The potential impact of human interventions at different scales in offshore wind farms to promote flat oyster (Ostrea edulis) reef development in the southern North Sea

Ter Hofstede, Remment; Williams, Gregory; Van Koningsveld, Mark

DOI
10.1051/alr/2023001

Publication date
2023

Document Version
Final published version

Published in
Aquatic Living Resources

Citation (APA)
Ter Hofstede, R., Williams, G., & Van Koningsveld, M. (2023). The potential impact of human interventions at different scales in offshore wind farms to promote flat oyster (Ostrea edulis) reef development in the southern North Sea. *Aquatic Living Resources*, *36*, Article 2023001. https://doi.org/10.1051/alr/2023001

Aquat. Living Resour. 2023, 36, 4
© R. ter Hofstede et al., Published by EDP Sciences 2023
https://doi.org/10.1051/alr/2023001

Aquatic
Living
Resources
Available online at:
www.alr-journal.org

Special Issue - NORA 4 - Native Oyster Restoration Alliance 4th Conference

RESEARCH ARTICLE

OPEN ACCESS

The potential impact of human interventions at different scales in offshore wind farms to promote flat oyster *(Ostrea edulis)* reef development in the southern North Sea

Remment ter Hofstede[1,2,*], Gregory Williams[2] and Mark van Koningsveld[1,2]

[1] Delft University of Technology, Civil Engineering and Geosciences, Stevinweg 1, 2628 NH Delft, The Netherlands
[2] Van Oord Dredging and Marine Contractors, Schaardijk 211, 3063 NH Rotterdam, The Netherlands

Received 29 June 2022 / Accepted 9 January 2023

Handling Editor: Pauline Kamermans

Abstract – Incorporation of ecology and ecosystem services into marine infrastructural developments has gained interest over the last decades. Growing attention is given to combine the massive roll-out of offshore wind farms in the North Sea with reinstating the once rich but nowadays nearly extinct European flat oyster (*Ostrea edulis*). However, the practical upscaling of these pilots is hindered by the absence of clear management objectives and the lack of quantitative knowledge on the effect of technical interventions that could stimulate oyster reef development. Consequently, it is unclear what scale of intervention would actually be required to achieve overall management objectives. This paper presents a stepwise procedure designed in particular to guide the selection of appropriate measures and their required scale for pro-actively facilitating flat oyster reef development in offshore wind farms, in order to reach a desired state for oyster reef inclusive wind farms. The stepwise procedure addresses the historical and current situation of the physical system and social environment, provides options for intervention that stimulate oyster reef development at a range of scales, from micro-scale (materials used) to mega-scale (connectivity between wind farms), and quantitatively assesses the potential effect of applying these interventions. Assumptions have been made in quantifying the effort required for developing oyster reefs in offshore wind farms, and refinement is obviously needed. However, this is a first attempt to make such estimates. The outcomes provide direction in identifying research needs to fill knowledge gaps, as well as in decision-making during the design process for inducing oyster reef development in offshore wind farms. Herewith, application of the stepwise procedure supports authorities in restoration management for the successful reinstatement of flat oyster reefs in the southern North Sea.

Keywords: Offshore wind / oyster / restoration / management

1 Introduction

Incorporation of ecology and ecosystem services into marine infrastructural developments in general has gained interest over the last decades. Initial focus lied primarily on coastal infrastructure (e.g. King and Lester, 1995; Capobianco and Stive, 2000; Lamberti and Zanuttigh, 2005; Swann, 2008; Borsje et al., 2010; Waterman, 2010; De Vriend et al., 2015; Laboyrie et al., 2018), but recently attention also goes out to offshore construction works, in particular wind farms (Dafforn et al., 2015a; Lengkeek et al., 2017; Van Duren et al., 2016; Degraer et al., 2020). For example in the Dutch part of the North Sea, the government now requires developers to include elements that benefit ecology in the design of offshore wind farms (e.g. Dutch Ministry of Economic Affairs and Climate, 2022). This implies that demonstrable efforts should be undertaken to design and build an offshore wind farm in an eco-friendly manner that actively helps to foster conservation goals for species and habitats.

The infrastructure in offshore wind farms, such as the piles of the turbines and the rock material placed at their base to prevent scouring of the seabed, provides hard-bottom habitat and three-dimensional structures used by marine life to settle, forage and shelter, generating a reef-effect (Petersen and Malm, 2006; Lindeboom et al., 2011; Coolen et al., 2020; Degraer et al., 2020). This spontaneously arising ecological value in terms of biodiversity and biomass of offshore wind

---

*Corresponding author: `r.terhofstede@tudelft.nl`

farms, can be enhanced by making deliberate adjustments to the conventional engineering design. One can include modified structures that enhance habitat complexity and promote the colonisation by selected target species. One can use materials that facilitate settlement of new species, such as shells or calciferous rock that contain a high amount of calcium, which is beneficial to shellfish species (Hidu et al., 1975; Soniat et al., 1991). Or one can create more shapes and cavities to provide areas and places in which animals can shelter, by making the constructions more organic in shape, or by installing artificial reef structures. The more variation in habitat one offers, the more variety one gets in marine life living in, at and around the marine infrastructure (Lapointe and Bourget, 1999; Firth et al., 2014). Furthermore, one can actively introduce certain target species to kickstart the colonisation of the infrastructure by preferred species. Such pro-active interventions to enforce nature could promote the ecological value of offshore wind farms facilitating their required permitting process and community acceptance. Or, more ambitious even, the huge momentum of offshore wind development can be used to achieve large scale restoration ambitions that would otherwise be unaffordable.

The aforementioned can be observed in practice in the growing attention to combine the construction of offshore wind farms in the North Sea with the reinstatement of hard substrate epibenthic communities, in particular of the European flat oysters (*Ostrea edulis*) (Kamermans et al., 2018; Sas et al., 2019). This species can form immense reefs; tower-like, biogenic structures with a height of 7 m, a length of 30–50 m, and a width of 10 m have been observed along the Bulgarian coast (Todorova et al., 2009). In a dynamic offshore environment as is the North sea, oyster reefs can ameliorate physical stresses by creating a hospitable habitat for organisms that would otherwise be unable to tolerate these conditions (Crain and Bertness, 2006). Oysters influence water quality by filtering the water (Dolmer, 2000; Newell, 2004), and their reefs provide a habitat for a diverse associated community (Coen and Luckenbach, 2000; Lown et al., 2021), from offering substrate for settlement of algae and sessile benthic fauna (e.g. sponges, anemones) to providing shelter and nesting area for fish species and crustaceans (e.g. crabs, lobsters). This reef dwelling marine life often includes species of commercial value, including the oysters themselves, showing the potential of oyster beds to contribute to valuable fisheries resources. Flat oyster reefs once covered large areas of the North Sea (Olsen, 1883), but went near to extinct due to overexploitation, bottom-dwelling fisheries and the outbreak of a disease (Gross and Smyth, 1946; Korringa, 1952). Overfishing in the past increased the isolation of the oyster populations in the southern North Sea, leading to a further deterioration of the remaining stock due to the reduced chance of fertilisation between the colonies (Gross and Smyth, 1946). The recent increasing amount of hard substrate offered by rock installations in offshore wind farms in the southern North Sea offers potential for connecting existing or new oyster reefs. Due to the geographic distribution of offshore wind farms, they can serve as stepping stones to connect species between otherwise isolated populations, as also observed for oil and gas platforms (Thorpe, 2012; Adams et al., 2014), thereby facilitating the colonization of new hard substrates in the future.

Oyster reef restoration in the North Sea is supported under the EU Marine Strategy Framework Directive, and a target in e.g. Dutch policy (Min. IenW & Min. LNV, 2018). Offshore wind farms are identified to potentially host these reefs, and accordingly, growing effort is being put in pilot studies stimulating oyster development in offshore wind farms (e.g. Didderen et al., 2019; Sas et al., 2019; Tonk et al., 2020). However, overarching management objectives are still lacking for the actual implementation of the research outcomes. This may be due to the lack of insight into the level at which to incorporate technical modifications of offshore wind farms, what the effect of these measures could be, and how much intervention is needed to be of significance. The successful development and implementation of a policy for oyster reef development in offshore wind farms requires a systematic approach to reach predefined objectives.

A method that was successfully applied in previous studies to assess the operational status of new policies is the ‘Frame of Reference’ approach (Van Koningsveld, 2003). It was originally derived to evaluate and re-define a sustainable coastal policy for the Netherlands (Van Koningsveld and Mulder, 2004) and has since then been used for a range civil engineering disciplines. For example, it was used to define coastal management policies for beach areas (Jiménez et al., 2007; Sutherland and Thomas, 2011; Gault et al., 2011), to develop environmental monitoring schemes for offshore renewable energy projects (Garel et al., 2014), and proposed as a tool to assess the sustainability of dredging projects (Laboyrie et al., 2018). The approach cyclically defines both a strategic and an operational objective and operationalizes these objectives in a 4-step decision recipe determining (i) a quantitative state concept, (ii) a bench marking procedure, (iii) an intervention procedure and (iv) an evaluation procedure (see Fig. 1).

For this study we use the Frame of Reference approach to analyze the operational maturity of nature inclusive policies related to oyster reef development in offshore wind farms. We focus on the second and third steps of the decision recipe, i.e. defining the gap between a current and a desired state and the intervention options available to close this gap (see grey area in Fig. 1). The aim of this paper is to provide a detailed procedure to select intervention measures for the design or adjustment of offshore wind farms, to induce oyster reef development at a desired scale. The selection of measures is supported by a quantitative estimation of their expected effect.

