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Original Article

Offshore wind farms affect the spatial distribution pattern of plaice *Pleuronectes platessa* at both the turbine and wind farm scale

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We investigated how the distribution of plaice *Pleuronectes platessa*, a typical soft-sediment fish species, has been affected by the introduction of hard substrate [turbines and scour protection layer (SPL)] at both turbine and wind farm scale in two Belgian offshore wind farms (OWFs). Diving transects (40 m) at 11 monopiles revealed four times higher plaice abundances on the sandy patches of the SPL (average radius 16.5 m) compared to the surrounding sand. We suggest that the configuration of the SPL, i.e. an open rock field, offering increased food and shelter opportunities, with sandy patches in between, facilitating the natural burrowing behaviour of plaice, forms the basis for the increased plaice abundances at the turbine scale. At the wind farm scale, beam trawl catches in between the turbines and in reference zones revealed significantly increased plaice abundances in one OWF, which suggests that wind farms can act as refuge areas for plaice, at least under specific conditions. Differences in environmental conditions, turbine foundation type, and surrounding fishing pressure may explain the equivocal findings between both OWFs, whereas low statistical power could have hampered the detection of general refuge effects. Next to the integration of different spatial scales (turbine/wind farm) within one study, longer-term monitoring and including extra life history parameters (e.g. length and sex ratio) might enhance the detectability of potential refuge effects.

Keywords: artificial reef, BACI, fisheries exclusion, North Sea, plaice, scour protection layer.

Introduction

Offshore wind farms (OWFs) are proliferating to meet the increasing demands for renewable energy. The introduction of artificial structures (turbines, scour protection, and cables) in soft-sediment areas can influence species distribution patterns directly through attraction to or avoidance of these structures (the so-called artificial reef effect), and indirectly through the fisheries exclusion effect (Bohnsack and Sutherland, 1985; Lindeboom *et al*., 2015; Stenberg *et al*., 2015; Gill *et al*., 2020; Mooney *et al*., 2020; van Berkel *et al*., 2020).

Hard structures related to OWFs are rapidly colonized by fouling communities, which, in turn, attract various fish species and epibenthic organisms that profit from the increased forage and shelter opportunities (Leonhard and Pedersen, 2006; Wilhelmsson *et al*., 2006; Degraer *et al*., 2020). Higher densities of benthopelagic fish and large invertebrates have been observed around hard substrates in different European wind farms, e.g. cod *Gadus morhua* (Reubens *et al*., 2013a), edible crab *Cancer pagurus*, and European lobster *Homarus gammarus* (Krone *et al*., 2017).

In most European wind farms, vessel movements are restricted due to safety considerations, except for maintenance and scientific research purposes. As a consequence, no fisheries activities are allowed within OWFs, making them essentially no-take zones, which creates opportunities for fish and crustacean species that experience high fishing pressure (Ashley *et al*., 2014; Coates *et al*., 2016). Studies regarding Marine Protected Areas (MPAs) have shown that fisheries exclusion can affect fish distribution patterns through increased local fish densities and spillover effects in adjacent areas (Guidetti *et al*., 2014). Spatial food web models calculated that up to 7% higher catches were to be expected near a wind farm in the extended Bay of Seine (Halouani *et al*., 2020), while a spillover effect for plaice was demonstrated in the field for some Belgian wind farms (De Backer *et al*., 2019).

So far, most studies that looked at the effects of OWFs on fish have concentrated on hard substrate-associated species (Reubens *et al*., 2013a; Krone *et al*., 2017). The consequences for soft-sediment species, such as flatfish, are less studied (Vandendriessche *et al*., 2015). Since flatfish spend the majority of their life in close contact with the seabed, their spatial distribution response to the introduction of artificial hard substrates might differ from that of (bentho)pelagic fish species (Wilber *et al*., 2018). A number of studies found no attraction of flatfish towards the scour protection layer (SPL) (Krone *et al*., 2017; van Hal *et al*., 2017) and no clear positive nor negative effects at the wind farm level (Lindeboom *et al*., 2011; Stenberg *et al*., 2015; Wilber *et al*., 2018). However, these studies might have missed an effect, as refuge effects are often only observed after a prolonged period (> 5 years) (Babcock *et al*., 2010; De Backer *et al*., 2020).

