These relate to: (i) artificial reef effects, (ii) the introduction of sound and energy, and (iii) mechanical sea-floor disturbance. Following the methodology applied in this study, future research could therefore target the following research on hypothesized paths:

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

All these cause–effect relationships have the potential to change the benthic system over large spatial scales and for a long term. An increase in phytoplankton's primary production by increased vertical mixing due to MREDs (reduced stratification during summer), and subsequent nutrient transport throughout the water column, was recently demonstrated by Floeter *et al.* (2017). Concurrently, local hydrographic turbulences by MREDs increase particulate matter that increases the attenuation of light (Devlin *et al.*, 2008; Baeye and Fettweis, 2015) affecting primary production of phytoplankton. Slavik *et al.* (2018) demonstrated that an increase in MREDs and the attached periphyton by mainly filter feeders in the North Sea, might lead to lower phytoplankton production. Water filtering by these species might lead to changes in clearance rates of the water (Newell, 2004; Gallardi, 2014), i.e. reducing phytoplankton bloom and larvae affecting larval settlement success. Furthermore, these changes may have measurable effects on the composition of the benthic assemblages close to MREDs (Coates *et al.*, 2014). However, all the interactions between water stratification and turbidity within the nutrient and light-limitation context, as well as the effect of filter-feeders on phytoplankton and larval settlement success have yet not been investigated effectively. These interactions may lead to changes in the zooplankton as well as in the benthos, affecting higher trophic levels in food webs and thus food provisioning of commercially important species.

MREDs may offer new pathways of invasion or range expansion by using the artificial hard substrate as stepping stones (Miller *et al.*, 2013). Species that are restricted in their distribution range to genuine clear water rock (stacks) and rocky coasts, such as in the English Channel (e.g. Brittany) and northern North Sea (e.g. Norwegian and Scottish coastlines), or rare stones in mostly soft bottom habitats, such as in the southern Baltic Sea, might use MREDs as stepping stones for their spread. First evidence of invasion and range expansion by MREDs is proven (De Mesel *et al.*, 2015; Coolen *et al.*, 2016, 2018) but suggest that range expansion in the subtidal will be marginal due to the species already known to inhabit existing habitats. However, the expansion of intertidal (invasive) species will be more pronounced as this represents a new habitat offshore (Kerckhof *et al.*, 2016) and future modelling and field studies are needed to identify the risk of invasions by MREDs.

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

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

"The unknown unknowns"

This study highlighted that the sensitivity of the benthos to the effects of MREDs was significantly higher than shown in previous studies (Bergström *et al.*, 2014). Available knowledge on the effects of artificial hard substrates on benthos has increased continuously during the last decades. Studies on oil and gas rigs, platforms, or other devices (incl. artificial reefs) (Wolfson *et al.*, 1979; Bohnsack, 1989) and more recently also on MREDs (Degraer *et al.*, 2016; Coolen *et al.*, 2018) have provided further insights into the ecological changes to the benthos by such structures and thus delivered basic knowledge on the potential changes. However, we still miss a full understanding of the ecological processes that might change the ecological functioning, as studying biodiversity related to ecological functioning is still in its infancy. For example, cascading effects on the benthic system by the presence of artificial hard substrates are more than likely (see e.g. feedback loops and hypothesized paths linking biotic to biotic compartments, Figure 1 and Table 2), but might not be foreseen due to our current lack of knowledge. Understanding the ecological processes has therefore been identified as the "*unknown unknowns*". Many studies targeted benthic recovery after trawling cessation and recently also in offshore wind farm context. However, even after several years, such studies were unable to demonstrate a significant benthic recovery (Duineveld *et al.*, 2007; Bergman *et al.*, 2015). This aspect raises general important considerations in terms of the scale over which impact studies are operating are missing important ecological processes for e.g. benthic recovery. To identify the "*unknown unknowns*", examination of causal pathway models (such as Figure 1) help to identify current knowledge gaps, as they form the scientific base to differentiate hypothesized paths on how a mechanism should theoretically act. Hypothesized paths can be tested through the validation of quantitative mechanistic models with field data. Results can point to gaps in knowledge and factors not yet considered effectively (such as the energy emissions of EMFs or heat from MRED cables), leading to hypothesis-driven and basic research (i.e. environmentally and biologically focused).

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

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

Effects of noise or sediment changes such as coarsening of the sediment might affect biogeochemical processes such as long-term carbon storage (Pratt *et al.*, 2014; Solan *et al.*, 2016). For example, the common heart urchin *Echinocardium cordatum* has been shown to be the most important bioturbator in the German part of the North Sea (Wrede *et al.*, 2017) and this species prefers organically enriched fine sediments (Wieking and Kröncke, 2003; Kröncke *et al.*, 2004). Sediment coarsening thus might lead in turn to a lower bioturbation activity of the species.

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

Recommendations for future research

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

- Including more hypothesis-driven questions, e.g. by targeted field studies or experiments, to support the current monitoring programmes to further our understanding of ecological patterns and processes on local scales;
- Defining relevant ecological scales and in particular looking at large-scale effects, supported by the hypothesis-driven research at smaller scales (i.e. local effects) complemented by modelling approaches to upscale potential ecological changes (Wilding *et al.*, 2017);
- Combining benthic research into ecosystem-based management approaches to ensure long-term sustainability of benthic systems and safeguard key processes of societal and ecological relevance (i.e. food webs, biogeochemical changes, biodiversity) under future marine development;
- Detailed knowledge of the natural variability of the benthic system in space and time is a prerequisite to distinguish potential changes induced by MREDs from the natural variability, to better understand the structure and dynamics of benthic ecosystems. Cooperation between studies groups and locations could enhance our ability to determine the factors affecting variability;
- Modelling approaches might also help to assess the likelihood of effects. Such detailed knowledge is the base to developing ecologically meaningful management approaches and, to understanding and potentially predicting ecological cascading effects which might lead to as yet unknown changes.

The linkages between environmental patterns, MREDs, other anthropogenic effects and ecological processes will be the major challenge in future marine research (Duffy *et al.*, 2007; Wilding *et al.*, 2017; Willsteed *et al.*, 2017). This type of work is essential to undertake ecosystem-based approaches for the sustainable use of offshore renewable energy, and to move beyond the case-by-case approach, i.e. the focusing on the most recent population changes by offshore renewables, rather than on understanding the intrinsic mechanisms (Jackson *et al.*, 2001; Elliott, 2002; Causon and Gill, 2018). Understanding ecological processes and patterns to maintain ecological and societal relevant services supported by the benthos calls for a holistic management, as *n*-order effects do not only affect the benthos but potentially change other ecosystem functions and ecological receptors. We hence submit a plea to integrate benthic research in an MRED impact assessment context into scientific approaches at the ecosystem level, studied across ecosystems and ecosystem components (Atkins *et al.*, 2011; Wilding *et al.*, 2017; Willsteed *et al.*, 2017).

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

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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