2 Methodology

2.1 Stepwise procedure

To provide direction in the selection of interventions for promoting flat oyster reef development by engineering offshore wind farms, a stepwise approach is required, addressing the physical and social environment and providing quantitative information on a range of interventions that can be taken to influence the current state towards the desired state (see Fig. 2). Such a stepwise procedure supports the selection of appropriate measures for pro-actively facilitating oyster reef development, taking into account dynamic interactions and the effects at varying spatial scales. To change the design of a conventional offshore wind farm void of oysters (current state)

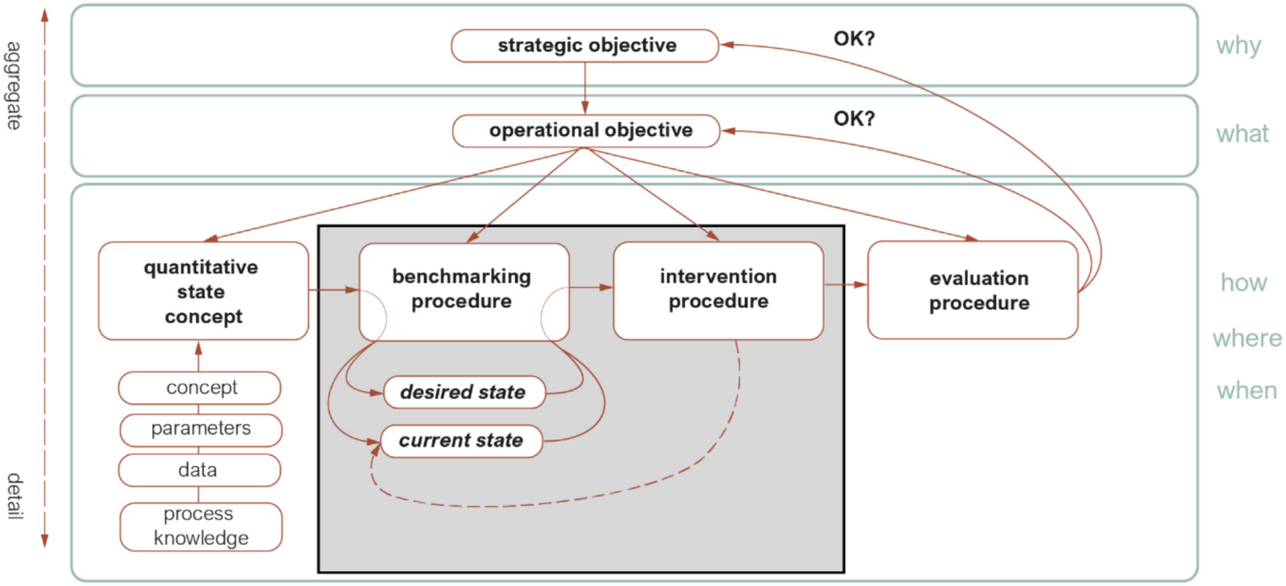

Fig. 1. A 'basic' frame of reference for policy development (source: Van Koningsveld et al., 2021). The grey area indicates the step addressed in this study.

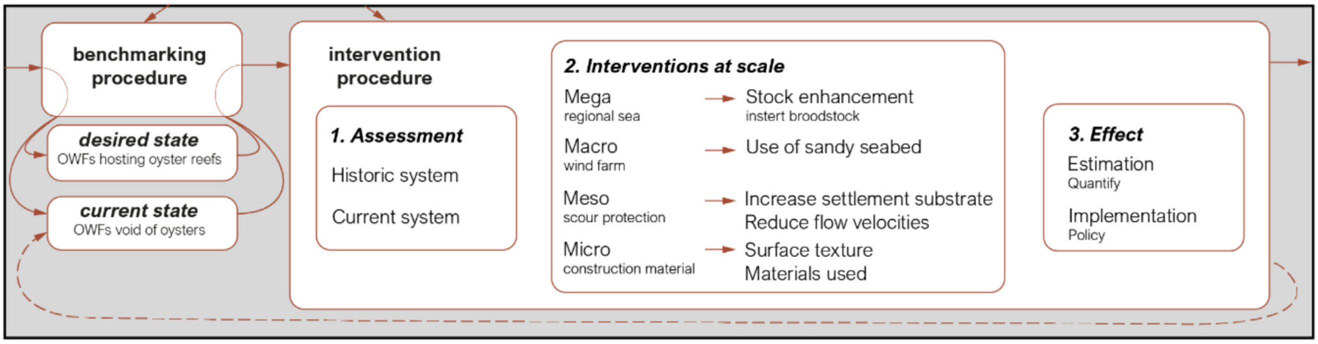

Fig. 2. Stepwise procedure to assess the potential effect of interventions at different scales on oyster reef development in an offshore wind farm, bringing a wind farm void of oysters towards one hosting oyster reefs.

into a wind farm hosting oyster reefs (desired state), the procedure comprises three steps. First, the historical and current situation are assessed of the socio-environmental system in which the wind farm is foreseen or situated, addressing the prevailing physical conditions and actors of influence (users, regulation). Second, it provides information on potential oyster-promoting interventions at different scales that can be incorporated in the design or after construction. And third, the procedure aids to quantify the effects that can be achieved with such modifications, to allow for a proper selection of the preferred intervention(s).

2.1.1 Step 1. Asses the system

First step is to assess the local system in which the wind farm is located or to be constructed. The historical and current situation of the area provides information whether it is suitable for the desired objective, in this case hosting oyster reefs. If the species is known to have been present in the past, or has been (incidentally) observed in or nearby the area, this would indicate a site's suitability for development of oyster beds. When assessing the area, not only presence, but also anthropogenic and environmental factors should be taken into account, as these both positively and negatively affect oysters. Promotional factors comprise food abundance, suitable substrate, and current for supply of oxygen and nutrients (e.g. Millican and Helm, 1994; Pogoda et al., 2011). Inhibiting factors include bottom-disturbing human activities (e.g. fishing), predators, water depth, competition for food and habitat, a minimum population size to obtain a healthy population, strong currents, sand waves, and diseases (e.g. Gerken and Schmidt, 2014; Korringa, 1940; Smyth et al., 2018). The absence of oyster beds is not an indication that an area is unsuitable for oyster reefs per se, as it can be influenced by a recent, often human-induced, decrease in the promotional, or increase in inhibiting factors. Therefore it is necessary to first investigate the historical situation of the area to verify its potential for oyster reef development.

Once the potential of an area for oyster reef development has been confirmed based upon the historical situation, the current situation should be assessed whether an area is already

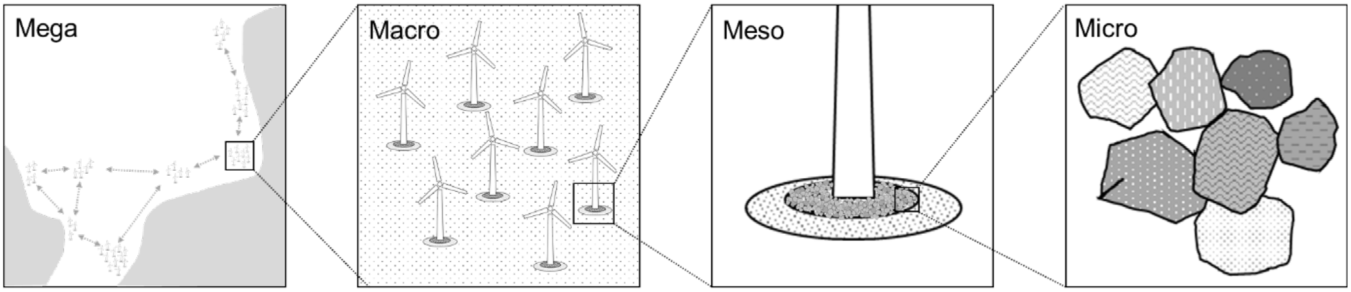

Fig. 3. Scale division of interventions that can be taken to stimulate oyster reef development in offshore wind farms. From left to right: Mega-scale: connectivity within a regional sea; Macro-scale: undisturbed seabed between turbines in a wind farm; Meso-scale: scour protection at the base of wind turbines (armour layer on top of filter layer); Micro-scale: characteristics of construction material.

or can be made suitable for oyster reef development. The assessment should include an investigation of the physical environment such as the presence or potential for a stable substrate, but also the social institutions should be addressed to identify prevailing regulations and societal desires. If the area is positively assessed for oyster reef development but not yet suitable, the assessment should indicate which promotional factors should be stimulated and which inhibiting factors minimized.

2.1.2 Step 2. Interventions at scale

An offshore wind farm in an area with environmental conditions suitable for oysters offers is in its existence the fundament for oyster reef development: Bottom-disturbing activities are excluded and substrate is provided by means of scour protection made of quarried rock installed at the base of the turbines or covering cables. Various measures at different scales can be taken to further promote oyster reef development, or should be taken to kickstart the development of an oyster reef. For example, providing more complexity in the scour protection than is functionally required, by means of shape, with irregular extensions in both vertical and horizontal directions, will increase surface area and provide more area for shelter. Also, the use of calcareous rock, such as limestone or marble, will trigger increased settlement by shellfish (Hidu et al., 1975; Soniat et al., 1991), opposed to the conventionally used non-calcareous rock such as granite and eclogite.

Four scales of potential interventions are defined: a region hosting wind farms (mega), a wind farm itself (macro), individual structures, i.e. scour protection (meso), and the construction material (micro) (see Fig. 3).

(i) Mega-scale – connectivity of different offshore wind farms in a seascape

The flat oyster is an immobile species who's populations only spread during the larvae stage prior to settlement. Larval dispersal depends on a number of factors including food availability, water temperature, current transport and suitable settlement sites (Kennedy and Roberts, 2006; Rodriguez-Perez et al., 2021). The larvae of the flat oyster have a pelagic stage with a dispersal potential being greater than 10 km (Berghahn and Ruth, 2005; Kamermans et al., 2018), though the larvae behaviour shows high self-recruitment, tailored to reduce dispersal away from parent populations (Rodriguez-Perez et al., 2020). Therefore, spread of larvae within a wind farm is likely once broodstock is present. However, oysters are not able to colonize newly built wind farms when the distance from existing populations is too large, and human intervention by means of introducing oysters in the wind farm might be required.