Within the Belgian part of the North Sea (BPNS), a weak attraction of plaice was found in the C-Power wind farm

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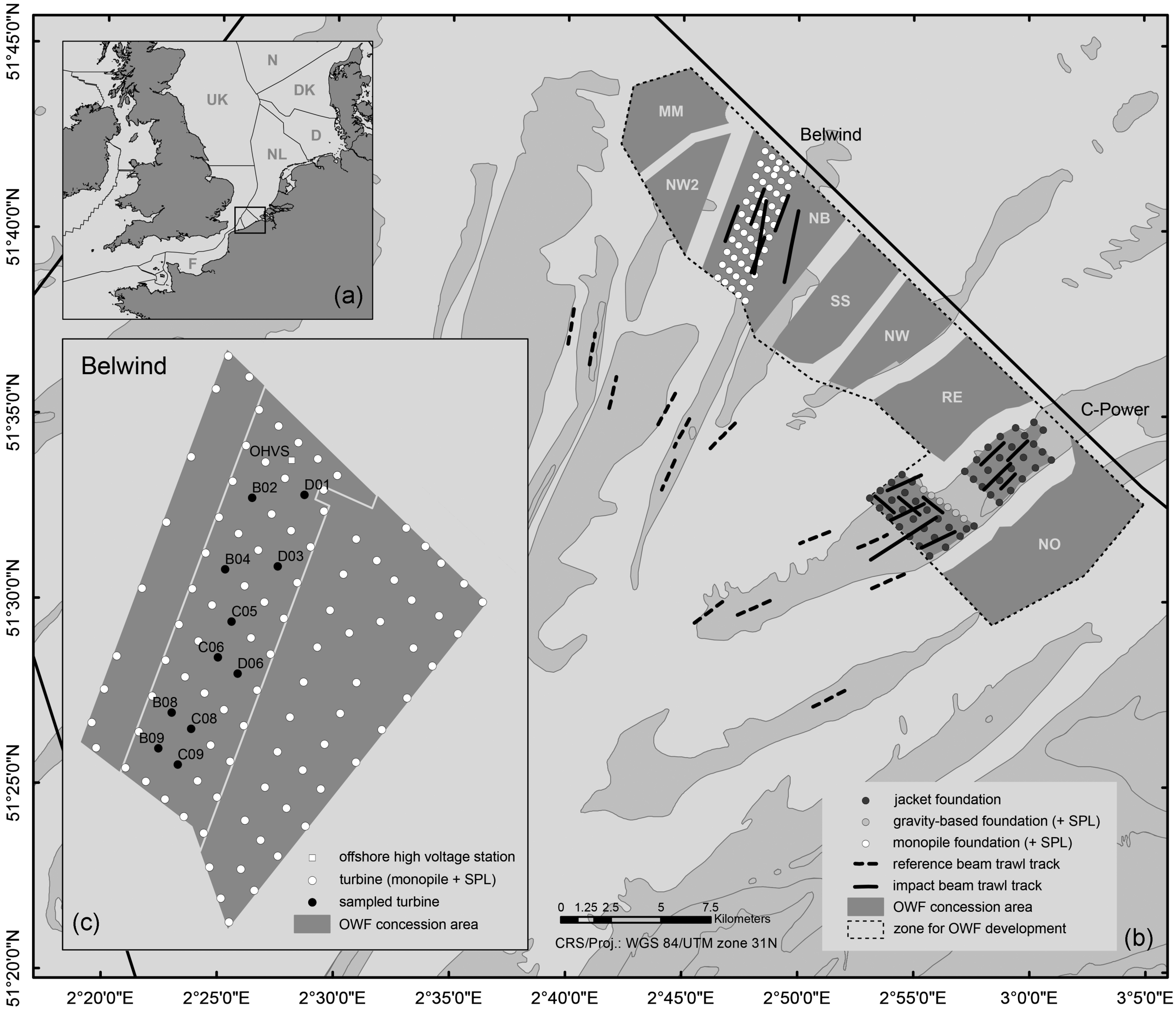

