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Summary

The Dutch government has the ambition to realise 3,5 GW in offshore wind farms before 2023. Longer term outlooks estimate 35 to 75 GW for 2050. This would result in the construction of 5,000 wind turbines in the Dutch North Sea. The introduction of artificial hard substrates by placing wind turbine foundations and scour protection facilitates epibenthic species and associated benthic fish. The addition of rocks could be considered as adding H1170 habitat (‘Reefs of open sea’) and as such has a positive impact on hard substrate associated benthic macrofauna and fish. The significance of this effect, however, is unclear on a scale outside the scour protection. This report describes the result of a quick-scan in which the significance of this positive effect is quantified. Negative impacts and effects of the turbine foundation and other man-made structures were not included in the quick-scan.

The aim of this quick-scan was to answer the following questions:

1. What is the biomass of benthic macrofauna on scour protection found in monitoring programmes to date?
2. Which benthic species, including macrofauna and hard substrate associated fish, have been found to date on and associated with scour protection?
3. When 5,000 wind turbines are installed in the Dutch Sea, each with 2,000 m^2 scour protection, would this significantly change the benthic communities?
    a. If not, what surface area would be needed to attain a significant change?
4. To what extent are benthic species’ populations on offshore wind turbine foundations interconnected?
5. What knowledge gaps prevent answering questions 1-4 with acceptable scientific certainty?

The questions were addressed by desk study combining data from scour protections and soft sediment seabed monitoring (MWTL). Biomass was extrapolated to the 2050 scenario by multiplying single turbine data to 5,000 turbines.

Values of biomass on scour protections were compared with the benthic community of a sandy seabed, with the following results:

- Total epibenthic species richness on scour protections may double when introducing scour protection at locations other than the current locations;
- Epibenthic biomass in the area covered by scour protection directly around a turbine (2,000 m^2) rises 24 times. On a wind farm scale (72 km^2), this increase is 4.9%.
- 5,000 offshore wind turbines, with a total of 10 km^2 scour protection, will increase total benthic biomass in the Dutch North Sea (57,000 km^2) with 3,400 tonnes (0.43%).
- To attain an increase of 5% on this scale, a total of 106 km^2 of scour protection should be added.
- The Dutch edible crab population may increase with 50 million individuals, an increase of 880% of the population on the sandy seabed.
- Fish may increase with hundreds of thousands of Atlantic cod, and many millions of smaller reef-species such as rock gunnel and goldsinny wrasse.
- Connectivity between populations of benthic species rises after the construction of wind farms but quantification is challenging due to differences in reported larval durations and lack of reported travel distances.

In general, data availability for scour protection species was low. Biomass data was available from only 5 locations and only a single fish dataset was formatted in a manner that could be extrapolated. The quick scan approached ignored potential variation caused by different scour protection types, negative impact on fish or infaunal benthic species, environmental differences and presence of additional man-made structure. These relevant variables need to be addressed in future research.

To increase our understanding of the ecological importance of wind farms with their turbines and scour protection, future monitoring should focus on the following:

- Understanding species ecology and system ecology, e.g. by starting a broad study of the impact (including turbines and scour protection) on the wider ecosystem and food web.
- Obtaining more field data on epibenthic fauna and fish on scour protections and connectivity between locations.
- Making industry data available to scientists to increase data availability.
- Investigate different forms of scour protection as well as ecological limitations of species, including attraction and production effects (including epifauna on foundations).
- For fish studies, more use of specific reef-fish sampling methods, such as baited video and fykes or traps, is recommended. All results should be considered against a background of sandy seabed covered with thousands of other man-made structures, including shipwrecks, buoys and platforms.

We advise TKI Wind op Zee and RVO to focus their funding scheme on the following topics:

1. Assessment of the effects of currently used scour protection types on biodiversity, in particular epibenthic species and scour protection associated fish, including quantification of biomass, numbers and densities.
2. Investigation of the impact new scour protection specifications in the current tenders for new offshore wind farms have on biodiversity, in particular epibenthic species and scour protection associated fish, including quantification of biomass, numbers and densities.
3. To evaluate the ecological success of the new scour protection specifications, results from the study on currently used types of scour protection should be compared to the altered types.

1 Introduction

1.1 Background

The Dutch government has the ambition to realise five offshore wind farms of 700 MW each before 2023. Three of these windfarms have been tendered and the tender of the next wind farms is currently ongoing. Additionally, the government has announced that they intend to realise 1,000 MW offshore wind annually between 2023 and 2030. This will result in a large increase of offshore wind production capacity. Longer term outlooks estimate that in 2050 between 35 and 75 GW offshore wind energy will be needed in the Dutch North Sea to reach climate goals (Ros and Daniëls, 2017).

TKI Wind op Zee together with the Dutch government have formulated challenges that need to be met to successfully upscale offshore wind energy in the Netherlands. One of the challenges is called “offshore wind and environment”, and focuses on a net-positive contribution of offshore wind to ecology. This includes mitigation of negative impacts and increasing positive effects to ecology and biodiversity.

1.2 Problem description

The introduction of artificial hard substrates by placing wind turbine foundations and scour protection on the seabed facilitates epibenthic species and associated benthic fish (Bouma and Lengkeek, 2013; Coolen et al., 2018b; Lindeboom et al., 2011; van Hal et al., 2017). Although these hard substrates cover the existing sandy seabed, most likely killing a significant part of the local benthic infauna, the net effect may be considered as positive since it increases local biodiversity by allowing colonisation of species that would otherwise be unable to populate the area. Scour protection holds a low percentage of non-indigenous species compared to turbine foundations (especially shallow parts of the foundation) while hosting a number of species that are also found on natural rocky reefs (Coolen et al., 2018b). Rocky marine habitats or biological concretions that rise from the seabed are defined as habitat 1170 (‘Reefs’) in the European habitat directive (European Commission, 2013) and have been recognized in the Netherlands on the Cleaver Bank (Directie Kennis Landbouw Natuur en Voeding, 2008). The addition of rocky scour protection could be considered as adding H1170 habitat and as such has a positive impact of offshore wind farms on populations of benthic species. The significance of this effect, however, is unclear on a scale outside the local impact area of the turbine and scour protection.

Depending on the diameter of the monopile, scour protections generally cover between 1,000 and several thousand square meters of seabed per foundation in addition to the foundation footprint (Zaaijer and Van der Tempel, 2004). In the Netherlands, 289 offshore wind turbines have been installed to date (Pineda, 2018) and several wind farms with almost 10,000 MW production capacity (approximately 1,000 turbines, assuming 10 MW per turbine) are being planned or tendered until 2026 (Rijksdienst voor Ondernemend Nederland, 2018). With scenarios predicting up to 75 GW capacity (Ros and Daniëls, 2017), approximately 5,000 wind turbines might be constructed in the Dutch North Sea (75 GW from 15 MW turbines) until 2050. Assuming scour protection is added to all these installations, a significant area of coarse, gravelly and rocky substrates will be added to the seabed. This area, however, is still small on a North Sea scale, covering less than 0.02% of the Dutch Exclusive Economic Zone (EEZ). Therefore the Netherlands Enterprise Agency (RVO) and Technology Knowledge and Innovation (TKI) Wind op Zee requested a quantification of the effect scour protection has on epibenthic macrofauna and hard substrate associated fish.