Oysters can be introduced in wind farms during different life stages, being adult or spat. The advantages of using adults for stock enhancement is that these are robust, and can contribute to the reef development already during the next spawning season. Using spat is beneficial as these are easier to obtain in large quantities and will have less impact on existing oyster populations. Both life stages require the use of a method that allows the oysters to survive, grow and reproduce to be able to become a thriving broodstock for reef initiation over time.

(ii) Macro-scale – surface area of the designated wind farm

Offshore wind farms are often constructed in a soft sediment system with varying abiotic conditions, ranging from fine mud to coarse sand, and from a stable seabed to highly moving sand waves. The development of oyster reefs requires stable settlement substrate. Adding hard substrates by means of artificial reef structures using natural or artificial materials, can create settlement opportunities for oyster larvae to initiate reef development. The infrastructure in wind farms, by means of the turbines and the scour protection at their base and at cable crossings, offers such settlement substrate, but the area between the infrastructure, which is the majority of a wind farm, remains a sandy seabed. A huge variety of artificial reef structures can be installed in this area to provide settlement opportunities for oysters. However, often these structures cannot cope with strong hydrodynamic currents and high sedimentation rates, and are generally prone to erosion around their base (e.g. Walles et al., 2016; Didderen et al., 2019).

A more sustainable approach would be to strive for establishing a biogenic oyster reef without interference of hard structures, which would transition the dynamic soft sediment system towards a self-sustaining hard and stable environment. The agglomeration of shells from living and dead oysters forms a complex matrix for settling juveniles, and associated fauna, therefore being crucial for reef persistence over time. It should be high enough to compensate for the losses due to sedimentation and shell degradation (Mann and Powell, 2007). Triggering the establishment of biogenic oyster reefs has occurred successfully by initiating high vertical relief reefs (>25 cm) made of a conglomeration of shell from living and dead oysters (Schulte et al., 2009; Scyphers et al., 2009), serving as the base for the extant population, spat settlement, and reef persistence (Schulte et al., 2009).

(iii) Meso-scale – shape and dimension of scour protection

Marine construction works often offer important refuges for marine life by means of crevices, pits and rock pools (e.g. Firth et al., 2014; Consoli et al., 2018). In offshore wind farms, this meso-scale habitat can be found in the scour protections at the base of wind turbines and at cable crossings. A scour protection prevents the seabed around wind farm infrastructure from erosion, and is generally composed of a filter layer of small-sized quarried rock, such as granite, topped with an armour layer of large-sized quarried rock. Promoting marine life at the scour protections, can be achieved through adjusting the dimensions and shapes to generate suitable habitat.

The European flat oyster benefits mostly from hard substrate surface to settle upon, and it should be stable as moving rocks cause physical damage or even mortality. Increasing the grading size of the rock material used for scour protection would increase its stability and provide a more stable substrate (Van Velzen et al., 2014). Furthermore, changing the horizontal and vertical dimension and shape of the scour protection would increase the area of hard substrate for settlement by oyster larvae, and could create areas with reduced flow velocity, which improve the opportunities for settlement (Korringa, 1940; Smaal et al., 2017).

(iv) Micro-scale – type and texture of construction material

The geological origin and surface roughness of building materials on a micro-scale (<1 cm) have a significant effect on the structure and functioning of colonising species assemblages (Coombes et al., 2011; Green et al., 2012). Small adaptations of both texture and structure of concrete constructions were observed to lead to better settlement and growth conditions for algae and macrobenthos in intertidal zones of the marine environment (Borsje et al., 2010). Similar effects are to be expected when adjusting the type and texture of installations in offshore wind farms. The larvae of *O. edulis* are able to attach themselves on a wide range of substrates, but appear to have a strong preference for shells or coralline algae (e.g. Gerken and Schmidt, 2014; Smyth et al., 2018; Allison et al., 2020), likely due to surface roughness and presence of calcium carbonate (e.g. Cuadrado-Rica et al., 2016). Tonk et al. (2020) tested various types of substrates for recruitment densities of *O. edulis* larvae, and observed that granite, marble and concrete were most successful for settlement per surface area. Potet et al. (2021) observed a positive effect on *O. edulis* larvae settlement of concrete that contains a high proportion of shell material and a surface texture that has a pattern with a coarse roughcast look resembling natural stone. Such micro-scale adaptations to materials used for infrastructure can be considered the basis for effective oyster reef development in offshore wind farms.

2.1.3 Step 3: Quantify effects

To determine whether measures that can be taken in the design and/or adjustment of offshore wind farms will have the desired effect on oyster reef development, the expected effects of the measures should be estimated. A quantitative assessment should be performed for each intervention based upon existing knowledge, taking into account the prevailing conditions in the designated area as much as feasible. This will allow the wind farm developer to make informed decisions on the selection of interventions to be implemented, when making a trade-off between desired impact and costs.

2.2 Application of the stepwise procedure to the southern North Sea

The stepwise procedure was applied to an existing situation, to assess its application for selecting quantified measures to modify offshore wind farms for facilitating oyster reef development. The area selected for this assessment is the southern North Sea, in which offshore wind farm development is growing rapidly. An inventory was made of all offshore wind farms present in the area up to the date 31 December 2020. The assessed wind farm data included general information on their capacity (MW), geographic location, area covered, number of turbines, foundation type, and pile diameter, and specific data on the scour protection, i.e. type, dimensions and rock size of the armour and filter layers. Data was obtained by approaching the wind farm owners, and if data was not provided upon request, information was obtained from the wind farm websites or from the web-based sources www.4coffshore.com and www.emodnet.ec.europe.eu.

The physical conditions that dominate oyster reef development in the southern North Sea are bed shear stress and suspended particle matter (Kamermans et al., 2018) The geographic locations of all wind farms were projected in maps showing shear stress (Kamermans et al., 2018) and suspended particle matter (Gayer, 2020) using GoogleEarth. From these maps, it was determined whether the prevailing conditions in a wind farm location fall within the boundaries suitable for oyster reefs, using thresholds provided by Kamermans et al. (2018), i.e. shear stress <0.6 Pa and suspended particle matter <60 mg/L.

3 Results

3.1 Asses the system

The area assessed is the southern North Sea, defined as the part of the North Sea south of the diagonal line between Scarborough (UK) and the tip of Jutland (Denmark), and north of the entrance of the Channel between Dover (UK) and Calais (F) (see Fig. 4). This line roughly follows a 50 m depth contour and is commonly used to make a north-south division of the North Sea, in which the southern part has a depth up to approximately 50 m, and the northern part from 50 m down to the continental slope (e.g. Lee, 1980; DEFRA, 2005; Christiansen, 2009). The division is reflected by large-scale ecological patterns in infaunal, epifaunal and demersal fish communities, resulting from differences in bottom water temperature, bottom water salinity and tidal stress (Reiss et al., 2010). The area is bordered by England (UK) on the west, and Belgium, The Netherlands, Germany and Denmark on the east. It has a surface area of approximately 200,000 km^2, and a maximum depth of approximately 40 m. A large sand bank, the Doggersbank lies centrally in the northern part at an average depth of 13 m, and many smaller sand banks and dunes are present in the south.

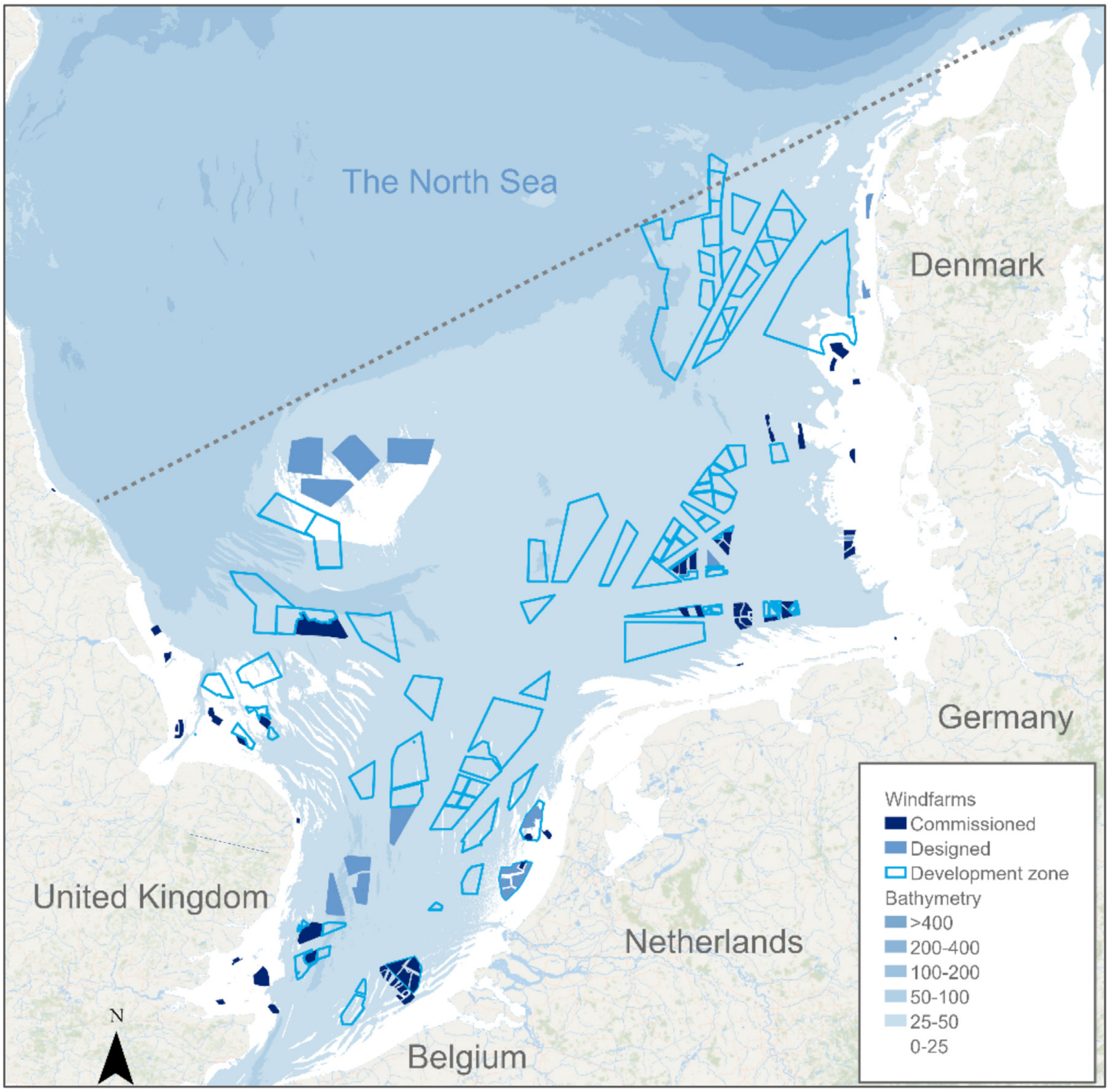

Fig. 4. Wind farms in the southern North Sea (d.d. 31/12/2020).