Figure 1. (a) Map indicating the location of the BPNS. (b) Sampling design used at the wind farm scale, showing the beam trawl tracks in the impact and reference sites for C-Power and Belwind; the other OWF concessions are also shown [NO: Norther (2019), RE: Rentel (2018), NW: Northwind (2014), SS: Seastar (2020), NB: Nobelwind (2017), NW2: Northwester 2 (2020), MM: Mermaid (2020)]. (c) Map of the Belwind OWF, highlighting the turbines where the diving transects were conducted to investigate the turbine scale patterns.

with higher densities at a distance of ∼ 200 m from the turbines compared to the control areas (De Backer *et al.*, 2020). Additionally, Derweduwen *et al.*, (2016) showed that the diet of dab *Limanda limanda* in the same wind farm clearly differed from the control areas. Furthermore, numerous plaice individuals were observed by divers between the rocks of the SPL in the Belgian Belwind wind farm (J. Reubens, pers. comm.). These findings suggest that the attraction of soft sediment-associated fish species might occur at both the wind farm scale and the much smaller turbine scale.

In this study, we investigated the spatial distribution patterns of plaice *Pleuronectes platessa*, a commercially important flatfish species, in two Belgian offshore wind farms at two spatial scales, i.e. the turbine and wind farm scale. We hypothesized that plaice is attracted at both spatial scales by the presence of hard substrate in the form of turbines and their surrounding SPL, and due to the exclusion of fisheries.

Material and methods

Study area

In 2004, a 238 km^2 zone was designated for the production of renewable energy in the eastern part of the BPNS along the Dutch EEZ-border, and nine OWF concessions (in total 2.26 GW) have been granted since (Maes *et al.*, 2005; Rumes and Brabant, 2020) (Figure 1). Our study focused on the oldest OWF concessions, namely C-Power and Belwind. Construction of C-Power on the Thorntonbank started in 2007 at a distance of 27–30 km from the shore at water depths of 14–28 m. The pilot phase finished by the end of 2008 and consisted of six gravity-based turbines (GBFs, 5 MW Senvion) surrounded by an SPL to prevent erosion of the sand due to changed current patterns (Sumer and Fredsøe, 2001). The second and third phases of C-Power were carried out between 2010 and 2013, with 48 turbines (6.15 MW Senvion) being installed on jacket foundations without surrounding scour protection, as currents can pass freely through the foundation structures

Table 1. Overview of construction start and fisheries closure at the different Belgian concession areas.

Wind farm	Start of sustained fisheries closure	Comments	Start construction	First power generated
C-Power phase 1	02/08	6 GBFs (+ 500m safety buffer)	05/08	01/09
Belwind	06/09		09/09	01/11
C-Power phase 2 and 3	01/11	Both zone A and B	04/11	09/13
NW	01/13		04/13	05/14
NB	02/16	South and north of Belwind	05/16	12/17
RE	04/17		07/17	01/19
NO	05/18		08/18	05/19
NW2	04/19		07/19	05/20
Seamade (MM + SS)	06/19	SS + MM concession areas	09/19	11/20

The area closed for fishing corresponds with the concession area (500 m of safety buffer around the turbines) for each wind farm, except for the first phase of C-Power. Corridors between two closed areas are also closed for shipping and fisheries activities.