2 Assignment

RVO and TKI Wind op Zee requested a quick-scan review of available scientific knowledge on the effects of scour protection on benthic fauna. During a kick-off meeting with RVO and TKI Offshore Wind, the goals were refined to assess the available information on the following questions:

1. What is the biomass of epibenthic macrofauna on scour protection found in monitoring programmes to date?
2. Which benthic species, including macrofauna and hard substrate associated fish, have been found to date on and associated with scour protection?
3. When 5,000 wind turbines are installed in the Dutch Sea, each with 2,000 m^2 scour protection, would this significantly change the benthic communities?
    a. If not, what surface area would be needed to attain a significant change?
4. To what extent are benthic species' populations on offshore wind turbine foundations interconnected?
5. What knowledge gaps prevent answering questions 1-4 with acceptable scientific certainty?

RVO and TKI Wind op Zee requested to be advised on the results before publication of the next TKI Offshore Wind call for proposals on 1 February 2019. This placed stringent time restrictions on the project plan. Therefore, the project was setup as a quick scan, to provide advice on short notice, allowing TKI Offshore Wind to include it in the call for proposals.

3 Materials and Methods

3.1 Biomass of macrofauna on scour protection

Data on benthic macrofauna biomass observed to date on scour protection in monitoring programmes were gathered from published datasets, reports and unpublished data available within Wageningen Marine Research. The data search resulted in data from the Dutch locations Offshore Wind Farm Egmond aan Zee (Bouma and Lengkeek, 2012, 2008), Princess Amalia Wind Farm (Vanagt et al., 2013; Vanagt and Faasse, 2014), the gas platforms L15-A and K9-A (operated by Neptune Energy) (Coolen et al., 2018b) and the Danish location Horns Rev (Leonhard and Frederiksen, 2006; Figure 3.1). German (Gutow et al., 2014; Krone et al., 2013) and Belgian (De Mesel et al., 2015) data were available via the unpublished UNDINE project dataset (Dannheim et al., 2018) but did not contain scour protection samples or biomass, respectively. No published data on biomass on scour protection in UK waters were found.

Data from scour protections around gas platforms were included since scour protection around oil and gas installations is similar to that in wind farms. Moreover, the gas platform data held locations in the Dutch EEZ but far from the two available wind farm datasets. The K9-A platform is located approximately 70 km from shore, which is farther offshore than the wind farms with available data.

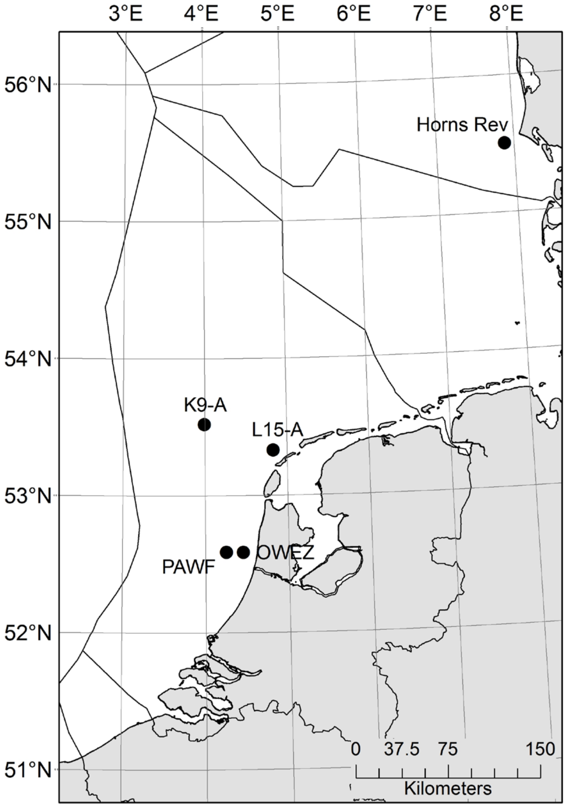

Figure 3.1 *Locations with available data on biomass of epibenthic communities on scour protection.*

Available data were extracted and combined in spreadsheets, which included sample number, project name, longitude and latitude in decimal degrees, depth sampled in meter below sea surface, biomass wet weight (WW) in gram per m^2 scraped surface area.

Since data were obtained from Dutch as well as Danish waters, analyses were performed with all data as well as data from Dutch waters only. The following descriptive statistics were calculated:

- Mean weight of samples (wet weight in $g.m^2$)
- Minimum weight
- Maximum weight
- Standard deviation

Furthermore, linear regression was performed to assess the impact of water depth and origin of the data. A generalised linear model was constructed using the wet weights as response variable and depth and project name as predictor. Since biomass attains any value ≥ zero, a gamma distribution was used. All analysis were carried out in R (R Core Team, 2018).

3.1.1 Edible crab density example

In addition to biomass studies, a study on densities of a large mobile epibenthic species (Krone et al., 2017) was included in the macrobenthic assessment. This provided direct extrapolation to 5,000 wind farms and showed that edible crabs (*Cancer pagurus*) increased significantly around monopiles with scour protections. This increase in density is then compared to a study in the Danish Horns Rev wind farm (Leonhard and Frederiksen, 2006) and to the background densities of edible crabs in the Dutch part of the North Sea (Steenbergen et al., 2012). The edible crab is provided as a case study since this was the only species where data on density on scour protection and on the natural seabed was readily available and since this is a species that is of commercial interest to fishermen (Steenbergen et al., 2012).

3.2 Species richness

3.2.1 Macrobenthic species

To assess which species are found on scour protection only published data were used as unpublished data were not available. The data were restricted to observations made in Dutch waters. Data from the Offshore Wind Farm Egmond aan Zee (Bouma and Lengkeek, 2012, 2008), Princess Amalia Wind Farm (Vanagt et al., 2013; Vanagt and Faasse, 2014) and the gas platforms L15-A and K9-A (operated by Neptune Energy) (Coolen et al., 2018b) were included.

3.2.2 Fish species

Many of the fish species that are influenced by offshore wind farm foundations and scour protections are reef-inhabiting species, so-called hard-substrate specialists. They typically live among rocks, and hide in between them when disturbed. Consequently, they are difficult to sample in a quantitative manner. As a result, studies that attempt this are scarce and they apply different survey methods, yielding different species lists and density information.

Hence, unlike the benthic macrofauna study, for fish we used a set of studies with different sampling techniques and there is only very limited information on densities. In order to get a realistic impression on the list of species concerned, studies were used from the Dutch EEZ or nearby in Belgian or German waters. We primarily focussed on offshore wind farm studies, but for the species list, we added data from shipwreck surveys and observations, because these represent a large and unique number of in-situ diver observations. All used data are published and publicly available.

To assemble the species list we used species lists from Lengkeek et al., 2013; van Hal et al. (2017); Kerckhof et al. (2018); Raoux et al. (2017) and Krone et al. (2017). Bos et al. (2016) was used to determine habitat preference (hard substrate, soft bottom substrate or both).

3.3 Upscaling to 5,000 wind turbines

3.3.1 Macrobenthic biomass

Based on the statistics obtained in 3.1, macrobenthic biomass found in sampled scour protections around offshore wind turbine foundations was extrapolated to the following values:

- Total biomass on scour protection around a single wind turbine;
- Total biomass on scour protection in an average wind farm;

- Total biomass on scour protection in all current wind farms;
- Total biomass on scour protection in all wind farms in the 2050 scenario (5,000 turbines).

Calculations were based on biomass values averaged over all samples, both including and excluding the Danish data. During these calculations, the following assumptions were made:

- Currently, 289 wind turbine foundations are present in four wind farms in the Dutch North Sea (Pineda, 2018);
- Currently, a typical wind farm contains 72 wind turbines (289 turbines in four wind farms);
- Wind turbines are 1,000 m apart within a typical wind farm;
- The seabed contained within a typical wind farm area covers 72 km^2;
- Each wind turbine foundation currently present in the Dutch North Sea as well as all future foundations is/will be surrounded by 2,000 m^2 of scour protection in of circular form with an extent up to 25 m from the foundation; Matutano et al. 2013);
- In 2050, a total of 5,000 wind turbine foundations will be present in the Dutch North Sea (Ros and Daniëls, 2017).