3.2 European flat oysters (*Ostrea edulis*)

The European flat oyster beds covered large areas in the southern North Sea (Olsen, 1883; Houziaux et al., 2008) with a conservatively estimated density of 1 oyster per 8 m^2 in an area of 21,202 km^2 (Berghahn and Ruth, 2005), which could imply a population of 2.65×10^9 oysters. After their decline due to primarily overexploitation and diseases in the 19th century, the remaining oyster populations were too small to reproduce successfully (Gross and Smyth, 1946) and currently the flat oyster has almost completely disappeared from the North Sea (De Vooys et al., 2004; Gerken and Schmidt, 2014). Also suitable habitat was declining, as the flat oyster prefers to settle on existing oyster or other shellfish reefs, which were also removed by the fishing activities (Korringa, 1952). The flat oyster has survived in estuaries surrounding the southern North Sea (Smaal et al., 2015) and recent records of pilots outplacements in open sea show survival, growth and fecundity (Didderen et al., 2019, 2020; Merk et al., 2020), indicating that the existing conditions in the southern North Sea may favour a large scale return of the flat oysters.

The historic data show that the southern North Sea offers suitable environmental conditions to host huge areas of flat oyster reefs. However, widespread bottom-disturbing activities, primarily fisheries and sand extraction, prevent stabilization of the sandy seabed, reef-formation of any type of shellfish species, and thereby inhibit oyster reef regeneration. In addition, considering the flat oyster larvae behaviour to reduce dispersal away from natal populations (Rodriguez-Perez et al., 2020), reef growth is only possible from nearby existing oyster beds, which are yet only present in small amounts in coastal areas. A recovery of flat oyster reefs throughout the southern North Sea is therefore not expected to occur naturally and requires human intervention. European institutions put focus on oyster reef restoration in the North Sea, as the OSPAR Convention lists *O. edulis* as a threatened species and habitat, worthy of protection and conservation, and the EU Habitats Directive and the Marine Strategy Framework Directive put particular emphasis on the

Table 1. Overview of offshore wind farms per country in the southern North Sea (d.d. 31/12/2020).

	Total capacity (MW)	Total area (km^2)	Total turbines (#)	Total monopiles (%)	Total armour rock (km^2)	Total soft seabed (km^2)
Denmark	776	170	220	100	0.08	170
Germany	6,567	749	1,268	78	0.67	748
Netherlands	2,461	391	462	100	0.18	391
Belgium	2,262	185	399	86	0.22	184
United Kingdom	8,532	1,893	1,610	94	0.65	1,892
Total	20,598	3,388	3,959	89	1.80	3,385

protection and conservation of biogenic reefs such as oyster reefs. It is generally acknowledged by experts from science, nature conservation, commercial production, bio-consulting and policy advisers, that native oyster restoration in Europe should be promoted (Pogoda et al., 2019).

3.3 Offshore wind farms

Up until the end of 2020, 62 wind farms with total surface of 3388 km^2 have been installed the southern North Sea (see Tab. 1), covering approximately 1.7% of the entire area, and many more wind farms are foreseen to be constructed. Information on the wind farms was provided by wind farm developers upon request for 27 out of the 62 wind farms. For the remaining wind farms, general information was obtained from web-based sources and specific data on the scour protection was estimated using the average of the 27 wind farms. The 62 wind farms in total produce 20.6 GW renewable energy per year from 3959 turbines (see Tab. 1), of which the most are installed on monopiles (89.0%), some on 4-legged jackets (2.7%) and tri-piles (6.1%), and few are gravity-based (2.0%). The foundations of the first three types are hammered or drilled into the seabed and are generally surrounded by a rock bed to prevent erosion. This so-called scour protection generally consists of a filter layer of granite rock (commonly used size ranges between 22/90 mm and 45/180 mm) with an average diameter of 33.4 (±8.5) m and thickness of 0.5 (±0.1) m ($N = 15$). The filter layer is generally topped with an armour layer of larger granite rock (common size ranges between 5–40 kg and 60–300 kg) with an average diameter of 26.0 (±6.5) m and thickness of 0.9 (±0.3) m ($N = 27$). The rock sizes and dimensions used in the scour protection depend on local water depth, geomorphological and hydrodynamical conditions, and diameter of the wind turbine foundation.

All countries bordering the southern North Sea, i.e. Belgium, The Netherlands, Germany, Denmark and the United Kingdom, are increasing their offshore wind capacity, and the construction of offshore wind farms offers great potential for nature development activities. New installed wind farms provide suitable seabed conditions by means of hard substrate for settlement and large undisturbed areas free from bottom trawling fisheries. Although bottom-disturbing fisheries are currently allowed in operational offshore wind farms in the UK, in practice most fishermen don't resume their activities in the wind farms due to the risks involved (Gray et al., 2016). Therefore, in our assessment all offshore wind farms in the southern North sea are considered to offer undisturbed areas. Thus far, the wind farms have only been designed taking into account technical and financial aspects, but currently a transition is taking place to incorporate the active enhancement of the ecosystem, for example through requirements as those set in The Netherlands that when developing wind energy at sea 'measures have been and will be taken to make and keep the ecosystem healthy and make its use more sustainable' (Dutch Ministry of Economic Affairs and Ministry of Infrastructure and Environment, 2015).

3.4 Interventions at scale

3.4.1 Mega-scale – connectivity

To initiate oyster reef development in offshore wind farms remotely located from natural oyster reefs, likely a broodstock should be provided to generate larvae locally, as the dispersion potential larvae is greater than 10 km, but their behaviour is aimed at self-recruitment (Berghahn and Ruth, 2014; Kamermans et al., 2018; Rodriguez-Perez et al., 2020). The average size of an offshore wind farm in the southern North Sea is 54.6 (±80.4) km^2, with 1 turbine per 2.3 (±2.1) km^2, meaning that it is safe to assume that each wind farm should at least have its own broodstock to initiate oyster reef development. As the proportion of females in an oyster population is observed to be higher for larger individuals (Kamphausen et al., 2010), the broodstock should consist of a population with different size classes, to ensure the inclusion of both sexes.

The recruitment of oyster stock is determined by density, as the fertilization success and thereby broodsize increases with density (Gercken and Schmidt, 2014); oysters with a nearest neighbour ≤ 1.5 m were found to brood significantly more larvae than individuals with nearest neighbours ≥ 1.5 m (Guy et al., 2018). Using broodstock structures as opposed to loosely distributed mature oysters will assure the high density of the broodstock. Kennedy and Roberts (2006) attributed an estimated total larval production per season of 1.08×10^{11} to a commercial stock size of 125,000 individuals, with sizes ranging between 50 and 109 mm shell diameter, i.e. 867,000 larvae per individual, indifferent of the ratio male/female. This means that a broodstock of 1000 individuals, for example as used in offshore wind farm Borssele V with an average size of 78.9 (±5.1) mm shell diameter (Schutter et al., 2021), could produce 8.7×10^8 larvae each spawning season.

The mortality rate of *O. edulis* during the planktonic phase and the first juvenile period of life is estimated to be very high: from 1 million larvae only 250 reach spat stage, of which 95% die before winter (Korringa, 1946). A broodstock of 1000

situation	intervention	Available surface (km^2)			Potential # oysters			
		Scour Protection	Soft Sediment	Shell Reef	Scour Protection	Soft Sediment	Shell Reef	Total
					6.8 oysters m^{-2} (Christianen *et al.* 2018)	0.125 oysters m^{-2} (Berghahn & Ruth 2005)	1,026 oysters m^{-2} (Schulte *et al.* 2009)	
A	none	2.80	3,385	0	-	-	-	-
B	only armour layer to ensure stability (disregard filter layer) (ter Hofstede *et al.* 2022)	1.80	3,385	0	-	-	-	-
C	only wind farms with suitable environmental conditions (Kamermans *et al.* 2018)	0.74	1,614	0	$5.03*10^6$	$2.02*10^8$	0	$2.07*10^8$
D	25 cm layer shell material at 1% of soft sediment (Schulte *et al.* 2009)	0.74	1,598	16,1	$5.03*10^6$	$2.00*10^8$	$1.65*10^{10}$	$1.67*10^{10}$
E	25 cm layer shell material at soft sediment, area size as armour layer (Schulte *et al.* 2009)	0.74	1,613	0.7	$5.03*10^6$	$2.02*10^8$	$7.59*10^8$	$9.66*10^8$
F	horizontal extension armour layer by 1 D_{pile}	1.27	1,613	0	$8.64*10^6$	$2.02*10^8$	0	$2.10*10^8$
G	marble armour layer (settlement x 1.33) (Tonk *et al.* 2020)	0.74	1,614	0	$6.69*10^6$	$2.02*10^8$	0	$2.08*10^8$

Fig. 5. Potential interventions in existing offshore wind farms, and the estimated order of magnitude effect on available substrate and the potential amount of oysters.

individuals could therefore lead to a recruitment of 10,837 juveniles (ignoring uncertainties) at the start of the winter. It is suggested that about 15% of these juveniles will reach the age of 1 year (Guerra, 2002), and 70% of them is estimated to survive until maturity (Bodoy et al., 1991), meaning that of the initial 1000 individuals, yearly 1137 individuals are estimated to be produced that eventually contribute to new broodstock. Assuming no mortalities of mature oysters caused by external factors, an initial broodstock of 1000 adults would then result in approximately 35,000 mature oysters after 10 years.