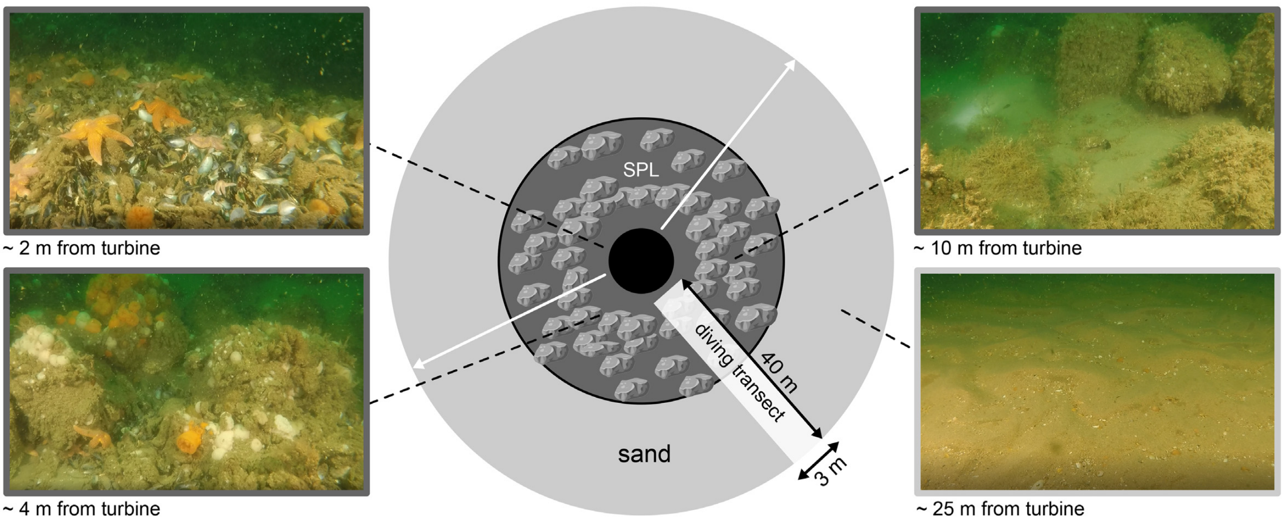

Figure 2. Schematic representation of the diving transects around the wind turbines in the Belwind OWF. The black circle in the middle represents the monopile; the dark grey band represents the SPL (radius of ∼16.5 m starting from the monopile) consisting of a visible armoured rock layer with sand patches in between the rocks. The number and density of rocks is higher close to the turbines and gradually decreases towards the sandy area (light grey band without rocks) directly surrounding the SPL. In the first meters right next to the turbines, almost no rocks are present as well. White arrows indicate potential transect lines conducted by the divers during one dive. The white rectangle shows a schematic representation of a diving transect of 40 by 3 m. Pictures (©Film Johan Devolder) show the typical habitat at the indicated locations.

(Colson *et al.*, 2017). Fishing activities were suspended around the six GBFs (+ 500m safety zone) in February 2008, while the rest of the concession zone was closed off in January 2011 (Table 1). The construction of the Belwind OWF started in September 2009 (fisheries exclusion from June 2009) and this OWF has been operational since 2010. Belwind is located on the Bligh Bank (46–52 km off the coast, 15–37 m water depth) and consists of 56 monopile turbines [55 Vestas (3 MW); 1 Haliade (6 MW, 2013)], all surrounded by an SPL with a radius of ∼16.5 m from the monopile. The SPL in the Belwind wind farm exists of a filter layer of smaller rocks with an armoured layer of larger rocks on top ($D_{50} = 0.37$ m, solid rock density = 2.65 ton m^{-3}). In most locations (especially farther from the turbines), sandy patches are present in between the rocks of the armoured layer due to sedimentation and the relatively low density of rocks.

Field sampling and data availability

Turbine-scale distribution patterns

To study whether plaice is attracted to the scour protection surrounding the wind turbines, 21 visual diving transects (each of length 40 m) crossing both the SPL and the surrounding open sand were conducted in the Belwind concession zone (Figure 2). This wind farm was chosen due to the higher visibility and water transparency, and the presence of an SPL around all turbines. Moreover, in contrast to C-Power, Belwind consists entirely of monopiles, which is the most commonly used foundation type in European OWFs (WindEurope, 2021).

Between June and August 2019, the presence of plaice was surveyed by divers around 11 randomly chosen turbines, each completely surrounded by other turbines to avoid fringe effects (Figure 1c). Depending on the prevailing conditions, such as visibility and current speed, one to three transects in different directions from the turbine could be covered within each dive (3 transects: turbine D1 and C6; 2 transects: turbines B2, B4, C8, C9, D3, and D6; 1 transect: turbines B8, B9, and C5). Two divers descended along the turbine, secured a measuring tape at the bottom of the monopile and started swimming in a straight line away from the turbine. A fixed distance of 40 m was covered during each transect to standardize the data, covering both the SPL (a combination of the rock armour layer and sandy patches in between the rocks) and the open sand

Table 2. Number of impact/reference beam trawl samples taken for each offshore wind farm over the entire study period.