Future wind farm projects will have a higher production capacity per turbine, foundations will be larger, may need larger scour protection and will be built further apart. Effects of these changes have not been included in the current study.

To assess the impact of scour protection (for the current situation as well as for the 2050 prediction), biomass calculations of the background macrobenthic community were made. Based on average values obtained from literature, the following biomass values were calculated:

- Biomass originally present in the seabed covered by scour protection of a single turbine;
- Total biomass in the seabed within a typical wind farm
- Total biomass in the seabed in the whole Dutch part of the North Sea.

For these calculations, the following assumptions were made:

- The Dutch part of the North Sea covers 57,000 km^2 (Dotinga and Trouwborst, 2009);
- The average biomass in the Dutch North Sea is 13.8 g ash free dry weight (AFDW) per m^2, which was calculated from benthic monitoring data from box corer samples taken in the Dutch offshore zone in 2014-2015 (Rijkswaterstaat, 2018);
- To compare between wet weight and AFDW data, AFDW was assumed to weigh 10.5% of wet weight for all samples (based on Ricciardi and Bourget, 1998).

Finally, comparisons between background macrobenthic biomass and biomass added by presence of scour protection were made, on a local scale as well as the Dutch North Sea scale. The following calculations were made:

- Change in biomass around a single wind turbine;
- Change in biomass in a typical wind farm;
- Change in biomass in the Dutch North Sea.

To assess the significance of the changes, the assumption was made that change is significant when biomass increases/reduces by >5%. To advice on the option to add additional structures to further upscale the effect, the area needed to be covered by scour protection-like materials to reach 5% change was calculated.

3.3.2 Macrobenthic species richness

Using the data from the PAWF and gas platforms, which was readily available with species records on sample level, the expected species richness on all present scour protection was estimated. To attain this the extrapolated species richness in a species pool was calculated using the specpool function from the R vegan package (Oksanen et al., 2017). Different estimators (Chao, first and second order Jacknife and bootstrap) are calculated in specpool, which were assumed here to be the minimum and maximum number of macrobenthic species present in the area. To estimate total epibenthic species richness on scour protection when installing wind farms outside the current locations, additional data from 11 samples taken on rocky reefs of the Borkum reef grounds (Coolen et al., 2015a) were included. The rocks present in the Borkum reef grounds were assumed to provide identical habitat as scour protection would.

3.3.3 Fish

Only a subset of the literature mentioned in § 3.2.2 contained information on densities of benthic reef-associated fish species, and could therefore be used for extrapolation.
Hence, there is a substantial gap in knowledge on densities of reef-fish species, and therefore the extrapolation is severely limited. Krone et al. (2017) and van Hal et al. (2017) were used to provide some information on densities and extrapolation.

Studies using bottom trawling-type of sampling gear are designed to sample close to the scour protection, but not the scour protection itself. They therefore provide no information on densities of the species actually living on the scour protection.

3.4 Interconnectivity

Interconnectivity between populations of macrobenthic species was assessed based on a literature review. The review only included recent reports and scientific papers on connectivity between offshore oil and gas platforms and wind farms in the North Sea.

4 Results

Data are reported with a decimal point (.) instead of a comma (,). Likewise, the 1000 separator is reported with a comma.

4.1 Biomass of macrofauna community

In total, data on 95 samples were obtained from the available datasets. Sample intensity varied strongly between locations, from 3 samples per gas platform location to 72 samples from the Danish Horns Rev wind farm (table 1).

Table 1
Available data with location name (abbreviations see text), type, country, location (WGS84 decimal degrees), distance from shore (in km to nearest shore line), average sampling depth, number of samples and weight measurement type (Ash Free Dry weight: AFDW, Wet Weigh: WW).

Location	Type	Country	Latitude	Longitude	km offshore	Depth	# samples	Type
OWEZ	Wind	NL	52.5838	4.4506	11	18	12	AFDW
PAWF	Wind	NL	52.5868	4.2460	25	23	5	WW
Horns Rev	Wind	DK	55.4989	7.8761	14	7	72	WW
L15-A	Gas	NL	53.3295	4.8301	11	22	3	WW
K9-A	Gas	NL	53.5202	3.9924	70	32	3	WW

The average wet weight per m^2 differed strongly between locations, with maximum average found in Horns Rev (13 kg) and minimum at L15-A (0.5 kg). The highest sample weight was found in OWEZ (35 kg). Within the Dutch locations, OWEZ held the highest mean weight (5 kg; table 2).

The average weight for all 95 samples was 10.7 (±7.7 standard deviation) kg per m^2, with an obvious dominance of the 72 Danish samples. Average Dutch samples only weighed 3.2 (±7.4) kg per m^2. The latter standard deviation shows the variation in the Dutch data to be relatively high, possibly caused by the high number of locations with a low number of samples.

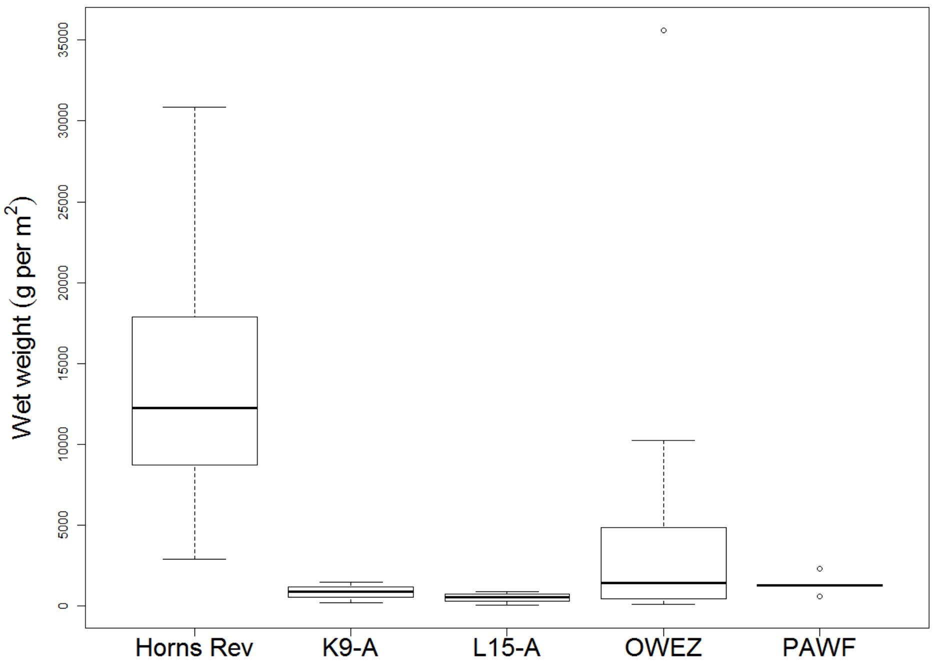

Figure 4.1 *Boxplots showing wet weights (g per m^2) in different locations. With median (middle thick bar), inter-quartile range (upper and lower boundaries of boxes, containing 50% of data) and minimum and maximum values (dotted whiskers) excluding outliers (upper point).*

Table 2
Mean, minimum and maximum weight (in g wet weight per m^2) and number of samples per location. Location abbreviation see table 1).