3.4.2 Macro-scale – soft sediment

In the southern North Sea, the area of undisturbed soft sediment in wind farms (total wind farm area minus the estimated amount of scour protection) is calculated to be 3385 km^2 (Situation A in Fig. 5). Comparison with the historical distribution of *O. edulis*, made Kamermans et al. (2018) assume that areas where bed shear stress is less than 0.6 N are suitable for the development of flat oyster beds. Following this, only 21 out of the 62 offshore wind farms can be considered suitable for oyster reef development, ruling out all wind farms in Belgium waters, most of those in Dutch and UK waters (except Gemini and Horn Sea 1 and 2) and some in German waters. The total amount of soft sediment available in these 21 wind farms with suitable conditions for oyster reef development is estimated to be 1614 km^2 (Situation C in Fig. 5). Densities of *O. edulis* in the North Sea system at a soft sediment seabed were conservatively estimated to be 0.125 individuals m^{-2} (Berghahn and Ruth, 2005). Once broodstock has been installed, this could result in a population of 2.02×10^8 oysters at the 1614 km^2 of suitable soft sediment in the southern North Sea (Situation C in Fig. 5).

Settlement and densities of oysters at the soft sediment in offshore wind farms can be increased by providing substrate by means of shell material, as is the case at natural oyster reefs (Allison et al., 2020). Initiating high vertical relief reefs (>25 cm) made of a conglomeration of shell from living and dead oysters could result in densities of 1026 oysters m^{-2} (Schulte et al., 2009; Scyphers et al., 2009). Applying this method to 1% of the soft sediment seabed in the 21 offshore wind farms suitable for oyster reefs, could result in an addition of 1.65×10^{10} oysters to the southern North Sea (Situation D in Fig. 5). However, it would require 4.13×10^6 m^3 of shell material, equivalent to a volume of 1652 Olympic swimming pools (a 2500 m^3). For comparison, covering a surface area with shell reef to a size equal to the available armour rock material (see below, 0.74 km^2), would result in an addition of 7.28×10^8 oysters (Situation E in Fig. 5), and require 1.82×10^5 m^3 of shell material, equivalent to the volume of 73 Olympic swimming pools.

3.4.3 Meso-scale – scour protection

While the subsea rock installations in existing offshore wind farms have been functionally designed for scour protection only, they provide hard substrate on which epibenthic rock dwelling species can thrive. During a dedicated scour protection monitoring survey undertaken in 4 Dutch wind farms in 2020, it was observed that filter layers largely disappear under a layer of sand (ter Hofstede et al., 2022). Therefore, only the armour layer is considered suitable for providing rocky habitat for oyster reef development. In the southern North Sea, the area of armour rock around a single monopile in a wind farm is on average 530.2 (±255.5) m^2 ($N = 27$). The total amount of armour layer available in the southern North Sea is estimated to be 1.80 km^2 (Situation B in Fig. 5). Considering only the 21 offshore wind farms with suitable conditions for oyster reef development based upon shear stress, the total amount of armour layer available is estimated to be 0.74 km^2 (Situation C in Fig. 5). Oyster densities at an existing bed in the Voordelta (Netherlands) were

Table 2. Overview of future offshore wind farms per country in the southern North Sea, designed and development zones. It is assumed that all turbines are built on a monopile and scour protection is applied.

Future wind farms	Total capacity (MW)	Total area (km^2)	Total turbines (#)	Total armour rock (km^2)	Total soft seabed (km^2)
Designed	13,025	3657	1,009	0.53	3,656
Development zone	93,116	26,141	7,213	3.82	26,134
Total	106,140	29,797	8,223	4.36	29,790

observed to be 6.8 ± 0.6 oysters m^{-2}, and these were most often found to grow in areas with hard substrate, i.e. rock and stones (Christianen et al., 2018). We assume this number as densities that can be expected at the available scour protection. Once broodstock has been installed, this could result in a population of 5.03×10^6 oysters at the available armour rock material (0.74 km^2) in the southern North Sea (Situation C in Fig. 5).

The diameter of the armour layer is on average 4.3 ± 1.1 times the diameter of the pile ($N = 27$). Increasing the horizontal extent of the armour layer of the scour protection with 1 pile diameter, a value taken arbitrary, would result in more armour surface area to support oyster reef development. The new total amount of armour layer available in the southern North Sea is estimated to be 2.91 km^2, of which 1.27 km^2 in de areas with suitable conditions (Situation F in Fig. 5). Using the density of 6.8 ± 0.6 oysters m^{-2} (Christianen et al., 2018), this could result in a population of 8.64×10^6 oysters at the scour protection in offshore wind farms in the southern North Sea.

3.4.4 Micro-scale – materials used

Interventions at micro-scale to promote oyster reef development in offshore wind farms are primarily intended to improve settlement rates of the larvae. Adjustments can be made in substrate surface texture and substrate type. Potet et al. (2021) observed that a surface structure mostly resembling natural stone led to highest larvae settlement of *O. edulis*, from which can be concluded that quarried rock as conventionally used as scour protection suffices. Tonk et al. (2020) found that calciferous-rich marble rock had a factor 1.33 higher settlement rates of *C. gigas* larvae than conventionally used granite rock. Assuming that a similar effect would occur for *O. edulis*, and that density of oysters would linearly increase with the settlement rate, adding a marble layer on top of all existing scour protection, could thus potentially result in a total population of $5.03 \times 10^6 \times 1.33 = 6.69 \times 10^6$ oysters on the scour protection in offshore wind farms the southern North Sea (Situation G in Fig. 5).

3.5 Future scenario

Our assessment of the system revealed that another 15 offshore wind farms are designed to be built in the southern North Sea the coming years (see Fig. 4), covering 3657 km^2 with a total of 1009 turbines delivering 13,025 MW of energy (see Tab. 2). Another 26,141 km^2 has been designated as development zone for offshore wind energy in the future (see Tab. 2). Assuming that the 15 designed wind farms are representative for the wind farms in the development zones, based on increase in surface area one may expect an addition of 7213 turbines delivering 93,116 MW from wind energy.

Assuming that all these wind turbines will be built on a monopile foundation with scour protection at its base of a similar dimension and design as currently are used (armour 530.2 (±255.5) m^2/pile; filter 388.4 (±337.1) m^2/pile), a total of 4.83 km^2 armour rock, 3.54 km^2 filter and 33,013 km^2 soft sediment will become available for oyster reef development in these future wind farms. When taking into account the assumed suitability of these wind farms for oyster reef development based upon bed shear stress, a total area of 23,321 km^2 is considered suitable for oyster reefs (70.6% of all wind farm development area). This could result in a population of 3.14×10^9 oysters within in the southern North Sea without interventions (Situation C). Interventions could lead population sizes of 2.59×10^{11} (situation D), 7.40×10^9 (Situation E), 3.16×10^9 (Situation F), 3.15×10^9 (Situation G) oysters.

3.6 The selection of interventions

Multiple interventions at different scales by means of introducing broodstock and suitable substrate have been presented, which all have the potential to contribute to oyster reef development in offshore wind farms in the southern North Sea. Each of these interventions will have a different effect on the oyster population. It is important to know the required effort, the effect, and the interaction of such interventions, in order to support decision-makers in defining their policy objectives.

Active oyster reef development in offshore wind farms starts with the confirmation that the environmental conditions are suitable for oysters. Once confirmed, human intervention to regenerate oyster reefs is likely required, due to the lack of connectivity between the scarce natural oyster reefs and the newly build offshore wind farms. Therefore, any oyster bed development programme in offshore wind farms would probably require a human-induced accumulation of oysters, for example broodstock. How much broodstock is needed depends on the desired population size. The average offshore wind farm in the southern North Sea contains 0.030 (±0.022) km^2 of armour rock and 54.6 (±80.4) km^2 of soft sediment, meaning it potentially can host an oyster population of 7.02×10^6 oysters, assuming the same densities used in the earlier calculations (Christianen et al., 2018; Berghahn and Ruth, 2005). Fully filling up such a wind farm in 15 years' time with oysters, would require an initial broodstock of roughly 39,000 oysters, based upon the assumptions that larvae reach maturity in 3 years, the broodstock increases over that period as calculated before (factor 1.137), and no mortalities of adults occur caused by external factors.

Increasing the numbers of oysters within an wind farm area can furthermore be facilitated by providing suitable substrate. Our calculations using the densities for the three habitat types shellfish reefs (Schulte et al., 2009), rock (Christianen et al., 2018), and soft sediment seabed (Berghahn and Ruth, 2005) show that most effect can be achieved by creating permanent reefs of shell material, as assumed densities at these reefs are thought to be 150 times higher than on rock material, and 8000 times higher than on a soft seabed.

If the objective of the oyster reef development would be to return the flat oyster reef population to its estimated size of 2.65×10^9 oysters in the 19^{th} century (Berghahn and Ruth, 2005) using the amount of wind farms currently available, only the creation of shell reefs would be an effective intervention (see Fig. 5). The total amount of habitat surface offered by the scour protection in the areas with assumed suitable conditions, is not large enough to host that size of a population, also not yet when interventions have been applied. However, creating shell reefs would require a large amount of shell material, which is difficult to purchase in practice, let alone the practical constraints for installation of permanent shell reefs in offshore waters. In the future scenario when all the offshore wind farms have been installed, sufficient area with suitable conditions (bed shear stress <0.6 Pa) will be available to host an oyster population as present in the 19th century. The only intervention then needed would be the introduction of broodstock to overcome connectivity issues and start oyster reef development.