Year	C-Power		Belwind	
	Impact	Reference	Impact	Reference
2004	2	3	–	–
2005	4	4	–	–
2006	1	1	–	–
2007	1	1	–	–
2008	4	4	3	6
2009	3	4	2	5
2010	4	4	–	7
2011	–	1	4	6
2012	6	4	4	6
2013	4	4	4	6
2014	2	4	2	2
2015	–	–	–	–
2016	4	4	2	3
2017	4	4	3	6
2018	4	4	4	7
2019	4	4	4	7
Total	47	50	32	61

The horizontal dashed lines indicate the before/after construction period for each wind farm.

directly surrounding the SPL (Figure 2). One diver visually scanned the area for plaice at both sides of the measuring tape (covering a width of ∼3 m), while the other diver filmed the transect with a GoPro camera. When a plaice individual was visually identified, the habitat (SPL or surrounding open sand) and its distance to the turbine were noted on a waterproof writing board. Water temperature, visibility, and transect direction were also logged for each transect. The end of the SPL (and thus the distinction between the two habitat types) was defined as the point where no rocks were present anymore over a distance of ∼2 m on the transect. The searched area per habitat type was calculated for each transect as

$$\text{Searched area SPL} = \text{length of the SPL} * \text{width of the transect } (\pm 3\,\text{m}),$$

$$\text{Searched area surrounding open sand} = (\text{total length of transect} - \text{length of SPL}) * \text{width of the transect } (\pm 3\,\text{m}).$$

Both the total searched area and the total number of plaice were then calculated per turbine by taking the sum of the searched area and the number of observed plaice per habitat type over all the transects.

Wind farm-scale distribution patterns

To investigate the wind farm-scale distribution patterns of plaice, beam trawl sampling was performed in autumn during the yearly environmental monitoring campaigns of the WinMon.BE-programme. Data from similar BACI-designs were used for the period 2004–2019 for C-Power and 2008–2019 for Belwind (Table 2). Beam trawl samples were taken in September–November within the concession areas and at reference locations with comparable environmental conditions both before and after the installation of the turbines (Figure 1). For a complete overview of the "before-construction" sampling design, the reader is referred to Vandendriessche *et al.*, (2015). Although the six gravity-based turbines in C-Power were already operational in 2009, for this study, we considered all data up till 2010 as "before construction" since the beam trawl tracks were located farther away from these six turbines and were as such not considered to be (or at least little) affected by the first construction phase. For Belwind, the construction phase ended in February 2010, i.e. after our sampling survey of 2009. Over the entire study period, the sampling design was adapted in relation to wind farm accessibility (e.g. restricted access during construction), weather conditions, and research vessel availability (e.g. no samples in 2015 due to the unavailability of the RV Belgica). Sampling was conducted with an 8-m beam trawl equipped with a shrimp net (22 mm in the cod end) and a bolder-chain. Until 2009, the net had been towed at an average speed of four knots during 30 min over ∼ 2 NM, after which this was reduced to 15 min over ∼ 1 NM, due to the limitations of the OWF design. Comparative studies in the BPNS and Australia did not find any significant effects of beam trawl tow duration on catch rates of individual species, which suggests that standardized results are comparable over the years (Rotherham *et al.*, 2008; Derweduwen *et al.*, 2010). Once on board, catches were sorted and processed and all fish individuals were identified, measured, and counted at species level. For this study, we only used the data on plaice abundances for further analyses.

Statistical analyses

To check whether there was a turbine-scale effect due to the presence of an SPL on plaice abundance, a general linear mixed model (GLMM) with a Poisson distribution was fitted, with the number of plaice individuals as the response variable and habitat type (SPL/sand) as a fixed effect. Turbine was included in the model as a random effect to take into account the nested nature of the design. A log-transformed offset variable, based on the searched area per habitat type, was added to correct for the variation in sampling effort. The final fitted model was

$$\text{Number of plaice} \sim \text{offset}(\log(\text{area searched})) + \text{f}(\text{habitat type}) + (1|\text{f}(\text{turbine})).$$

Further, mean densities of plaice over all the transects were calculated for each 4 m-segment of the standardized 40 m-transect to describe distribution patterns of plaice in function of distance.