Location	Mean	Min	Max	# samples
OWEZ	5,322	91	35,611	12
PAWF	1,352	609	2,319	5
Horns Rev	13,074	2,906	30,840	72
L15-A	490	34	902	3
K9-A	866	202	1,492	3

The linear model analysis showed a significant difference between locations, Horns Rev weights were shown to be significantly higher than all Dutch locations ($p<0.001$). Sampling depth varied between 7 m on average in Horns Rev to 32 m around K9-A but as locations and sampling depth were collinear (similar sampling depths within each location) a possible depth effect cannot be separated from location. The model combining depth and location explained 45% of the variation in the data. The remaining 55% of the variation was not explained by the model. This variation is caused in part by random differences due to unknown natural processes, and may in part be explained by environmental differences such as temperature, salinity, current velocity, food availability, sampling season, and many others. These were not explored any further.

Since Danish data differed significantly from Dutch data, further analysis was based only on Dutch data. Although removing a large amount of data from the set, this approach seemed to be most representative for Dutch waters.

4.1.1.1 *Edible crab density example*

Densities of edible crabs were studied in the Riffgat wind farm in the German bight of the North Sea (Krone et al., 2017). Densities of other benthic species were studies as well but only the edible crab is presented here, as an example of a potential species that might be harvested in future wind farms. On average, 5,080 (±722 standard deviation) edible crabs were present on a footprint (monopile + scour protection) of 1,013 m^2.

A single other report was available on edible crab densities on scour protection, from the Horns Rev wind farm (Leonhard and Frederiksen, 2006). They state that the mean cover of edible crabs on scour protection is 4.1%. Assuming an average crab size of 100 cm^2, this would result in approximately 8,200 edible crabs on 2,000 m^2 scour protection, which is close to the German results.

In the Netherlands, densities of approximately 100 edible crabs per km^2 were reported in an assessment of the potential for targeted fisheries on edible crab, using pots (Steenbergen et al., 2012). These data originated from beam trawl surveys along the Dutch coast.

4.2 Species richness

4.2.1 Macrobenthic species

In total, 98 species have been observed on scour protections in OWEZ, PAWF and the L15-A and K9-A gas platforms (Annex 1). The communities on scour protection are mostly made up of gammarid crustaceans (i.a. *Jassa herdmani*, *Monocorophium* spp. and *Stenothoe monoculoides*), the plumose sea anemone *Metridium senile* and bryozoans such as *Conopeum reticulum* and *Electra pilosa*. A common large mobile species in the community is the starfish *Asterias rubens*. Species that are highly abundant near the water surface, such as the blue mussel *Mytilus edulis*, are also found on the scour protection but often not in such high densities, especially in deeper locations. Notable exceptions here are very high biomasses observed in OWEZ, caused by mussels in densities up to 19,500 individuals per m^2, in the same sample that held a wet weight over 35 kg per m^2.

4.2.2 Fish species

Table 3 presents the list of 48 demersal fish species observed in offshore wind farms or shipwrecks on or nearby the Dutch EEZ. Especially the species marked as HS (hard substrate) and not as SS (soft substrate) depend on the presence of reef structures. For those species, suitable habitat increases linearly with area of scour protection. For species that are both HS and SS, habitat also increases / improves with increased surface area of scour protection, but the relationship may be more complex through food web relations (Raoux et al., 2017) or habitat requirements in certain life stages.

Table 3
*List of 48 North Sea fish species associated with hard substrate, with scientific name, English name, preference for hard substrate (HS) and/or soft sediment (SS) according to Bos et al. 2016 and based on surveys in OWFs in the southern North Sea and English Channel: 1. Lengkeek et al. 2013 (shipwrecks); 2. Van Hal et al. 2017; 3. Kerckhof et al. 2018; 4. Raoux et al. 2017; 5. Krone et al. 2017. * not in Bos et al. 2016, habitat preference based on expert judgement. ** habitat preference different from Bos et al. 2016, based on expert judgement.*

Scientific name	English name	HS	SS	1	2	3	4	5
Agonus cataphractus	Hooknose	1**	1					1
Aphia minuta	Transparent goby	1	1	1				
Arnoglossus laterna	Scaldfish	1	1		1			
Atherina presbyter	Sand smelt	1	1	1				
Ballistes capriscus	Grey triggerfish	1**			1			
Buglossidium luteum	Solenette	1	1		1			
Callionymus lyra	Dragonfish	1	1	1	1	1		1
Chelidonichthys lucerna	tub gurnard	1	1		1			
Chelon labrosus	Thicklip grey mullet	1	1	1				
Ciliata mustela	Fivebeard rockling	1	1	1	1			1
Ctenolabrus rupestris	Goldsinny wrasse	1	**		1			1
Dicentrarchus labrax	Sea Bass	1	1	1	1	1	1	
Enchelyopus cimbrius	Fourbeard rockling	1	**					1
Gadus morhua	Atlantic Cod	1	1	1	1	1	1	1
Gaidropsarus vulgaris	Three-bearded rockling	1	1	1				
Gasterosteus aculeatus aculeatus	Three-spined stickleback	1	1	1				
Gobius niger	Black goby	1	**	1				
Hyperoplus lanceolatus	Greater Sandeel		1		1			
Labrus bergylta	Ballan Wrasse	1	**	1		1		
Limanda limanda	Dab	1	1		1	1		
Lophius piscatorius	Anglerfish	1	1	1				
Merlangius merlangus	Whiting	1	1	1	1	1	1	
Microstomus kitt	Lemon Sole	1	1		1	1		
Molva molva	Common ling	1	*	1				
Mullus surmuletus	Red mullet	1	1	1	1	1		
Myoxocephalus scorpius	Bull Rout	1	**		1	1		1
Parablennius gattorugine	Tompot Blenny	1	**	1		1		
Pholis gunnellus	Rock gunnel	1	**	1	1			1
Platichthys flesus	Flounder	1	1		1			
Pleuronectes platessa	European Plaice	1	1		1	1	1	1
*Pollachius pollachius**	Pollack	1	1	1		1		
*Pollachius virens**	Saithe	1	1	1		1		
Pomatoschistus pictus	Painted goby	1	1	1				
Raniceps raninus	Tadpole Fish	1	*	1		1		
Sardina pilchardus	Pilchard		1		1		1	
Scomber scombrus	Mackerel	1**	1		1	1	1	
Scyliorhinus canicula	Lesser spotted dogfish	1	1	1				
Solea solea	Common Sole	1	1		1	1	1	
Spondyliosoma cantharus	Black Seabream	1	1			1	1	
Sprattus sprattus	Sprat		1		1		1	
Symphodus bailloni	Baillon's wrasse	1		1				
Symphodus melops	Corkwing wrasse	1	**	1				
Taurulus bubalis	Longspined Bullhead	1	**		1	1		1
Thorogobius ephippiatus	Leopard-spotted goby	1		1				
Trachurus trachurus	Horse Mackerel	1	1	1	1	1	1	1
Trisopterus luscus	Pouting	1	1	1	1	1	1	1
Trisopterus minutus	Poor Cod	1	1	1	1	1	1	
Zoarces viviparus	Eelpout	1	**	1				
totals	48	42	32	29	26	21	12	11

4.3 Upscaling to 5,000 wind turbines

4.3.1 Macrobenthic biomass

The mean biomass on scour protection on Dutch locations was assumed to be 3,248 g wet weight per m^2, which converted to AFDW was 341 g per m^2. With a surface area covered of 2,000 m^2 around a single turbine foundation, biomass directly around a turbine increased from 28 to 681 kg AFDW, a 24-fold increase. On the scale of the Dutch EEZ, the increase is 0.43% if 5,000 turbines are installed (table 4).

