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Review

Beneath the blades: Marine wind farms support parts of local biodiversity - a systematic review

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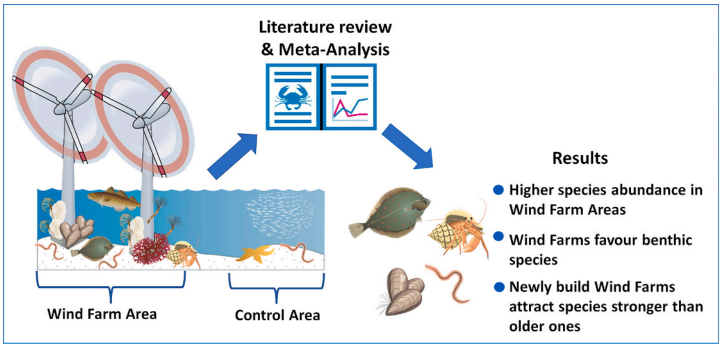
HIGHLIGHTS

- There is higher species abundance in wind farm areas compared to control sites.
- The difference is stronger in newly-constructed wind farms.
- Wind farm areas favour soft-bottom invertebrates and demersal fish species.
- Long-term studies with unified methods are needed for future reference.

GRAPHICAL ABSTRACT



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ABSTRACT

Offshore wind energy developments in European waters are rapidly expanding to meet the increasing global demand for renewable energy. These developments provide new substrates for species colonisation, but also introduce changes in electromagnetic fields, noise levels, and hydrological conditions. Understanding how these man-made structures affect marine biodiversity across various species groups is crucial, yet our knowledge in this field remains incomplete. In this synthesis paper, based on 14 case studies conducted in northeastern Atlantic (North, Irish and Baltic seas), we aggregated species-level data on abundance, biomass, and other quantity proxies spanning the entire food chain from invertebrates to mammals, and compared these variables between wind farms and nearby control sites. Overall, our analysis revealed that in wind farm areas, species tend to occur at higher quantities than in control areas. Additionally, we noticed a slight trend where the positive effect of wind farms was more pronounced in newly established ones, gradually diminishing as wind farms aged. None of the tested covariates (depth, distance from coastline, years in commission) nor species' characteristics (habitat and spawning types, trophic level) showed statistical significance. When examining species groups individually, there was a tendency for wind farm areas to harbour higher quantities of polychaetes, echinoderms and demersal fishes. These findings suggest that wind farms contribute to the so-called reef-effect, providing shelter and food supplies to their inhabitants and acting as no-take-zones. Our results support the idea that wind farms could serve

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as zones of increased local biodiversity, potentially facilitating spillover effects to nearby areas for certain species groups. Further studies are necessary to gain a more comprehensive understanding of the adverse effects of wind farms on associated biodiversity, while also exploring avenues to amplify their positive impacts.

1. Introduction

Offshore wind energy developments in European waters are growing rapidly. As of the end of 2021, a total of 57 GW offshore wind farm capacity had been installed worldwide (GWEC, 2022), of which Europe was responsible for 18.1 GW. By 2030, in accordance with the United Nations Sustainable Development Goals, the objective is to significantly boost the proportion of renewable energy in the global energy mix (United Nations, 2018). The European Union alone requires 32 GW of new wind capacity each year until 2030 to achieve its carbon neutrality target by 2050 (GWEC, 2022). This sector of energy production is also highly dynamic, with new solutions for wind farm construction constantly being developed. For example, floating offshore wind farms have the potential to expand rapidly, and old turbines are to be replaced with fewer and larger turbines with higher power ratings (GWEC, 2022). Moreover, the wind farms built are not planned to stay forever: after 20 to 25 years temporary wind farms are planned to be decommissioned (DecomTools, 2024), while the effects of decommission are largely unknown.

The high volume of new artificial structures inevitably affects marine environments and their biodiversity through factors such as electromagnetic fields, noise, changes in hydrological conditions (Wilhelmsson et al., 2006). Alongside various other artificial structures, including oil and gas platforms, ship-wrecks, breakwaters, seawalls, and piers, wind farms contribute to a phenomenon called ‘ocean sprawl’ (Bishop et al., 2017) wherein marine ecosystems increasingly become dominated by man-made structures. In addition to the abiotic environmental changes, the irregular and rough surfaces of the wind farms' submersed parts promote the settlement of sessile organisms, facilitating the establishment of fouling communities (Hixon and Brostoff, 1985; Kerckhof et al., 2010; De Troch et al., 2013). This phenomenon, known as the artificial reef effect, mirrors the zonation patterns observed in adjacent rocky shore communities (Langhamer, 2012).