4 Discussion

4.1 Nature enhancement of marine infrastructure

When introducing marine infrastructure into an ecosystem, the impact on the original environment should be taken into account, even if the purpose is restoration. The addition of hard structures on the seascape can cause significant losses of soft-sediment habitats, affecting the diversity and function of marine systems in general (Bulleri and Chapman, 2010; Dafforn et al., 2015a). The creation of new hard substrate habitats, albeit often essential for infrastructural purposes and considered valuable for nature enhancement, have shown loss of soft-sediment communities and their services (Davis et al., 1982; Martin et al., 2005). The losses of the original habitat need be assessed and minimised if possible (Dafforn et al., 2015b). In situations where hard structures cannot be avoided, such as when used to prevent scouring around the foundation of a wind turbine in offshore wind farms, there is the potential for eco-engineering to mitigate the impacts of these structures and to maximise potential ecological outcomes. The scour protection can for example be engineered to enhance biodiversity through the addition of complexity and micro-habitats. Small adaptations in material use, texture, and shape can improve the conditions for settlement, growth and use by a variety of marine life, while keeping the function of the scour protection intact. Also, nature enhancement can be beneficial for the marine infrastructure itself. For example, oyster presence at the scour protection of wind turbines will affect the connection of rocks and thereby its stability. The extent of this effect depends on the coverage ratio of oysters and the rock size. Smaller rock gradings such as those in the filter layer will experience a greater stability increase compared to larger rock gradings under the same coverage ratios because they require fewer oysters for effective binding (Domisse, 2020).

The spatial scale to which artificial hard structures can affect the marine environment has been found to range from 10s of metres to 1000s of kilometres (Dafforn et al., 2015a). Efforts to enrich nature by adjusting infrastructure have been tested throughout the marine environment, most of these are at meso- and micro-scale. For example at meso-scale, the addition of artificial rock pools in a seawall that retain water during low tide, led to an increase in biodiversity at the seawall (Chapman and Blockley, 2009). Also at micro-scale, more often consideration is given to the use of materials, not only for the integrity of a structure, but also to promote the development of marine life (e.g. Firth et al., 2014, Tonk et al., 2020). At a macro- and mega-scale, the spatial arrangement of how near or far artificial structures are positioned from each other determines their impact on the environment, as it has the potential to affect the connectivity of marine organisms. The construction of offshore wind farms results in the creation of isolated rocky habitats used as scour protection at the base of each wind turbine. The isolation of these modified habitats is likely to cease as the hydrodynamics will lead to the exchange of small marine life such as larvae and seeds between the rocky habitats, and larger species will migrate within the wind farm. At a larger scale, climate change drives species range shifts (e.g. ter Hofstede et al., 2010), and the expansion of marine infrastructure such as offshore wind farms may enhance these movements by providing stepping stones for rock-dwelling species by means of these small scour protections (Adams, 2014). Studies on the impact of the construction of offshore wind farms should be undertaken to not only assess possible long-term effects of the infrastructure at a local scale, but also to take into account regional scales, resulting from the potential connectivity of wind farms and consequently the introduction of invasive species.

4.2 Estimating the effect of interventions to support oyster reef development

The effects of interventions to initiate and facilitate oyster reef development as presented are rough estimates. Substantial assumptions have been made throughout the assessment to provide a quantitative prediction of the effect of taking interventions for developing oyster reefs in offshore wind farms, and refinement is needed. The actual outcomes of the interventions presented would remain unknown until being put in practice and will vary at each location where implemented. Nevertheless, the calculations do provide a first estimate to obtain insight into the magnitude of effort required to reach a desired effect with the interventions.

The assumptions were taken across all scales when quantifying the effects of interventions to stimulate oyster reef development in offshore wind farms. For example, at a macro-scale the assessment included only offshore wind farms that are considered suitable for the development of flat oyster beds based upon the prevailing environmental conditions. However, oyster presence can still be observed in the wind farms that are not included in this assessment, such as in the 2006-erected Dutch offshore wind farm Egmond aan Zee. Here, despite the assumed unfavorable conditions, European flat oysters were documented being settled at the top of the monopile in the intertidal zone in 2011, though noteworthy no oysters were found in the scour protection area (Bouma and Lengkeek, 2012). At meso-scale, an example of an assumption made relates to flow velocities and related settlement opportunities of oyster larvae at the scour protections. Increased turbulence generation may amplify the bed shear stress to 5–11 times higher near the foundation of a monopile than at the remainder of the scour protection (Sumer and Fredsøe, 2002). However, this variation was not taken not account as it is impossible to predict what the exact bed shear stress will be where, and when these become unsuitable for settlement. Furthermore, substantial assumptions were made on oyster densities during the quantification. Fixed oyster densities were used for the three habitat types, i.e. rocky scour protection, soft sediment seabed, and shell reefs, but of course in practice, many hydrological, morphological and biological factors will determine the actual densities, which are all location specific and will vary throughout time. For example, the timing of the installation of substrate such as rock material is crucial for the settlement success of oyster spat. Settlement rates are highest if the substrate is placed during the peak of larval abundance, and if placed too early, it will be fouled with other organisms that prevent oyster spat from settling, or overgrow spat that does manage to settle (MacKenzie 1970; van den Brink et al., 2020). However, the construction of offshore wind farms takes place year-round, mostly outside of the short spawning period of oysters, meaning that much of the available substrate for oyster spat is likely to have been colonised by competing organisms.

Also, the interventions available for enhancing oyster reefs in offshore wind farms are not limited to the ones presented here, and more options can be considered. For example, instead of introducing oyster broodstock to initiate reef development in a wind farm, one can also consider the introduction of oyster spat. Although it will take a couple of years before the spat has matured and can start producing larvae to distribute throughout the wind farm, spat is easier to obtain in large quantities with less impact on existing oyster populations. Another example, at a meso-scale, adding vertical variability is a method to create low-current areas, which can benefit the settlement of oyster larvae. This can be done by creating piles of rock or installing artificial reef structures. The benefit of creating a piles of rocks is that it can be done by using the same type of rock as is used for the scour protection, which is easier to acquire. If rock of similar size is used, the same equipment for installation of the scour protection can be used. If larger rocks or artificial reef structures are used, one might need to install a filter layer to stabilize the seabed first if installed independently, or account for secondary scour if these structures are installed on-top of the scour protection itself, and other equipment for installation might be required, which complicates the installation procedure.

5 Conclusion

Innovative eco-designs for marine constructions are developed to be beneficial for marine life and associated societal interests, and should become an integral part of large-scale infrastructural development. It remains to be determined how the various elements of marine infrastructure can be used or attuned to positively influence the marine ecosystem, not in the last place because it is not clearly defined and even arguable what changes may be considered positive. Currently, clear objectives are lacking for stimulating nature values in offshore wind farms, which inhibits a coordinated implementation of knowledge gained from small scale pilots into larger scale policies. This also requires thinking beyond individual pilots, and consideration of the effect of each intervention across different scales.

This paper presents a stepwise procedure to quantitatively estimate the potential effects of interventions at various scales, from micro-scale (materials used) to mega-scale (connectivity between wind farms). It has been applied using the knowledge available for initiating oyster reefs in the current and future wind farms in the southern North Sea. The stepwise procedure provides insight in what are the most promising measures, and where uncertainty or lack of knowledge is cause for concern. This may guide future research, as well as contribute to determining a coordinated selection of interventions to adjust conventional designs of wind farms to promote flat oyster reef development, with the aim to establish significant effects in a regional seascape.

The inclusion of hard substrate and the absence of seabed disturbing fisheries are the main components of wind farms in the southern North Sea to be suitable for flat oyster reef development. The presence of hard substrate provides settlement opportunities for the flat oyster spat, which can be increased with selected interventions. The absence of bottom disturbing fisheries within a wind park provides the opportunity for oysters to build their reef without having the habitat being destroyed. Due to the lack of connectivity between natural oyster reefs and the wind farms, active introduction of oysters in the wind farms is required to kickstart the development of eventually self-sustainable oyster reefs.

Acknowledgements. This work was financed by the Dutch Research Council NWO [grant number 17671 (North Sea ReVIFES)]; and Van Oord Dredging and Marine Contractors. The authors acknowledge Martijn Peters for his support in creating Figure 4.

References

Adams T, Miller RG, Aleynik D, Burrows MT. 2014. Offshore marine renewable energy devices as stepping stones across biogeographical boundaries. *J Appl Ecol* 51: 330–338.

Allison S, Hardy M, Hayward K, Cameron TC, Underwood GJC. 2020. Strongholds of *Ostrea edulis* populations in estuaries in Essex, SE England and their association with traditional oyster aquaculture: evidence to support a MPA designation. *J Mar Biol Assoc U K* 100: 27–36.

Berghahn R, Ruth M. 2005. The disappearance of oysters from the Wadden Sea: a cautionary tale for no-take zones. *Aquat Conserv* 15: 91–104.

Bodoy A, Bougrier S, Geairon P, Garnier J, Boulo V, Heurtebise S. 1991. Does the prevalence of *Bonamia* and *Marteilia* diseases be reduced on flat oysters (*Ostrea edulis*) of Atlantic and Mediterranean origin, when they are reared together with the Japanese oyster (*Crassostrea gigas*) in tidal ponds? *ICES CM* K 28: 1–9

Borsje BW, van Wesenbeeck BK, Dekker F, Paalvast P, Bouma TJ, van Katwijk MM, de Vries MB. 2010. How ecological engineering can serve in coastal protection. *Ecol Eng* 37: 113–122.

Bouma S, Lengkeek W. 2012. Benthic communities on hard substrates of the offshore wind farm Egmond aan Zee (OWEZ) including results of samples collected in scour holes. Report Bureau Waardenburg, 84 pp.

Bulleri F, Chapman MG. 2010. The introduction of coastal infrastructure as a driver of change in marine environments. *J Appl Ecol* 47: 26–35.