Table 4
Calculated increase in biomass due to addition of scour protection to the background benthic macrofauna community, on different scales. Biomass is given in ash free dry weight and sizes in km^2. Note that the size of wind farms equals the number of turbines since the area around a turbine was assumed to be 1 km^2.

Scale	Area (km^2)	Biomass hard substrate (scour protection) (in 1,000 kg)	Biomass soft substrate (sandy seabed) (in 1,000 kg)	Increase (%)
Biomass per m^2	0.000001	0.003	0.00001	2,432
Scour protection	0.002	0.681	0.028	2,432
Wind farm	72	49.1	996.4	4.93
Current wind farms	289	197	3,999	4.93
5,000 wind turbines	5000	3,410	69,193	4.93
Whole EEZ	57000	3,410	788,801	0.43

Thus, in the scenario in which 5,000 offshore wind turbines are constructed in the Dutch North Sea before 2050, the total benthic macrofauna biomass will increase with 0.43%. This increase is caused by the addition of 10 km^2 of scour protection. If a significant increase of 5% is to be attained, additional scour protection-like material covering 106 km^2 should be added, which is 21,200 m^2 of scour protection around each of the 5,000 wind turbines, with a radius of approximately 82 meters from the foundation.

4.3.1.1 ***Edible crab density example***

With an average of 5,080 edible crabs on 1,013 m^2 around a monopile foundation, Krone et al. (2017) extrapolated to 5,000 monopile foundations in the German North Sea (assuming installations identical to the monopile studied). They estimate that the construction of these installations will allow the edible crab population to increase with 25.4 million individuals. With a background density of 100 edible crabs per km^2 (Steenbergen et al., 2012), the Dutch population on the natural seabed would be approximately 5.7 million. Thus, with the introduction of 5,000 monopile foundations the population of edible crabs in the Dutch North Sea would increase with 4.5 times (450%) that of the background population. When assuming scour protections of 2,000 m^2, the estimate may even increase to 50 million, which is 8.8 times that of the background population.

4.3.2 Macrobenthic species richness

The total extrapolated species richness in a species pool was estimated to be between 105 and 138 epibenthic species when considering only samples taken on scour protection in PAWF, L15-A and K9-A. Compared to the 95 species that had already been observed, the potential increase in species richness after taking more samples in the studied locations, would be between 11% and 45%. When including the Borkum Reef Grounds data (11 samples), the extrapolated species richness on scour protection was estimated to be between 141 and 194, indicating an increase in species richness between 48% and 104%. This suggests that total epibenthic species richness on scour protection may almost double when introducing scour protection at locations outside the current study range. An even higher increase may be expected when wind farms will be deployed in other, more offshore, parts of the Dutch EEZ than in the regions incorporated in this study.

4.3.3 Fish

In general, some studies find significant (positive) effects of offshore wind farms on demersal fish densities (Krone et al., 2017; Raoux et al., 2017), and other studies do not (e.g. Bergström et al., 2013; Vandendriessche et al., 2014). However, it appears that in studies that do not find significant effects, fish are mostly sampled with bottom-trawling type of sampling gear, which could sample near the scour protection, but not directly on the scour protection itself. When methods are applied that actually sample the reef habitat itself, such as scientific diving, sonar or gill nets, significant differences are generally found between the wind turbine foundation habitat and the surrounding sandy seabed (Bergström et al., 2013; Krone et al., 2017; Stenberg et al., 2015; van Hal et al., 2017).

Based on Krone et al. (2017), who sampled four wind turbine foundations with substrate surface area of 1050 m^2, using scientific divers), we made an extrapolation to the future scenario of 5,000 scour protection layers of 2,000 m^2 each, for 7 species associated with scour protection (table 5).

Table 5
Numbers of 7 fish species with standard deviation (SD) associated with scour protection observed by scuba diving on one monopile foundation in a wind farm in the southern North Sea and extrapolated to 5,000 monopiles (Krone et al. 2017).

		Observed on 1 monopile foundation 1050 m^2 (Krone et al., 2017)		Extrapolation to 5000 x 2000 m^2	
Scientific name	Common name	Number	SD	Number	SD
Callionymus spp.	Dragonet	17	29	161.905	276.190
Ctenolabrus rupestris	Goldsinny Wrasse	152	88	1.447.619	838.095
Pholis gunnellus	Butterfish	1032	712	9.828.571	6.780.952
Myoxocephalus scorpius	Bullrout	106	69	1.009.524	657.143
Taurulus bubalis	Sea scorpion	34	34	323.810	323.810
Gadus morhua	Cod	17	29	161.905	276.190
Trisopterus luscus	Pouting	625	969	5.952.381	9.228.571

*Agonus cataphractus was also quantified by Krone et al., 2017, but was omitted here because it is not a hard substrate specialist.

* Numbers are based on the monopile-data by Krone et al., 2017 only, because that foundation optimally resembles foundations in the Dutch EEZ.

Table 5 presents numbers of demersal fish species, observed on or near a monopile foundation in an offshore wind farm, and to be expected in a future scenario with 5000 wind turbines and a scour protection of 2000 m^2 each. For some species expected numbers in the future scenario reach in the millions.

Van Hal et al. (2017) do not present data in a form allowing such an extrapolation. They do, however, show that the species Atlantic cod (*Gadus morhua*), pouting (*Trisopterus luscus*), bullrout (*Myoxocephalus scorpius*), common dragonet (*Callionymus lyra*) and sea scorpion (*Taurulus bubalis*) occur in significantly higher numbers on the scour protection than in the surrounding soft seabed. This provides further support for the extrapolation based on Krone et al. (2017).

For the other species listed in table 3, that are not mentioned in table 5, data do not form a base for extrapolation.

4.4 Interconnectivity

Most studies investigating interconnectivity between offshore installations in the North Sea have been performed using larval dispersal models. To date, a limited number of studies have been published on the topic (Coolen et al., 2018a; Dannheim et al., 2018; Henry et al., 2018; Kamermans et al., 2018; van der Molen et al., 2018). Larval dispersal models use modelled water currents based on tidal currents and weather patterns from past years to hind-cast the path virtual larvae from a certain species travelled from their origin to their settlement location. Since different species have different pelagic larval durations, or no pelagic (free floating) stage at all, these models are species-specific. Studies on species that are not known for the Netherlands are not presented here. The different studies worked on the following species:

- Blue mussel *Mytilus edulis* (Coolen et al., 2018a; Henry et al., 2017; van der Molen et al., 2018)
- Amphipod *Jassa herdmani* (Coolen et al., 2018a)
- European flat oyster *Ostrea edulis* (Dannheim et al., 2018; Kamermans et al., 2018),
- Common limpet *Patella vulgata* (Dannheim et al., 2018)
- Dead man's finders *Alcyonium digitatum* (Henry et al., 2017; van der Molen et al., 2018)
- Edible sea urchin *Echinus esculentus* (van der Molen et al., 2018)
- Plumose anemone *Metridium senile* (Henry et al., 2017; van der Molen et al., 2018)
- Slipper limpet *Crepidula fornicata* (van der Molen et al., 2018)
- Sponges Porifera (van der Molen et al., 2018)

The models help explain observed patterns. Questions to be answered: why are some species never observed far offshore while others are common; which locations are connected and which not; do species use locations in-between as stepping stone to reach locations further offshore; what would be the impact when installations are removed from these de-facto networks.