Submerged artificial structures, after initial biofouling, begin to serve as an important food source and shelter for various other organisms (De Troch et al., 2013). Fouling organisms, alongside other reef inhabitants, alter the local food web, introducing a new food source that was previously absent in the open sea (van Hal et al., 2017). These additional hard substrate habitats often support higher biodiversity and species abundance than the surrounding soft bottom habitats (Langhamer, 2012). Moreover, these habitats serve as additional nursery areas and shelter for attracted fauna (Leonhard and Pedersen, 2005). These positive effects are known to attract a diverse array of species, ranging from fish to invertebrates, present in the nearby areas (Zintzen et al., 2006; Wilhelmsson et al., 2006). The submerged parts of offshore wind turbines can thus be regarded as ‘artificial reefs’ or ‘reef-like structures’ - constructions deliberately deployed to influence processes related to marine life (Bortone and Seaman, 2002). This approach is commonly employed while decommissioning old oil rigs in the framework of the ‘rig-to-reef’ programme, where large submerged structures have proved to generate new underwater habitats that attract marine life and function akin to natural reefs (Macreadie et al., 2011). Although the scientific literature mostly agrees that there is likely to be a positive effect of wind farms on biodiversity, the nature of the effect heavily depends on the location, and the characteristics of the native populations at the time of introducing the artificial reef (Vandendriessche et al., 2015; Degraer et al., 2013; Langhamer, 2012). A comprehensive understanding of the potential ecological consequences of building offshore wind farms requires knowledge not only of the artificial reef effect, but also of the effects on the sand habitats and their inhabitants (van Deurs et al., 2012). This is because changes in soft sediment communities between the turbines often take a long time before the reef effects expand into the sandy space between the turbine rows (Vandendriessche et al., 2015).

These complex processes underscore the need to study the biodiversity effects of offshore wind farms beyond the scope of individual species or populations. Most research on wind farms has focused either on their impact on biodiversity within specific sites (e.g., Bergman et al., 2015; Andersson and Öhman, 2010; Langhamer and Wilhelmsson, 2009), or on particular species and species groups (e.g., Ruebens et al., 2013, Vallejo et al., 2017, Russell et al., 2016), whereas there is a lack of more comprehensive studies focusing on community changes in wind farm areas on a broader scale. The most comprehensive study to date is a meta-analysis by Methratta and Dardick (2019), studying the impact of artificial reefs on finfish abundance. Overall, the authors found a higher abundance of finfish within wind farm areas, with these effects being dependent on the bottom type with which species was associated.

The world's most extensive offshore wind farm areas are located in Europe, in the North Sea and adjacent seas (GWEC, 2022). These wind farms boast the distinction of being also the oldest, with their construction dating back to 1991 (e.g., Vindeby wind farm, Denmark) (Jensen et al., 2018), affording us the opportunity to observe profound ecosystem changes over time. In this study, we aggregate quantitative data across the food chain, ranging from macrozoobenthos to marine mammals, based on case studies and monitoring programmes. Our objective is to synthesize changes in different species attributes, such as species abundance, biomass, and catch per unit effort (CPUE)), following the wind farm construction. Through this analysis, we aim to delineate species groups that benefit from wind farms and those that do not, and discuss possible ecosystem-wide impacts of these community shifts.

2. Materials and methods

2.1. Literature search

A thorough systematic literature review was conducted to collect the primary data for this synthesis. To evaluate the effect of wind farm structures on associated fauna, we conducted a search in ISI Web of Science Core Collection to identify case studies reporting quantitative proxies of species quantity, including abundance, biomass, and CPUE, of various marine species in wind farm areas and comparable control areas without artificial structures. Our focus was limited to studies conducted in the northern Atlantic, including the North and Baltic seas (Fig. 1). Searches were performed prior to or on April 18th, 2022. The following search query was used in the All-fields search: (windfarm OR “wind farm” OR “wind park” OR “windpark”) AND (macrozoobenthos OR fish OR “marine mammal*”) AND (abundance OR biomass). No restriction was set on the language or publication year of primary studies. As the number of results was not particularly high (447 studies altogether), all identified papers were subjected to full-text and reference review, during which the eligibility of the identified studies was evaluated, and possible additional studies were searched for (including reports, such as Lancester et al. (2011), for Entec UK Limited, 2011). For a study to be considered in our synthesis, species-specific data on abundance, biomass or CPUE, along with respective sample sizes, for both the studied wind farm area as well as a control area had to be reported. We additionally extracted data on wind farm commission years, distances from shore, and depths of the studied areas. To minimise any search-related biases, we deliberately used only search queries that were strictly neutral concerning the focal questions of our synthesis. The search resulted in a total of 14 eligible studies (Table 1), which had been performed at 11 different wind parks.

2.2. Species traits

We did not impose any limitations on species selection, and thus a wide range of species groups were included in our synthesis. The majority of the species represented benthic or sessile fauna (e.g. benthic: hermit crabs, crabs, flatfishes, polychaetes; and sessile: barnacles, mussels, hydrozoans). The species list also included seabirds, as well as marine mammals and pelagic fish species. All species were assigned to a trait group on the basis of their trophic level, life history, reproductive behaviour and habitat type (benthic, demersal or pelagic). Trait information was gathered from two scientific online databases: Fishbase.org (Froese and Pauly, 2000) and sealifebase.org (Palomares and Pauly, 2023).

The trophic level estimations for each species (Table S1, SI) were generated using the methodology outlined by Raoux et al. (2017) with the Ecopath with Ecosim (EwE) software. This methodology was developed to simulate the potential impact of wind farm construction and operation on the trophic webs of the associated ecosystem. In principle, the model consists of two components: one that builds a snapshot of ecosystem functioning and another that simulates its dynamic evolution over time. Specifically, ecological network analysis (ENA) indices were calculated for the "before" and "after" periods to compare network functioning and the overall structural properties of the

Table 1
The list of articles, studied wind farms, their location and available data.