Capobianco M, Stive MJF. 2000. Soft intervention technology as a tool for integrated coastal zone management. *J Coast Conserv* 6: 33–40.

Chapman MG, Blockley DJ. 2009. Engineering novel habitats on urban infrastructure to increase intertidal biodiversity. *Oecologia* 161: 625–635.

Christianen MJA, Lengkeek W, Bergsma JH, Coolen JWP, Didderen K, Dorenbosch M, Driessen FMF, Kamermans P, Reuchlin-Hugenholtz E, Sas H, Smaal A, van den Wijngaard KA, van der Have TM. 2018. Return of the native facilitated by the invasive? Population composition, substrate preferences and epibenthic species richness of a recently discovered shellfish reef with native European flat oysters (*Ostrea edulis*) in the North Sea. *Mar Biol Res* 14: 590–597.

Christiansen S. 2009. Towards Good Environmental Status – a network of Marine Protected Areas for the North Sea. Report WWF Gemany, 104 pp.

Coen LD, Luckenbach MW. 2000. Developing success criteria and goals for evaluating oyster reef restoration: ecological function or resource exploitation? *Ecol Eng* 15: 323–343.

Consoli P, Mangano MC, Sarà G, Romeo T, Andaloro F. 2018. The influence of habitat complexity on fish assemblages associated with extractive platforms in the central Mediterranean Sea. *Adv. Oceanogr Limnol* 9: 59–67.

Coolen JWP, van der Weide F BE, Cuperus J, Blomberg M, van Moorsel GWNM, Faasse MA, Bos OG, Degrear S, Lindeboom HJ. 2020. Benthic biodiversity on old platforms, young wind farms and rocky reefs. *ICES J Mar Sci* 77: 1250–1265.

Coombes MA, Naylor LA, Thompson RC, Roast SD, Gómez-Pujol L, Fairhurst RL. 2011. Colonisation and weathering of engineering materials by marine microorganisms: an SEM study. *Earth Surf Process Landf* 36: 582–593.

Crain CM, Bertness MD. 2006. Ecosystemengineering across environmental gradients: implications for conservation and management. *Bioscience* 56: 211–218.

Cuadrado-Rica H, Sebaibi N, Boutouil M, Boudart B. 2016. Properties of ordinary concretes incorporating crushed queen scallop shells. *Mater Struct* 49: 1805–1816.

Dafforn KA, Glasby TM, Airoldi L, Rivero NK, Mayer-Pinto M, Johnston EL. 2015a. Marine urbanisation: an ecological framework for designing multifunctional artificial structures. *Front Ecol Environ* 13: 82–90.

Dafforn KA, Mayer-Pinto M, Morris RL, Waltham NJ. 2015b. Application of management tools to integrate ecological principles with the design of marine infrastructure. *J Environ Manage* 158: 61–73.

Davis N, Van Blaricom GM, Dayton PK. 1982. Man-made structures on marine sediments: effects on adjacent benthic communities. *Mar Biol* 70: 295–303.

DEFRA. 2005. Charting Progress. An Integrated Assessment of the State of the UK Seas, London, 120 pp.

Degraer S, Carey DA, Coolen JWP, Hutchison ZL, Kerckhof F, Rumes B, Vanaverbeke J. 2020. Offshore wind farm artificial reefs affect ecosystem structure and functioning. *Oceanography* 33: 48–57.

De Vooys C, Dapper R, Van der Meer F J, Lavaleye M, Lindeboom H. 2004. Het macrobenthos op het Nederlands Continentale Plat in de Noordzee in de periode 1870–1914 en een poging tot vergelijking met de situatie in de periode 1970–2000. Report Koninklijk Nederlands Instituut voor Onderzoek der Zee, 79 pp.

De Vriend HJ, van Koningsveld M, Aarninkhof SGJ, de Vries MB, Baptist MJ. 2015. Sustainable hydraulic engineering through building with nature. *J Hydro-environ Res* 9: 159–171.

Didderen K, Bergsma JH, Kamermans P. 2019. Offshore flat oyster pilot Luchterduinen wind farm: Results campaign 2 (July 2019) and lessons learned. Report Bureau Waardenburg 19-184, 48 pp.

Didderen K, Lengkeek W, Bergsma JH, van Dongen U, Driessen FMF, Kamermans P. 2020. WWF and ARK Borkum Reef Ground oyster pilot. Active restoration of native oysters in the North Sea. Monitoring September 2019. Report Bureau Waardenburg 19-227, 40 pp.

Dolmer P. 2000. Algal concentration profiles above mussel beds. *J Sea Res* 43: 113–119.

Domisse W. 2020. Shellfish as a protection of revetments: A case study in the port of Rotterdam. Master thesis Delft University of Technology, The Netherlands, 107 pp.

Dutch Ministry of Economic Affairs and Ministry of Infrastructure and Environment. 2015. National Water Plan 2016-2021, 78 pp.

Dutch Ministry of Economic Affairs and Climate. 2022. Regeling vergunningverlening windenergiegebied Hollandse Kust (west) kavel VI. *Staatscourant* 7107: 16.

Firth LB, Thompson RC, Bohna K, Abbiati M, Airoldi L, Bouma TJ, Bozzeda F, Ceccherelli VU, Colangelo MA, Evans A, Ferrario F, Hanley ME, Hinz H, Hoggart SPG, Jackson JE, Moore P, Morgan EH, Perkol-Finkel S, Skov MW, Strain EM, van Belzen J, Hawkins SJ. 2014. Between a rock and a hard place: Environmental and engineering considerations when designing coastal defence structures. *Coast Eng* 87: 122–135.

Garel E, Camba C, Ferreira Ó, Van Koningsveld M. 2014. Applicability of the “Frame of Reference” approach for environmental monitoring of offshore renewable energy projects. *J Environ Manage* 141: 16–28.

Gault J, O’Hagan AM, Cummins V, Murphy J, Vial T. 2011. Erosion management in inch beach, south west Ireland. *Ocean Coast Manag* 54: 930–942.

Gayer G. 2020. Suspended particulate matter distribution in the North Sea. Available from: http://www.coastalwiki.org/wiki/Suspended_particulate_matter_distribution_in_the_North_Sea

Gerken J, Schmidt A. 2014. Current status of the European oyster (*Ostrea edulis*) and possibilities for restoration in the German North Sea. Report Bundesambt fur Naturschutz, 88 pp.

Gray M, Stromberg PL, Rodmell D. 2016. Changes to fishing practices around the UK as a result of the development of offshore wind farms – Phase 1 (Revised). Report The Crown Estate, 121 pp.

Green DS, Chapman MG, Blockley DJ. 2012. Ecological consequences of the type of rock used in the construction of artificial boulder-fields. *Ecol Eng* 46: 1–10.

Gross F, Smyth J. 1946. The decline of oyster populations. *Nature* 157: 540–542.

Guerra A. 2002. La ostricultura. Técnicas de producción. In: Polanco E. (ed.), Impulso, Desarrollo y Potenciación de la Ostricultura en España. Madrid: Fundación Martín Escudero y Ediciones Mundi Prensa, pp. 70–97.

Guy CI, Smyth D, Roberts D. 2018. The importance of population density and inter-individual distance in conserving the European oyster *Ostrea edulis*. *J Mar Biol Assoc UK* 99: 1–7.

Hidu H, Chapman S, Soule PW. 1975. Cultchless setting of European oysters, *Ostrea edulis*, using polished marble. *Proc Natl Shellfish Ass* 65: 13–14.

Houziaux JS, Kerckhof F, Degrendele K, Roche M, Norro A. 2008. The Hinder banks: yet an important area for the Belgian marine biodiversity? Belgian Science Policy, Scientific support plan for as sustainable development policy (SPSD II), Final Report, Research contract n° EV/36/45: 259 pp

Jiménez JA, Osorio A, Marino-Tapia I, Davidson M, Medina R, Kroon A, Archetti R, Ciavola P, Aarnikhof S. 2007. Beach recreation planning using video-derived coastal state indicators. *Coast Eng* 54: 507–521.

Kamermans P, Walles B, Kraan M, van Duren L, Kleissen F, van der Have T, Smaal AC, Poelman M. 2018. Offshore wind farms as potential locations for flat oyster (*Ostrea edulis*) restoration in the Dutch North Sea. *Sustainability* 10, 3942.

Kamphausen L, Jensen A, Hawkins L. 2010. Unusually high proportion of males in a collapsing population of commercially fished oysters (*Ostrea edulis*) in the Solent, United Kingdom. *J Shellfish Re*s 30: 217–222.

Kennedy RJ, Roberts D. 2006. Commercial oyster stocks as a potential source of larvae in the regeneration of *Ostrea edulis* in Strangford Lough, Northern Ireland. *J Mar Biol Assoc UK* 86: 153–159.

King SE, Lester JN. 1995. The value of salt-marsh as a sea protection. *Mar Pollut Bull* 30: 180–189.

Korringa P. 1940. Experiments and observations on swarming, pelagic life and setting in the European flat oyster, *Ostrea edulis* L. PhD thesis University of Amsterdam, the Netherlands, 249 pp.

Korringa P. 1946. A revival of natural oyster beds? *Nature* 158: 586–587.

Korringa P. 1952. Recent advances in oyster biology. *Q Rev Biol* 27: 339–365.

Laboyrie P, van Koningsveld M, Aarninkhof S, Van Parys M, Lee M, Jensen AAC, Kolman R (Eds.). 2018. Dredging for Sustainable Infrastructure. CEDA, The Netherlands, 336 pp.

Lamberti A, Zanuttigh B. 2005. An integrated approach to beach management in Lido di Dante, Italy. *Estuar Coast Shelf Sci* 62: 441–451.

Lapointe L, Bourget E. 1999. Influence of substratum heterogeneity scales and complexity on a temperate epibenthic marine community. *Mar Ecol Prog Ser* 189: 159–170.