As with the models, the question to what degree benthic species' populations on offshore wind turbine foundations are interconnected, is species dependent. Some species may be found on every location, such as *Metridium senile* and *Jassa herdmani*. Other species, such as the blue mussel *M. edulis,* are common on offshore platforms and wind farms, but rare on subtidal reefs such as shipwrecks (Coolen et al., 2018a). In general, species with long pelagic larval stages, such as mussels (70 days), have interconnected populations on offshore installations (Coolen et al., 2018a; Henry et al., 2017). Species with short pelagic stages have populations that are mostly isolated, or are even lacking from offshore installations, such as the European flat oyster (larval stage 10 days, absent offshore; Dannheim *et al.*, 2018; Kamermans *et al.*, 2018). This would imply that this species would benefit from restoration projects in offshore wind farms. Dannheim et al. (2018) shows that these new populations would serve as a source population for the southern North Sea.

Ecological information used in the different studies, varied. For example, while in one report a pelagic larval duration (PLD) of 22 days for *M. senile* is used (Henry et al., 2017), other authors state a duration of 180 days (van der Molen et al., 2018). For blue mussels PLD varies between 30 and 70 days (Coolen et al., 2018a; Henry et al., 2017; van der Molen et al., 2018).

A single study (Coolen et al., 2018a) attempted to validate the predictions from the larval dispersal model, for *M. edulis*. Coolen et al. obtained samples from gas platforms, wind turbine foundations, navigational buoys and coastal locations in the United Kingdom, France, Belgium, the Netherlands, Germany and Denmark. Connectivity between locations was modelled using larvae dispersal models and validated using genetic techniques. Although mussels were found at every investigated location, only a low percentage of variation was explained in the correlation between modelled distance and genetic distance. Coolen et al. (2018) attribute this to a large set of potential causes, the main problem being that they opportunistically sampled a large set of locations which were later modelled not to be connected directly. This resulted in a dataset with mostly zero connections, making correlation with genetic results challenging. They suggest studying locations in closer proximity in similar research in the future.

None of the studies advise on distances between offshore installations specifically, however, with an assumed net water movement between 1.7 and 6.9 km per day (Coolen et al., 2015b; Thorpe, 2012), species with a pelagic larval duration of 10 days could travel a mean distance of 43 km. This is in the same range as the distances reported for flat oyster larvae in Dutch wind farms (Kamermans et al., 2018).

5 Discussion and recommendations

5.1 Discussion

5.1.1 Macrobenthos

Data variation was high, the highest mean biomass (at OWEZ) was 10 times the lowest mean (at L15-A). This may have been caused by environmental differences, such as food availability and salinity, but given the low number of locations, correlation with environmental variables other than depth could not be assessed and random differences cannot be discounted. The Danish wind farms data differed significantly from the Dutch, most likely due to these environmental differences, and was excluded. Structures such as wind turbines and platforms may influence the surrounding benthic community differently (Degraer et al 2018). Only four locations in the Netherlands have been investigated so far. These do not capture the complete set of possible environmental conditions relevant for future predictions or scour protection types. Our extrapolation to the whole Dutch EEZ is informative and provides a first estimate but should be interpreted with care. Offshore locations in the Netherlands vary strongly in their concentration of food for the mostly filter feeding epibenthic community, such as chlorophyll a or zooplankton ("EMODnet OOPS zooplankton abundances (10 year AVG) - Datasets," 2018; MYOCEAN, 2015). Therefore, production by their consumers and the resulting biomass build up may vary strongly between locations.

Wet-weight biomass data were converted to ash free dry weight for comparison between them. This was performed in a very simplified manner, taking 10.5% of the wet weight to obtain ash free dry weight. Conversion factors, however, vary between species, with a range from 3.5% for certain echinoderms to 27.2% for some molluscs (Ricciardi and Bourget, 1998). As a result of this simplification the actual ash free dry weight may have been lower or higher than reported here.

Densities and biomasses reported here were compared to natural background populations (when available). These background populations, however, were calculated based on surveys of the natural sediment. Many structures with substrates similar to turbine foundations and scour protections are present in the Dutch North Sea (Coolen et al. 2018), these host much of the same species (Gmelig Meyling et al. 2012; Lengkeek et al. 2013; Lengkeek et al. 2013). The impact of presence of these other structures has not been included in the calculations presented in this report. The absolute increase due to the construction of wind farms may not change, but the increase relative to a background of natural sediments + thousands other man-made structures, is likely to be lower than reported here.

Impacts on the macrobenthic community surrounding the scour protection, was not included in this study. A study in a Belgian wind farm, however, showed an increase in density as well as biomass in the seabed directly surrounding the scour protection (Coates et al., 2011). This effect will further enhance the increasing effect the scour protection has on biomass and possibly species richness.

In all calculations, but especially in the edible crab example, differences in attraction of species from the larger area versus production of these species in the local area were not taken in to account. When available habitat increases, individuals from surrounding less suitable habitats may be attracted to the new habitat. When other environmental variables, e.g. food availability, are limiting for the species, the total population may not increase as a result of the increase of suitable habitat. The extrapolations to extremes such as for edible crab should therefore be interpreted with care.

5.1.2 Fish

For species that occur exclusively on hard substrates, such as rock gunnel (*Pholis gunnellus*), and the goldsinny wrasse (*Ctenolabrus rupestris*) this may be a realistic way to extrapolate. For species such as cod, a linear relationship may not be realistic: they do have a strong relationship with the scour protection zone (van Hal et al., 2017) but possibly through a more complex mechanism such as food web structure, and they are also known to occur on soft seabed habitats.

The fish species list is based on five different studies, using multiple research techniques including scientific diving. This should form a reliable basis.
For the densities, however, no such reliable base is available. The information that was available in sufficient detail for extrapolation came only from one study, based on the examination of four monopile foundations.

5.1.3 Connectivity

Connectivity is not only driven by water currents (as reviewed here) connecting species by pelagic larval dispersal. Many species also use floating objects for travel between locations (Thiel and Gutow, 2005). Furthermore, many vessels travel the North Sea, exchanging ballast water as well as hull fouling between ports (Cariton and Geller, 1993; Nall et al., 2015), increasing connectivity even further (Coolen et al., 2016). Large species also may travel by rolling over the seafloor (personal observation Joop Coolen). Within a month after deployment of artificial reefs off Noordwijk large sea anemones already 'settled' on the boulders (Van Moorsel, 1994).

5.1.4 Available habitat

The surface area available within scour protection was assumed to be 1 m^2 rock per 1 m^2 seabed covered by the scour protection. In reality the rocks in the scour protection are stacked on top of and next to each other, leaving surface area available in between them as well as on top. Therefore, the available surface area is much higher than the seabed covered. When both top, bottom and sides of rocks are exposed they possibly provide more than double surface area when compared the original seabed surface. This may result in an even larger total biomass compared to the assumption of 1 m^2 rock per 1 m^2 seabed. Contrary to this habitat increasing effect, scour protections also tend to become filled with sand over time (personal observation Marco Faasse, eCoast), reducing the available habitat, perhaps approaching that of the seabed covered again.

All scour protections were assumed to be 2,000 m^2. In reality, not all wind turbines are constructed with scour protection. Furthermore, some foundations are built with larger scour protections, others smaller than 2,000 m^2 (Krone et al., 2017).

Scour protections come in different forms, with and without a filter layer of gravel-like material covered with smaller or larger rocks. Design of scour protections is location dependant, differences depend on sea water depth, currents and sediment characteristics (Matutano et al., 2013; Zaaijer and Van der Tempel, 2004).