Reference	Wind farm	Location	Measure
Andersson and Öhman (2010)	Utgrunden	Baltic Sea	Mean abundance
Stenberg et al. (2015)	Horns Rev. 1	North Sea	CPUE
Ruebens et al. (2013)	Thornton Bank	North Sea	CPUE
Griffin et al. (2016)	Walney Offshore	Irish Sea	Mean abundance
Hvidt et al. (2006)	Nysted and Horns Rev. 1	North Sea	Total biomass and total abundance
Wilhelmsson et al. (2006)	Utgrunden	Baltic sea	Mean abundance
Lancester et al. (2011)	Teesside	North Sea	Number per catch
Langhamer (2010)	Lysekil Research Site	North Sea	Average biomass
Wilhelmsson and Malm (2008)	Utgrunden	Baltic Sea	Average biomass
Langhamer and Wilhelmsson (2009)	Lysekil Research Site	North Sea	Mean abundance
Atalah et al. (2013)	Arklow Bank	Irish Sea	Mean abundance
Coates et al. (2016)	Bligh Bank	North Sea	Mean abundance
Bergman et al. (2015)	OWEZ	North Sea	Mean abundance
Vallejo et al. (2017)	Robin Rigg	Irish Sea	Total abundance

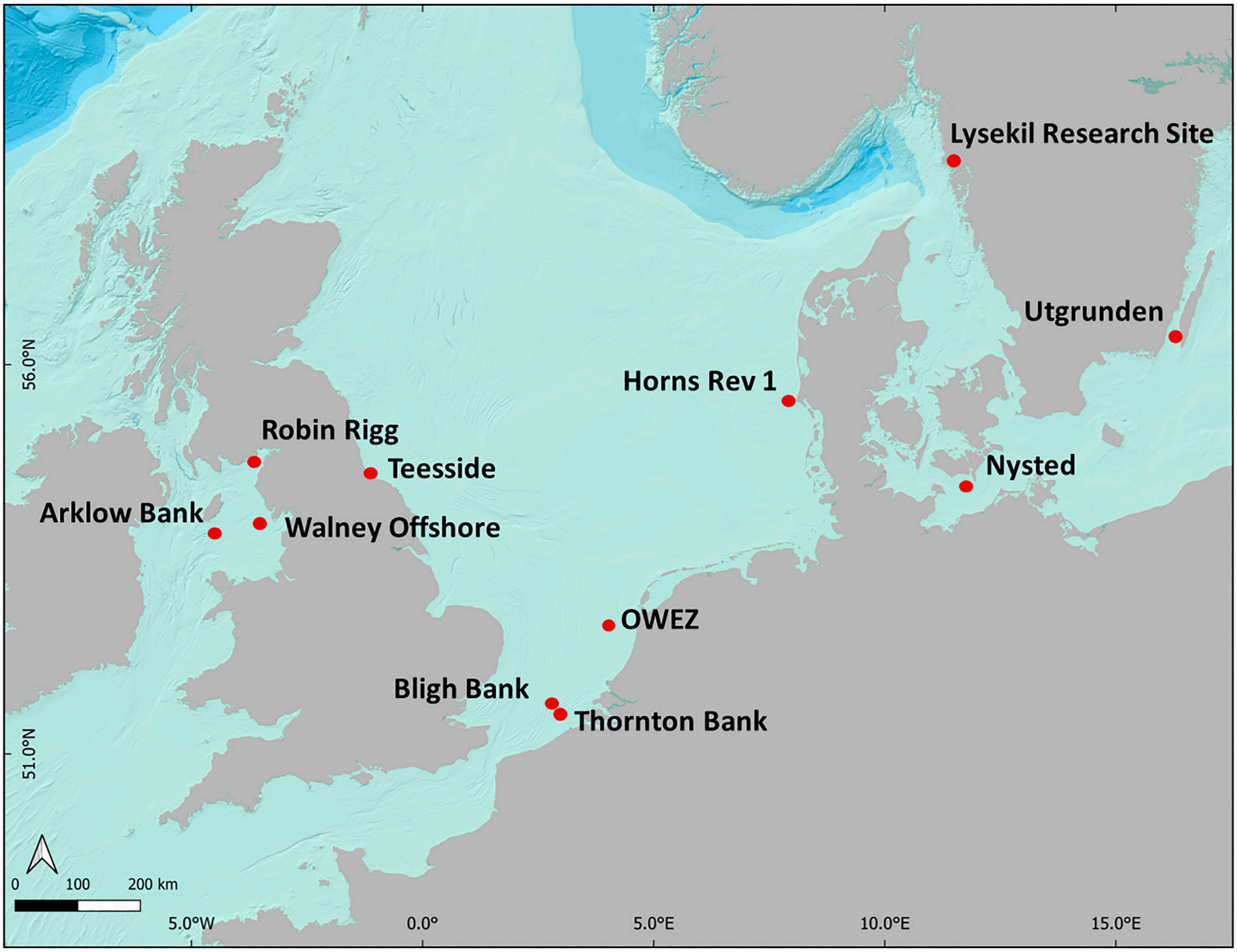

Fig. 1. Map depicting the position of the wind farms investigated in the case studies. Edited by Kai Pfennings.

food web. The model is parameterised with biomasses, production-to-biomass ratios, consumption-to-biomass ratios, and a diet matrix, which establishes the interactions between predators and prey in the ecosystem. We have utilised these projected trophic level values as a reference for the trophic levels of organisms in the present study.