Lee AJ. 1980. North Sea: physical oceanography. In: Banner FT, Collins MB, Massie KS (Eds.), The North-West European Shelf Seas: The Sea Bed and the Sea in Motion, Vol. II. Elsevier, Amsterdam, pp. 467–493.

Lengkeek W, Didderen K, Teunis M, Driessen FMF, Coolen JWP, Bos OG, Vergouwen SA, Raaijmakers T, de Vries MB, van Koningsveld M. 2017. Eco-friendly design of scour protection: potential enhancement of ecological functioning in offshore wind farms—Towards an implementation guide and experimental set-up. Report Bureau Waardenburg 17-001, 98 pp.

Lindeboom HJ, Kouwenhoven HJ, Bergman MJN, Bouma S, Brasseur S, Daan R, Fijn RC, de Haan D, Dirksen S, van Hal R, Hille Ris Lambers R, ter Hofstede R, Krijgsveld KL, Leopold M, Scheidat M. 2011. Short-term ecological effects of an offshore wind farm in the Dutch coastal zone; a compilation. *Environ Res Lett* 6: 035101–13.

Lown AE, Hepburn LJ, Heywood JL, Cameron TC. 2021. European native oysters and associated species richness in the presence of non-native species in a southern North Sea estuary complex. *Conserv Sci Pract* 3: e361.

MacKenzie CL. 1970. Causes of oyster spat mortality conditions of oyster setting beds and recommendations for oyster bed management. *Proc Natl Shellfish Ass* 60: 59–67.

Mann R, Powell EN. 2007. Why oyster restoration goals in the Chesapeake Bay are not and probably cannot be achieved. *J Sea Res* 26: 905–917.

Martin D, Bertasi F, Colangelo MA, de Vries M, Frost M, Hawkins SJ, Macpherson E, Moschella PS, Satta MP, Thompson RC, Ceccherelli VU. 2005. Ecological impact of coastal defence structures on sediments and mobile infauna: evaluating and forecasting consequences of unavoidable modifications of native habitats. *Coast Eng* 52: 1027–1051.

Merk V, Colsoul B, Pogoda B. 2020. Return of the native: survival, growth and condition of European oysters reintroduced to German offshore waters. *Aquat Conserv* 30: 2180–2190.

Millican P, Helm M. 1994. Effects of nutrition on larvae production in the European flat oyster, *Ostrea edulis*. *Aquaculture* 123: 83–94.

Ministerie van Infrastructuur en Waterstaat en Ministerie van LNV [Min. IenW & Min. LNV]. 2018. Marine Strategy (part 1): update of current environmental status, good environmental status, environmental targets and indicators; 2018-2024, The Hague, 268 pp.

Newell RIE. 2004. Ecosystem influences of natural and cultivated populations of suspension-feeding bivalve mollusks: a review. *J Shellfish Res* 23: 51–61.

Olsen OT. 1883. The Piscatorial Atlas of the North Sea, English and St. George's Channels, Illustrating the Fishing Ports, Boats, Gear, Species of Fish (How, Where, and When Caught), and Other Information Concerning Fish and Fisheries. Taylor and Francis, London, 50 pp.

Petersen JK, Malm T. 2006. Offshore windmill farms: Threats to or possibilities for the marine environment. *Ambio* 35: 75–80.

Pogoda B, Buck B, Hagen W. 2011. Growth performance and condition of oysters (Crassostrea gigas and *Ostrea edulis*) farmed in an offshore environment (North Sea, Germany). *Aquaculture* 319: 484–492.

Pogoda B, Brown J, Hancock B, Preston J, Pouvreau S, Kamermans P, Sanderson W, von Nordheim H. 2019. The Native Oyster Restoration Alliance (NORA) and the Berlin Oyster Recommendation: bringing back a key ecosystem engineer by developing and supporting best practice in Europe. *Aquat Living Resour* 32: 13.

Potet M, Fabien A, Chaudemanche S, Sebaibi N, Guillet T, Gachelin S, Cochet H, Boutouil M, Pouvreau S. 2021. Which concrete substrate suits you? *Ostrea edulis* larval preferences and implications for shellfish restoration in Europe. *Ecol Eng* 162: 106159.

Reiss H, Degraer S, Duineveld GCA, Kroncke I, Aldridge J, Craeymeersch J, Eggleton JD, Hillewaert H, Lavaleye MSS, Moll A, Pohlmann T, Rachor E, Robertson M, vanden Berghe E, van Hoey G, Rees HL. 2010. Spatial patterns of infauna, epifauna, and demersal fish communities in the North Sea. *ICES J Mar Sci* 67: 278–293.

Rodriguez-Perez A, Sanderson WG, Møller LF, Henry TB, James M. 2020. Return to sender: The influence of larval behaviour on the distribution and settlement of the European oyster *Ostrea edulis*. *Aquat Conserv* 30: 2116–2132.

Rodriguez-Perez A, James MA, Sanderson WG. 2021. A small step or a giant leap: Accounting for settlement delay and dispersal in restoration planning. *PLoS ONE* 16: e 0256369.

Sas H, Didderen K, van der Have T, Kamermans P, van den Wijngaard K, Reuchlin E. 2019. Recommendations for flat oyster restoration in the North Sea. Report ARK/WWF, 34 pp.

Scyphers SB, Powers SP, Heck KL, Byron D. 2009. Oyster reefs as natural breakwaters mitigate shoreline loss and facilitate fisheries. *Plos ONE* 6: e22396.

Schulte DM, Burke RP, Lipcius RN. 2009. Unprecedented restoration of a native oyster metapopulation. *Science* 325: 1124–1128.

Schutter M, Tonk L, Kamermans P, Kardinaal E, ter Hofstede R. 2021. EcoScour project Borssele V – Outplacement methods of European flat oysters. Report Bureau Waardenburg 21-328, 62 pp.

Smaal AC, Kamermans P, van der Have F T, Engelsma M, Sas HJW. 2015. Feasibility of Flat Oyster (*Ostrea edulis* L.) restoration in the Dutch part of the North Sea. Report IMARES Wageningen UR C028/15, 58 pp.

Smaal A, Kamermans P, Kleissen F, van Duren L. 2017. Flat oysters on offshore wind farms. Report Wageningen Marine Research C052/17, 54 pp.

Smyth D, Mahon AM, Roberts D, Kregting L. 2018. Settlement of *Ostrea edulis* is determined by the availability of hard substrata rather than by its nature: Implications for stock recovery and restoration of the European oyster. *Aquat Conserv* 28: 662–671.

Soniat TM, Broadhurst RC, Haywood EL. 1991. Alternatives to clamshell as cultch for oysters, and the use of gypsum for the production of cultchless oysters. *J Shellfish Res* 10: 405–410.

Sumer B, Fredsøe J. 2002. The Mechanics of Scour in the Marine Environment. *Adv Ser Ocean Eng* 17: 536.

Sutherland J, Thomas I. 2011. The management of Pevensey shingle barrier. *Ocean Coast Manag* 54: 919–929.

Swann L. 2008. The use of living shorelines to mitigate the effects of storm events on Dauphin Island, Alabama, USA. *Am Fish Soc Symp* 64: 47–57.

ter Hofstede R, Hiddink JG, Rijnsdorp AD. 2010. Regional warming changes the species richness of marine fish in the eastern North Atlantic Ocean. *Mar Ecol Prog Ser* 414: 1–9.

ter Hofstede R, Driessen F, Elzinga J, Van Koningsveld M, Schutter M. 2022. Offshore wind farms contribute to epibenthic biodiversity in the North Sea. *J Sea Res* 185: 102229.

Thorpe SA. 2012. On the biological connectivity of oil and gas platforms in the North Sea. *Mar Pollut Bull* 64: 2770–2781.

Todorova V, Micu D, Klisurow L. 2009. Unique oyster reef discovered in the Bulgarian Black Sea. *C R Acad Bulg Sci* 62: 871–874.

Tonk L, Witte S, Kamermans P. 2020. Flat oyster (*Ostrea edulis*) settlement on scour protection material. Report Wageningen Marine Research C063/20, 56 pp.

Van den Brink AM, Maathuis M, Kamermans P. 2020. Optimization of off-bottom spat collectors for restoration and production of the European flat oyster (*Ostrea edulis*) in Dutch coastal waters. *Aquat Conserv* 30: 2087–2100.

Van Duren LA, Gittenberger A, Smaal AC, van Koningsveld M, Osinga R, Cado van der Lelij JA, de Vries MB. 2016. Rijke riffen in de Noordzee: Verkenning naar het stimuleren van natuurlijke riffen en gebruik van kunstmatig hard substraat. Report Deltares 1221293-000-ZKS-009, 82 pp.

Van Koningsveld M. 2003. Matching Specialist Knowledge with End User Needs. PhD Thesis University of Twente, The Netherlands, 173 pp.

Van Koningsveld M, Mulder JPM. 2004. Sustainable Coastal Policy Developments in The Netherlands. A systematic approach revealed. *J Coast Res* 20: 375–385.

Van Koningsveld M (Ed.), Verheij HJ, Taneja P, De Vriend HJ. 2021. Ports and Waterways – Navigating the changing world. Textbook Delft University of Technology, The Netherlands, Revision no. 1284, 513 pp.

Van Velzen B, Raaijmakers T, Mattieu J. 2014. Scour protection GEMINI Offshore Wind Farm. Report Deltares. Unpublished.

Walles B, Troost K, van den Ende D, Nieuwhof S, Smaal AC, Ysebaert T. 2016. From artificial structures to self-sustaining oyster reefs. *J Sea Res* 108: 1–9.

Waterman RE. 2010. Integrated coastal policy via Building With Nature. PhD-thesis Delft University of Technology, the Netherlands, 74 pp.

Cite this article as: ter Hofstede R, Williams G, van Koningsveld M. 2023. The potential impact of human interventions at different scales in offshore wind farms to promote flat oyster *(Ostrea edulis)* reef development in the southern North Sea. *Aquat. Living Resour.* 36: 4