Scour protection is not the only hard surfaced material added to a wind farm. The wind turbine foundations themselves also act as artificial reefs, as well as cable crossings with anti-scouring material. Furthermore, the cable to land may at some locations be covered by rock dump. This all adds to the surface available to fouling macrobenthos. Depending on sizes of foundations, added surface could be as much as an additional 50%, since an 8 m diameter monopile in 40 m water already provides 1,000 m^2 surface area. Furthermore, the foundations hold biomasses of up to 90 kg wet weight per m^2 (Coolen unpublished data), which is much higher than the maximum observed on scour protections. Furthermore, mussels present on the foundation fall off (Krone et al., 2013) and may be retained in and around the scour protection, increasing the availability of hard substrate by coarsening of the sediment (personal observation Marco Faasse, eCoast).

Epibenthic species richness on scour protections is high and may double when installing wind farms at other locations than investigated here. However, most species found in the scour protections, had already been reported for natural or artificial hard substrates in the North Sea (Van Moorsel, 2014). Since scour protection is present on the seabed, mostly subtidal species are present and the community is similar to that found on reefs composed of larger rocks (Coolen et al. 2018). Furthermore, many other man-made structures are present in the North Sea, such as oil and gas installations (with scour protection), and an estimated number of 10,000 shipwrecks (Leewis et al. 2000; Lettens 2015). The number of wrecks includes many small remnants, so it should be considered as such, but constitutes an order of magnitude comparable to 5,000 wind turbines. At the moment, most, if not all, species present on scour protection are also present on part of these other substrates which act as the habitat for these species. So, although not essential for the survival of these benthic species, scour protection likely does play a role in the survival by allowing more local populations to exist in the North Sea and possibly connecting more populations than would be connected without the presence of scour protection. It is even possible that a significant increase of hard-substrate patches facilitates colonization by a number of benthic species with limited larval dispersal.

5.1.5 Example of an extensive assessment of the impact of wind farms on fish and benthic fauna

Most blue mussels grow higher up the wind turbine foundation and form up to 90% of the total faunal biomass on the wind turbine including scour protection (Maar et al., 2009; Raoux et al., 2017). In addition, changes in macrofauna and fish assemblages will have a wider impact on the complete food web up to apex predators (Lindeboom et al., 2011). This prompted Raoux et al. (2017) to study the potential impacts of benthos and fish aggregations caused by the introduction of hard substrates from both the monopiles and scour protections on the wider ecosystem with trophic web modelling tools (Ecopath with Ecosim, cf. Dannheim et al. 2018). This study is summarised here to provide an example of an extensive study of the impact of wind farms on these species groups.

An ecopath ecosystem model (compartments including phytoplankton to seabirds) was built to describe the ecosystem before the construction of a 50 km^2 offshore wind farm in 20 m depth. Subsequently, an Ecosim projection over 30 years was performed based on the biomass increase of benthic and fish compartments. The overall structural properties of the food web were compared before and after wind farm construction. The fish species included six functional groups: benthos feeders, gurnards, piscivorous, planktivorous, sharks and rays and other flatfish species. In addition, 12 hard substrate and commercial fish species were also included (cod, horse mackerel, mackerel, sea bass, poor cod, pouting, whiting, pilchard, sprat, sea bream, common sole and plaice). The reef effect generated a variation in biomass of the functional groups. The increase in substrates on both scour protection and turbine foundation available for epibenthic sessile organisms (mainly mussels) and fish resulted in a 40% increase of the total system biomass in the 50 km^2 wind farm area. Functional groups with increased biomass included cod, whiting, pouting, fish benthos feeders, sole and other flatfish (dominated by dab) and surface-feeding seabirds (dominated by *Larus* sp). Other groups with increased biomass included all top predators (except for diving seabirds), sea bream and plaice. In contrast, several groups declined strongly, including horse mackerel, poor cod and piscivorous fish. Pouting had the highest keystoneness index, which is probably related to its high omnivory.

The main results are that the total ecosystem activity and system omnivory increased after construction of the wind farm and that higher trophic levels, including marine mammals and seabirds responded positively to the increase in biomass on the piles and turbine scour protections (as hypothesized by Lindeboom et al. 2011). The study suggests further that the high abundance of mussels (up to double the biomass of filter feeders compared to before the OWF construction) could be responsible for a shift from primary producers and grazers dominated food web towards a more detritus feeing community. It also shows densities of some other species declined.

5.2 Knowledge gaps

During the quick scan performed for this report, a number of knowledge gaps have been identified. In general, there is a low amount of data available on macrobenthos on both natural and artificial hard substrates in Dutch waters. The information that is available originates from a small number of locations, most of which are located near shore, the PAWF and OWEZ wind farms. These data were obtained in only a limited number of years. Many man-made structures are present in the North Sea, but for most, no quantitative data on species numbers and biomass is available. Furthermore, within a wind farm, other structures such as scour protection on cables and cable crossings are present. No data on this was included the current study.

Technical specifications of the future scour protections are lacking. A better approximation of the expected amount of scour protection could improve the estimates presented here. Furthermore, the amount of habitat available for macrobenthic species within the scour protection could be better estimated when detailed measurements become available.

There is a general lack of detailed quantitative data on the group of demersal fish species that will benefit from an increase in offshore wind projects. This detailed information is absent, both for wind farm studies, and for knowledge about their natural occurrence in the Dutch EEZ. This is, amongst other reasons, caused by the difficulty to measure their abundance, as these fishes live hidden in a substrate that cannot be sampled. Most traditional fish surveys rely on bottom-trawling type nets, which need to be dragged over soft sediments, or on gill nets, for which many of these species are too small. Many reef studies in tropical waters rely on use of manta boards, scuba diving or video monitoring. In the North Sea wind farms, however, wind farm owners generally don’t allow any form of diving anymore and visibility conditions are often considered too poor for conventional video monitoring, especially in the current relatively near shore wind farms.

Location data of the expected 5,000 wind turbines were not included in this study. Once more data on macrobenthos becomes available, data on the expected turbine locations could be used to better estimate impacts at different locations. Differences might arise from variation in depth, distance from coastal populations, water mass origin, food availability and seabed sediments.

5.3 Suggested research topics

The following research topics are suggested to increase our understanding of the importance of wind farms and their scour protection:

- In general, monitoring should focus on understanding species ecology and system ecology. In addition to counting which species are where, it is equally important to understand the environmental and ecological drivers behind the data.
- A broad study of the impact of the reef effect on the wider ecosystem and food web (from phytoplankton to apex predators) should be initiated.

Furthermore, we suggest the following group specific research, for benthic macrofauna:

- Focus on obtaining more data on benthic macrofauna, on scour protection as well as on turbine foundations, from a wide geographic range to account for environmental differences. Use similar objects, such as buoys or shipwrecks to obtain ‘easy’ data. Obtain ash free dry weights as well as wet weights, species names and numbers to make these new data compatible with all previous data.
- Investigate connectivity by taking field samples to validate larval distribution models. Sampling locations should be selected based on larval dispersal modelling results since the field data is needed to validate the modelling data. Locations should include sets of directly connected, indirectly connected as well as unconnected locations.

- Industry holds data on marine growth, e.g. thickness/volume of growth with qualification of growth type (hard/soft). Try to make these data available for research. Validate these data by obtaining weight and volume data from samples from the same locations.
- Additional data could be obtained by studying structures during removal, e.g. objects such as buoys and platforms that are taken to shore or shallow locations. With knowledge on recent location and exposure time this could feed a valuable database.
- Different forms of scour protection are likely to have different effects on fauna (Hiscock et al., 2002; Lengkeek et al., 2017). For example, by varying in size range or adding structures such as reef balls or pipes. This could be investigated using field tests with different forms, followed by measurements to estimate abundance and biomass of various species, including fish.
- Investigate ecological limitations of target species such as edible crab to assess the full potential for population increase within the North Sea system.