2.3. Data handling and analyses

Based on the original data of 14 articles, we created the main data sheet (Table S1, SI), which contains the species name and taxonomic affiliation, values of species quantity (abundance, biomass, CPUE) and respective sample sizes in wind farm and control areas, species' ecological traits, and details of the sampling and study area. Each row in the data sheet represents a response variable per one species within a single sampling event, e.g., line 51 should be read as follows: during 2011 (two years after wind farm commission) autumn sampling event in Bligh Bank, *Asbjornsenia pygmaea* were collected from 9 sampling sites in the wind farm area and 18 sites from the control area. This resulted in a mean abundance of 4 (SE = 3) animals in the wind farm area and 17 (SE = 4) animals in the control area (Coates et al., 2016). Each data row is considered an individual observation from this point onwards.

In the used articles, different response variables (total biomass, average biomass, number per catch, mean abundance, total abundance, CPUE) were used to describe the measures of species quantity in the study areas. All these variables (Table 2) are common measures of species quantity in marine biodiversity assessments and community studies. There is no bias expected based on the used variables, since all these estimates, although gathered with different methodologies, measure either weight or number of the animals (Table 2).

Different quantity-related variables were used in concert to compare wind farm areas to the control. Producing a single common quantitative effect-size metric to compare species quantities in wind farm and control areas was not attempted, as this (if at all possible) would have involved a high level of subjectivity due to the fact that variables were obtained using different methodological backgrounds. Instead, we opted for a simple and straightforward approach, largely corresponding to a sign test with proper random effects. This had the additional benefit of being able to incorporate studies that did not (fully) report variability in their estimates. More precisely, the response variable was coded 1 when the particular species had been recorded in larger quantities in the wind farm area, and 0 when it occurred in larger quantities in the control area. A random effect was also included in the model, with each study-year combination having an independent value and contributing a different random-effect level. The effect of wind farms was then tested with a binomial mixed model (with the test for the model intercept).

Table 2
Description of the used variables.

Used variable	Description of the variable	Used in
Total biomass	The total weight of organisms or an organism group in a given area	Hvidt et al., 2006
Average biomass	The average weight of a specific organism group within a given area	Hvidt et al., 2006; Langhamer, 2010; Wilhelmsson and Malm, 2008
Number per catch	Number of individuals within a specific group per gear deployment	Lancester et al., 2011
Total abundance	Total number of observed individuals from a specific group in a given area	Vallejo et al., 2017
Mean abundance	The mean number of observed individuals from a specific group in a given area	Griffin et al., 2016; Wilhelmsson et al., 2006; Langhamer and Wilhelmsson, 2009; Atalah et al., 2013; Coates et al., 2016; Bergman et al., 2015;
Total abundance	Number of observed individuals within a predefined area	Andersson and Öhman, 2010
Catch per unit effort	The number of fish caught by an amount of effort	Stenberg et al., 2015; Ruebens et al., 2013

At the next step, study-level covariates (depth, distance, years in commission) were added to the model, firstly as linear and then also as second-order polynomial effects.

All models were fitted using the lme4 package in R (Bates et al., 2015; R Core Team, 2021).

3. Results

Based on the 14 case studies, 319 species-level responses were retrieved, with a single response representing species quantity in the wind farm vs. control area within a single sampling event. The collected dataset encompassed data on 124 species in 11 taxonomic classes, from invertebrates to mammals. The most commonly studied species groups were benthic fish, polychaetes, and crustaceans.

3.1. The effect of wind farms on overall quantity of species

In the intercept-only model, a net positive effect of wind farms on overall quantity-related variables was detected (estimate = 0.454, SE = 0.147, z = 3.09, $p = 0.002$), which remained statistically significant regardless of the model composition (in terms of added covariates). In other words, species tended to occur in greater quantities in wind farm areas compared to control areas. None of the study-level covariates were significant, neither linearly nor when included as second-order polynomials.

When using only data from the commission year (i.e., commission year = 0), the positive effect of wind farms on species quantity remained marginally non-significant (estimate = 1.29, SE = 0.68, z = 1.89, $p = 0.059$). Nevertheless, there is a perceivable trend that, as wind farms age, the overall quantity of animals in the wind farm areas becomes more similar to that of control areas (i.e., closer to 50/50), implying that in newly established wind farms (years_from_commision = 0), the positive effect (attractiveness to animals) may be more pronounced (Fig. 2).

3.2. The effect of wind farms on species groups

When evaluating the wind farm effect on species quantity by species groups, no statistically significant effects were detected. This can be primarily attributed to the high within-group heterogeneity of the wind farm effects and low sample sizes. The most notable difference between wind farm and control areas was found in demersal fishes ($p = 0.07$). In Table 3, we provide the raw counts of positive and negative responses, corresponding to the relative frequencies of species occurring in larger quantities in wind farm area vs. those occurring in larger quantities in control areas, across different taxonomic and functional groups. Notably, among echinoderms, polychaetes, and fishes, the majority of species occurred in greater quantities in wind farm areas. Among different functional groups of fishes, a similar trend is discernible in demersal and nesting fishes, whereas in pelagic fishes, our species tend to occur in greater quantities in control areas.

4. Discussion

Both positive and negative effects on marine organisms occur at offshore wind farms (Methratta and Dardick, 2019). In our review, we have focused on synthesising case studies that have compared different measures of species quantity (like biomass, CPUE, abundance) of marine animals in wind farm areas with those in control areas (i.e., comparable areas without artificial structures). In our synthesis, spanning animal groups from benthic invertebrates to marine mammals, and despite a conservative statistical approach, we saw that wind farm areas generally harbour larger quantities of animals than nearby control areas. Man-made underwater structures have been described as attracting

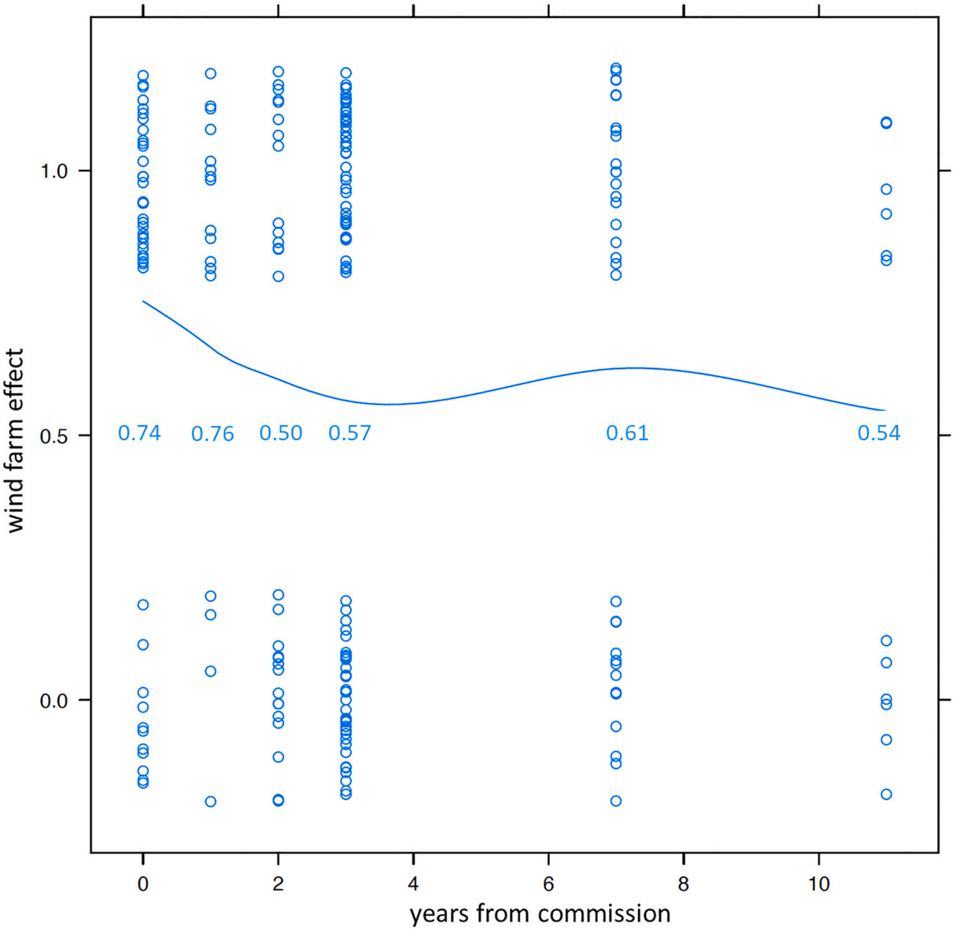

Fig. 2. Change in the wind farm effect on species' quantity over the years following commissioning. Each point represents a binary response variable, measured at the species level within a single sampling event in a given year after commissioning, and is coded as 1 when the species occurred in greater quantity in the wind farm area, and 0 when in the control area. For visual clarity, the points are shifted away from each other along the y-axis Proportions of ones are numerically displayed, with the values >0.5 representing situations where species was more common in wind farm areas. The line represents the moving average.

different groups of species in various case studies focusing on oil rigs, wind farms or pipelines (De Mesel et al., 2015; Nall et al., 2017; Dannheim et al., 2020), suggesting that artificial structures are rapidly colonised by various organisms, mainly sessile invertebrate fauna (the so-called reef effect). Often, this increase in sessile species also attracts higher trophic level predators like fish and seabirds (Wilhelmsson et al., 2006; Ruebens et al., 2013; Vallejo et al., 2017). However, none of the case studies have investigated these effects throughout the entire trophic chain of marine ecosystems.

It is important to highlight that many stressors and disturbances, such as electromagnetic fields (Öhman et al., 2007) and noise (Katsaprakakis, 2012) accompany the building and operation of wind farm structures, and these factors can have an effect on animals' physiology, behaviour, and possibly fitness. Wind farm areas have been described as the stepping stones of epibenthic non-indigenous species (NIS) (De Mesel et al., 2015), with well-studied negative impacts on species of conservation value (Degraer et al., 2020). In addition, increased shipping activities due to the wind farm servicing vessels could enhance the colonisation by NIS (Dannheim et al., 2020). Several open questions concerning artificial structures and their influences on marine ecosystems need to be answered in order to comprehensively understand the impact of wind farms on marine ecosystems (Dannheim et al., 2020), as such, one should not interpret the higher overall quantities of animals in wind farm areas as an entirely positive effect.