To assess the impact of increased offshore wind projects on North Sea demersal fish populations, more research needs to be carried out into:

- Quantifying densities of demersal fish species on/near offshore wind foundations, by using modern research techniques such as Baited Video (when diving surveys are not possible) or other techniques novel to this setting such as fykes;
- Comparing these densities with occurrence outside offshore wind farms;
- Investigate the causes of the higher densities of species such as cod and sea bass. Is their production increased on a locally or on a North Sea scale? Are they attracted to the wind farm from elsewhere? Or are they initially attracted, followed by production increase due to a rise in carrying capacity caused by the wind farm habitat?

The latter is of importance to the question whether wind farms have a positive effect on commercial fish stock. Recent developments in monitoring techniques, may provide adequate solutions for these research topics. One example comes from recent developments with Baited Underwater Video set-ups, which have been applied in wind farm studies in the Irish Sea (Griffin et al., 2016). Baited camera set-ups are particularly good for comparing two adjacent habitats, such as scour protection and sand bottoms, and can provide valuable insight in the changes of fish densities in offshore wind farms. A more conventional, but in wind farms rarely applied, research techniques is the use of fykes or cage traps. Fykes, with or without bait, are used successfully to compare reef fish assemblages across habitats, for instance in the Wadden Sea near shellfish reefs.

5.4 Conclusion

Based on the results and discussion, the following conclusions can be drawn from this quick-scan:

- The addition of scour protection to offshore wind turbine foundations causes a very high biomass increase of 24 times (2,400%) that of the background macrofauna community in the area covered by scour protection.
- When considering this change on the scale of a wind farm of 72 km^2, the increase is lower but still important with 5%.
- With the addition of 5,000 offshore wind turbines, with a total of 10 km^2 scour protection, total biomass increases with approximately 3,400 tonnes, which is an increase of 0.43% compared to the biomass of the Dutch EEZ (57,000 km^2) without wind farms.
- The Dutch population of edible crabs, may increase with 50 million individuals after construction of 5,000 turbines with scour protection. This is a very high increase (880%) when compared to the 5.7 million edible crabs present on the Dutch natural seabed.
- 95 Epibenthic species have been observed in total on scour protection in the Netherlands. When additional wind farms are constructed, this number is expected double.
- A total of 48 fish species associated with hard substrate has been observed on or near scour protection in offshore wind farms, or shipwrecks on or nearby the Dutch EEZ. Wind farm observations include commercially important species such as cod, sea bass and mackerel. Especially cod, appears to have a strong preference for the direct vicinity of the wind turbine foundations and its scour protection, at least in large parts of the year (Degraer et al., 2018).

- Construction of 5,000 future wind turbines with scour protection may increase the available habitat for hundreds of thousands of cod, and many millions of smaller reef-species such as rock gunnel and goldsinny wrasse. For some species this may only be a relatively small contribution to its North-Sea wide habitat and their population, but for other species, such as the goldsinny wrasse, it may increase their population on the Dutch EEZ significantly.

5.4.1 Opportunities for TKI Wind op Zee related research

In general, and in particular for fish species, density and biomass data of macrofauna associated with hard substrate are scarce. This quick-scan was performed within the limits of these available data. Many opportunities for research aiming to increase our understanding of ecological processes arise, but we advise TKI Wind op Zee to focus their attention to the following wind farm and scour protection related research:

1. Proper baseline data is fundamental when assessing changes. Therefore, new projects should be to quantify the effects of currently used scour protection types on epibenthic species and scour protection associated fish, including quantification of biomass, numbers and densities, and compare these to the reference situation of soft sediment habitat.
2. Since the Dutch government has included scour protection specifications in the current tenders for new offshore wind farms, further research should focus on quantifying the impact these changes have on epibenthic species and scour protection associated fish, including quantification of biomass, numbers and densities.
3. To evaluate the ecological success of the new scour protection specifications, results from the study on currently used types of scour protection should be compared to the altered types.

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7 Quality Assurance

Wageningen Marine Research utilises an ISO 9001:2015 certified quality management system. This certificate is valid until 15 December 2021. The organisation has been certified since 27 February 2001. The certification was issued by DNV GL.

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Justification

Report C008/19.
Project Number: 4315100108.

The scientific quality of this report has been peer reviewed by a colleague scientist and a member of the Management Team of Wageningen Marine Research

Approved:	Sander Glorius Researcher
Signature:	
Date:	16th of April 2019

Approved:	Tammo Bult Director
Signature:	
Date:	16th of April 2019

Annex 1 Species list macrofauna

Total species list of all macrofauna species observed on scour protection in OWEZ, PAWF, L15-A and K9-A.

Phylum	Scientific name
Annelida	
	Eulalia viridis
	Eunereis longissima
	Harmothoe clavigera
	Harmothoe extenuata
	Harmothoe fernandi
	Harmothoe impar
	Lanice conchilega
	Lepidonotus squamatus
	Nereis pelagica
	Notomastus latericeus
	Phyllodoce groenlandica
	Phyllodoce longipes
	Phyllodoce maculata
	Sabellaria spinulosa
	Spirobranchus triqueter
	Sthenelais boa
	Subadyte pellucida
	Syllis armillaris
	Syllis prolifera
Arthropoda	
	Abludomelita obtusata
	Aora gracilis
	Balanus balanus
	Balanus crenatus
	Cancer pagurus
	Caprella linearis
	Eualus cranchii
	Galathea intermedia
	Homarus gammarus
	Jassa herdmani
	Liocarcinus depurator
	Metopa alderi
	Metopa borealis
	Microprotopus maculatus
	Monocorophium acherusicum
	Monocorophium sextonae
	Nototropis swammerdamei
	Perforatus perforatus
	Phtisica marina
	Pilumnus hirtellus
	Pisidia longicornis
	Semibalanus balanoides
	Stenothoe marina
	Stenothoe monoculoides
	Stenothoe valida
	Tryphosa nana
	Verruca stroemia
Bryozoa	
	Alcyonidioides mytili
	Alcyonidium condylocinereum
	Alcyonidium mamillatum
	Arachnidium fibrosum
	Aspidelectra melolontha
	Bugulina turbinata
	Callopora dumerilii
	Celleporella hyalina
	Conopeum reticulum
	Cribrilina punctata
	Electra monostachys
	Electra pilosa
	Escharella immersa
	Fenestrulina delicia
	Microporella ciliata
	Schizomavella (Schizomavella) linearis
	Scruparia chelata
Cnidaria	
	Alcyonium digitatum
	Clytia gracilis
	Clytia hemisphaerica
	Diadumene cincta
	Diadumene lineata
	Ectopleura larynx
	Halecium halecinum
	Metridium senile
	Obelia bidentata
	Obelia longissima
	Sagartia elegans
	Sagartia troglodytes
	Sagartiogeton undatus
	Tubularia indivisa
Echinodermata	
	Asterias rubens
	Ophiothrix fragilis
	Psammechinus miliaris
Mollusca	
	Acanthodoris pilosa
	Aeolidia papillosa
	Aequipecten opercularis
	Brachystomia scalaris
	Corbula gibba
	Crepidula fornicata
	Epitonium clathratulum
	Eubranchus exiguus
	Heteranomia squamula
	Hiatella arctica
	Kurtiella bidentata
	Lepton squamosum
	Mytilus edulis
	Onchidoris bilamellata
	Tergipes tergipes
	Venerupis corrugata
Porifera	
	Halichondria (Halichondria) panicea
	Protosuberites denhartogi

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