Our results indicate that as wind farms age, their species quantities tend to converge towards those observed in control areas. In these terms we would like to highlight that our study consisted of a variety of species from invertebrates to marine mammals, in which indeed the first years of colonisations presented the strongest effect. Nevertheless, this does not necessarily hold true for all species. For example, Kristensen et al. (2017) demonstrated that, in the case of Atlantic cod, positive reef effects may persist for years after reef deployment. The results of our synthesis suggest that the initial attraction effect of newly established wind farms on animals is particularly strong, implying a phased colonisation process for new habitats, where the first wave of pioneers is especially prominent. Also, Degraer et al. (2013) have described the subtidal community of macrozoobenthic animals on wind turbine foundations, predominantly establishing during the first two years following the introduction of substrates into the marine environment. It appears that following the commission, animals actively colonise wind farms and occupy vacant niches, but it may take 10 years or longer for this effect to level out (Kerckhof et al., 2019). Different waves of colonisation have also been described previously. For example, Todd et al. (2020) described a pioneer wave of fish and invertebrate colonisation before and one year after establishment of a new offshore petroleum platform in the North Sea. Another study (Todd et al., 2020) reported a new colonisation wave taking place two years after commission. This study delineated a notable difference between the first and second waves of colonisation, wherein the second wave of motile colonisers exhibited greater species diversity (compared to the pioneering community) and more balanced representation of species across different trophic levels (Todd et al., 2020). In the case studies included in our review, the

Table 3

Relative frequencies of species occurring in larger quantities in wind farm areas versus those occurring in larger quantities in control areas across various taxonomic, phylogenetic, and functional ecological species groups. Note the consistency in the responses of different taxonomic and ecological groups: in all groups but pelagic fishes, species tend to occur in larger quantities in wind farm areas.

Species group	Variable	Number of observations		Reference
		Higher in wind farm	Higher in control	
Echinodermata	Average biomass	8	0	Coates et al., 2016; Langhamer, 2010; Wilhelmsson and Malm, 2008
Polychaeta	Average biomass	18	7	Coates et al., 2016; Langhamer, 2010; Wilhelmsson and Malm, 2008
	Average abundance	14	6	Coates et al., 2016; Langhamer, 2010; Wilhelmsson and Malm, 2008
Pisces	Total biomass	14	8	Griffin et al., 2016; Stenberg et al., 2015; Atalah et al., 2013; Lancester et al., 2011; Andersson and Öhman, 2010; Langhamer and Wilhelmsson, 2009; Hvidt et al., 2006; Wilhelmsson et al., 2006
	Average abundance	18	12	
	Total abundance	14	7	
	CPUE	17	12	
Demersal fishes	All measures	18	3	Griffin et al., 2016; Stenberg et al., 2015; Ruebens et al., 2013; Lancester et al., 2011; Langhamer and Wilhelmsson, 2009; Hvidt et al., 2006; Wilhelmsson et al., 2006
Pelagic fishes	All measures	1	4	Stenberg et al., 2015; Hvidt et al., 2006
Nesting fishes	All measures	17	9	Griffin et al., 2016; Stenberg et al., 2015; Atalah et al., 2013; Andersson and Öhman, 2010; Langhamer and Wilhelmsson, 2009; Hvidt et al., 2006; Wilhelmsson et al., 2006

maximum time slot that was studied was 11 years. This is a relatively short period of time in the context of marine ecosystem change (Degraer et al., 2020; Geist and Hawkins, 2016). Due to a high yearly and seasonal variation (Degraer et al., 2013), long-term monitoring studies spanning at least a couple of decades would increase our knowledge in this matter.

4.1. *The effects on fishes*

After decades of discussions, debates remain as to whether wind farms are generating new biomass (i.e., serving as source habitats for populations) or merely attracting life from the surrounding areas (De Mesel et al., 2015; Pickering and Whitmarsh, 1997). Nevertheless, the epifaunal community is known to be different in artificial reefs compared to natural ones, in terms of species composition, diversity and biomass (De Mesel et al., 2015). Both scenarios are plausible and not mutually exclusive: the creation of biomass in the vicinity of hard substrates may benefit nearby fish stocks by establishing food-webs, thereby enhancing abundance and diversity. Alternatively, artificial structures might simply attract existing biomass from nearby areas, e.g., for seeking shelter (Stenberg et al., 2015; Lindeboom et al., 2011). The latter scenario would result in a spatial redistribution in the biocoenosis with a questionable overall positive effect. For example, Bergström et al. (2013) observed increased densities of all studied piscivores at smaller spatial scales. They hypothesised that the effect is probably attributable mainly to local changes in distribution rather than immigration or increased local productivity.

Maritime spatial planning regulations classify offshore wind farm areas primarily as restricted passage and no-take zones, with specific rules varying between countries and regions. For example, Dutch government regulations (Rijkswaterstaat, 2018) prohibit passage for vessels over 24 m in length, with no trawling and anchoring permitted. This effectively designates wind farms as marine protected areas (Coates et al., 2016). Discussions have even emerged regarding the co-location of offshore wind farms and marine protected areas (MPAs) (Ashley et al., 2014).

It is likely that higher quantities of many fish species, especially demersal fish in wind farm areas, as suggested by our synthesis, could also at least partly be attributed to restricted fishing and shipping activities, since fishing activity in OWF areas is generally disallowed (although exceptions exist) (Schupp et al., 2021). Increases in biomass and generally healthier populations have also been reported for two benthic fish species, turbot (*Scophthalmus maximus*) and European flounder (*Platichthys flesus*), within a large no-take-zone in the Baltic Sea (Florin et al., 2013). Moreover, the no-take-zone had older individuals, a lower length-at-age, and a more balanced sex ratio. Similarly, Coates et al. (2016) documented larger individuals of plaice (*Pleuronectes platessa*) and turbot (*S. maximus*) within the Bligh Bank offshore wind farm, suggesting a refuge effect due to the prohibition of fishing activities. We propose that future studies should account for variations in restrictive regulations (such as fishing and shipping) among different wind farms to better inform management and policy-making regarding wind farms.

In our review, seven case studies measured the abundance of demersal (bottom-dwelling) fishes. goldsinny-wrasse (*Ctenolabrus rupestris*), atlantic cod (*Gadus morhua*), whiting (*Merlangius merlangus*) and pouting (*Trisopterus luscus*) were the species most abundant in wind farm areas. Among these, cod has been described as a species that seeks shelter using manmade underwater structures (Stenberg et al., 2015; Lindeboom et al., 2011). Shelter provided by submersed structures is a possible explanation for why wind farms, compared to control areas, harboured relatively larger quantities of other demersal fish species as well. Similar distribution patterns were discernible in nesting fish. Nesting fish species, constructing nests for spawning and reproduction, are known to favour converted habitats with crevices, cavities and hiding places to safe guard their eggs (Moyle and Cech Jr., 2004). The underwater structures of wind farms evidently provide such habitats.

We may expect that greater quantities of demersal fish species in wind farm areas correlates with larger quantities of mid-trophic level predators (mesopredators) like atlantic cod (*Gadus morhua*), pouting (*Trisopterus luscus*) and whiting (*Merlangius merlangus*), that prey upon smaller animals while being preyed upon by larger predators. Many marine ecosystems are characterized by a few dominant mid-trophic species that channel energy and nutrients from planktonic primary and secondary producers to top predators, thus playing a vital role in regulating ecosystem dynamics (Frederiksen et al., 2006). At the same time, mesopredator dominance is often associated with degraded ecosystems, leading to trophic cascades that exacerbate algal blooms, degrade habitat-forming benthic vegetation, and worsen the effects of eutrophication (Eklöf et al., 2020). The loss of apex predators (marine birds and mammals, but also large size-classes of cod) can result in the proliferation of mid-trophic level predators, which is indicative of an unhealthy ecosystem. This phenomenon, known as mesopredator release, has been observed across a range of degraded communities and ecosystems (Prugh et al., 2009).

Thus, besides the previously described effects, such as no-take-zones and wind farm structures providing shelter, the elevated quantities of demersal fish species (that can be considered as mesopredators) in wind farm areas could also stem from two additional factors:

- First, the effect could potentially result from the loss of apex predators. There is evidence suggesting that the coexistence of apex predators and mesopredators may be facilitated in lower-productivity environments where apex predators may not reach sufficient densities to suppress mesopredators (Linnell and Strand, 2000; Creel, 2001). This scenario is less likely in the North and Baltic Seas, which are known for their high productivity; therefore, the loss of apex predators (especially seals and harbour porpoise) could contribute to the abundance of mesopredators (smaller Atlantic cod, Whiting, etc.).

  In our synthesis, we found too few suitable case studies to thoroughly test the hypothesis regarding the impact of apex predators. Nevertheless, Vallejo et al. (2017) provided evidence of a significant reduction in the relative abundance of harbour porpoises both within and around the Robin Rigg offshore wind farm, particularly during its construction phase. The authors discuss that such short-term displacement is most likely resulting from increased levels of anthropogenic noise due to pile driving during the construction phase. In contrast, Lindeboom et al. (2011) reported more porpoise (*Phocoena phocoena*) clicks inside the offshore wind farm compared to the control areas outside the farm, presumably due to higher overall biodiversity. Several bird species were observed to avoid the wind farm in their study, whereas Vallejo et al. (2017) did not find any effects to relative abundance of common guillemot (*Uria aalge*). These contrasting findings suggest that more research focusing on offshore wind farm effects on apex predators (e.g., quantity, behaviour, health) is needed to reveal possible shifts in ecosystem trophic levels and to improve predator management in an increasingly occupied maritime environment. Mesopredator outbreaks are known to cause high ecological, economic, and social costs around the world (Prugh et al., 2009). Yet, comprehending the intricate interactions between apex and mesopredators can be exceptionally challenging, as replicating the full suite of influences exerted by apex predators on mesopredators is inherently complex (Prugh et al., 2009).
- Second, the relatively higher quantities of demersal fish species in wind farm areas could be due to anthropogenic habitat alterations. Similar phenomena have been observed in urban settings by Larivière (2004) and Prange and Gehrt (2004), where an increase in mesopredator abundance was associated with enhanced food availability rather than the absence of apex predators. Urbanisation often leads to habitat fragmentation, a trend mirrored in wind farms, where the sandy sea bed is disturbed by the presence of wind turbines and associated structures. These structures harbour numerous marine primary and secondary producers, providing abundant food resources and shelter for organisms across trophic levels, including mesopredators.

The abundance of demersal mesopredators is likely the combination of all above mentioned effects: wind farms acting as no-take zones, providing shelter, loss of apex predators and the effect of anthropogenic habitat change.

4.2. *The effects on invertebrates*

For our review, we were able to identify three case-studies that measured the relative abundance of echinoderms and polychaetes in wind farm areas. Among echinoderms, the most abundant species in windfarm areas, compared to the control non-wind farm areas, were brittle stars (*Amphiura filiformis*) and yellow sea potatos (*Echinocardium flavescens*); among polychaetes, these were *Aonides paucibranchiata*, *Glycera* spp., *Ophelia borealis*, *Spio* spp., *Spiophanes bombyx*, and representatives of the Terebellidae family. Exceptionally, the bristle worm *Nephtys cirrosa* was uniformly more abundant in control areas. *N. cirrosa* typically inhabits clean and muddy sand banks and coastal areas, and occasionally, silty muddy soils. However, it tends to avoid strong surf areas (Hartmann-Schröder, 1996), similar to the turbulence generated by underwater structures of wind turbines. The latter factor could explain the lower relative quantity of this species in wind farm areas. Other invertebrate groups examined in the primary studies included bivalves, crustaceans, poriferans, gastropods, cnidarians and annelids. However, either the number of such observations was insufficient for a meaningful discussion, or there was no discernible difference between wind farm and control areas (see Table S1 in SI for detailed data).

Consistent with Langhamer (2010), our findings indicate that, overall, soft-bottom macrofauna in no-take wind farm areas is more abundant than in the control sites. Soft-bottom macrofauna, such as clams, worms, and crustaceans, inhabit the seafloor and burrow into sediments, thus forming an important link between sediments and the water column (HELCOM, 2018). Bottom (beam) trawling has affected macrobenthic assemblages for decades, especially delicate and long-lived species (Coates et al., 2016), such as polychaete species in the Terebellidae family. With bottom trawling prohibited in many offshore wind farms, such areas provide unique opportunities to investigate the potential of recovery of vulnerable macrozoobenthic species. Moreover, as wind farms continue to expand in the future (United Nations, 2018), the likely increase of dense Terebellidae patches (e.g., *Lanice conchilega* reefs) within the no-take zones could serve as ecologically important large-scale refugia for higher trophic levels as well (Coates et al., 2016; De Smet et al., 2015). This includes demersal fish species (Bergström et al., 2013, Kaiser et al., 2002, Petersen and Malm, 2006), which rely on amphipods, decapods, mysids and polychaetes as their primary prey (Vandendriessche et al., 2013). By providing undisturbed habitats, these biotopes within offshore wind farms have the potential to enhance food availability, benefitting the whole ecosystem. Finally, one should also consider the extension of the reef effect into the surrounding soft-bottom areas, known as the spillover effect. For example, Vandendriessche et al. (2015) have described observations of lobsters on the soft sediments, suggesting that the reef effect generated by the wind turbines expanding into the sandy habitats in between the turbines.

In summary, the predominantly positive impact of wind farms on macrozoobenthos is likely a result of the absence of bottom trawling rather than the reef-effect, as there was no positive effect of wind farms on substrate-dependent bivalve species. However, it also cannot be excluded that the reef effect may require more time to emerge than has been available within the timeframe of current case studies. This conclusion is supported by the study of Wilhelmsson and Malm (2008), which compared the assemblage composition of epibiota and motile invertebrates on wind farm monopile structures to natural underwater boulders. Their findings revealed significantly lower species richness and Shannon–Wiener diversity on the wind power plants. While turbines seemed to enhance the biomass of some species, particularly filter feeders, others, such as algae and some bivalves, were largely missing on the monopiles. Consequently, these artificial substrates could not be considered substitutes for natural hard substrates (Wilhelmsson and Malm, 2008).

5. Conclusions

Offshore wind parks in European waters are expanding rapidly (GWEC, 2022), and there is an urgent need for information on their effects on marine ecosystems. Despite being assessed in several case studies, many large-scale questions remain unanswered, and at the same time the extent and technical characteristics of wind parks are constantly changing. Our synthesis provides evidence to a number of aspects:

- Wind park effects can be positive for at least some animal groups. Our synthesis revealed a trend wherein demersal fish species appear to be especially attracted by wind farms; many macrozoobenthic species may also benefit from wind farms as protected no-take areas. Nevertheless, the fact that we see larger abundance of some species in the vicinity of wind farms does not necessarily mean that such structures are overall beneficial in marine ecosystem contexts. Therefore, it is crucial to emphasize that any positive effect of wind farms highlighted in this review should be considered within the broader context.

- The data regarding the impact of wind farms on many groups of animals, including apex predators, are still notably scarce. Moreover, while assessing the impact of wind farms on population dynamics is crucial, there is still a large knowledge gap of their effects on various other aspects of animal life, such as their physiological and behavioural performance within wind farm areas.
- More practically, there is need for more applied studies focusing on strengthening of the positive effects of offshore wind farms and exploring the consequences of decommissioning outdated wind farms. For a better understanding of the intricate effects of wind farms on marine ecosystems, and to improve the quality of decision -making, we advocate for an emphasis on long-term monitoring studies. Similar to Methratta and Dardick (2019) we highlight the need for regional, national, and international collaboration on monitoring approaches and data sharing.
- Finally, wind parks are managed in various ways with regard to shipping, fishing, and other activities. These aspects may strongly affect the suitability of wind parks for different taxonomic and functional groups. Current data are too scarce to account for such effects in this synthesis, but they deserve to be considered in future studies.

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CRediT authorship contribution statement

Alexander H. Knorrn: Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Tiit Teder:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Ants Kaasik:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Randel Kreitsberg:** Conceptualization, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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