The potential wind farm effect on plaice abundance was investigated using a GLMM with a negative binomial distribution. This distribution was chosen over a Poisson distribution to deal with the overdispersion of the data. A three-way interaction between a time factor BA (before/after construction), an impact level factor RI (reference/impacted area), and a wind farm factor WF (C-Power/Belwind) was added as the fixed part of the model. A significant interaction between BA and RI represents a wind farm effect (positive or negative), while a significant three-way interaction indicates that the potential wind farm effect is expressed differently for both wind farms. Two random effects year and station were included in the model to incorporate the nested nature of the sampling design at both temporal and spatial scales. A factor top/gully was added as a random effect as well, as previous studies within this area showed an influence of sampling location on or next to a sandbank on fish abundances (Derweduwen *et al.*, 2010; Vandendriessche *et al.*, 2015). To correct for the differences in sampling effort, the trawled distance was added as a log-

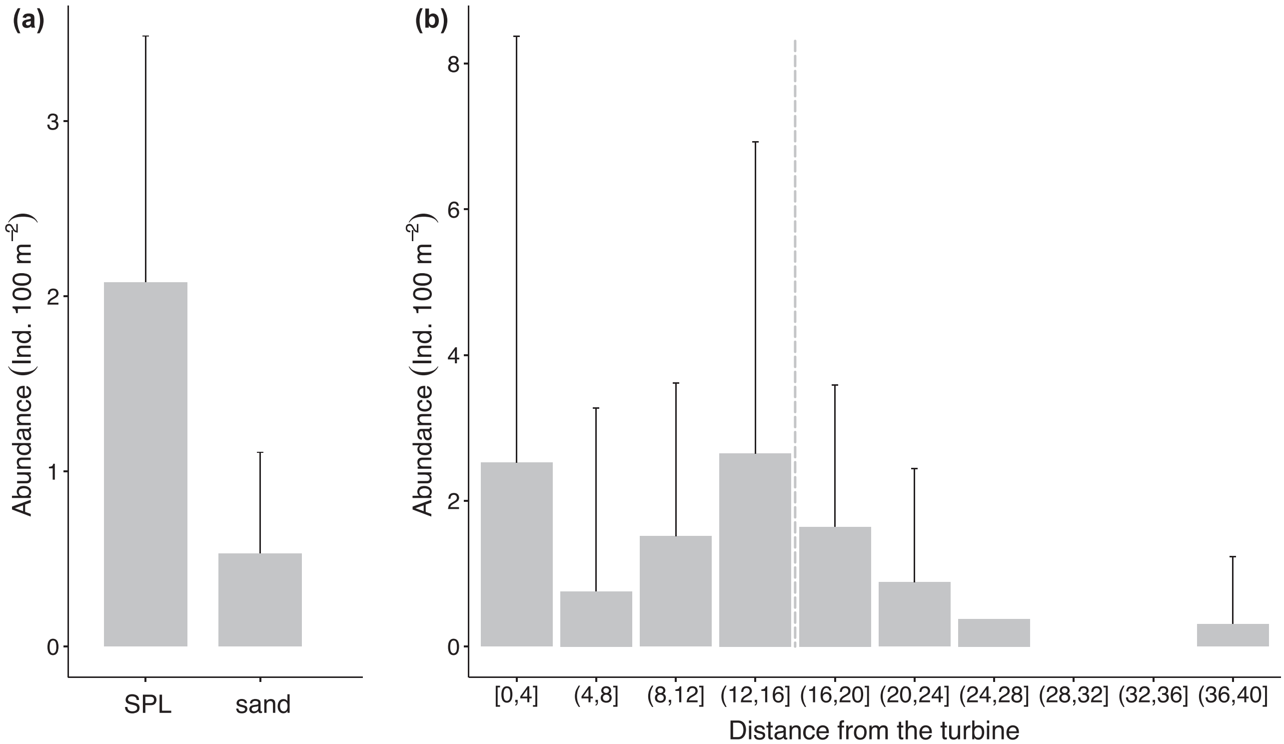

Figure 3. Plaice distribution in the Belwind OWF at the turbine-scale (a) Estimated marginal means for the final GLMM showing the number of plaice per 100 m^2 for both habitat types (SPL = scour protection layer). (b) Plot showing the mean plaice abundances across all diving transects in relation to distance intervals starting from the turbine; the vertical dashed line indicates the average width of the SPL. Error bars show standard deviation values.

transformed offset. The full fitted model was

$$\text{Number of plaice} \sim \text{offset}\left(\log\left(\text{distance trawled}\right)\right) + \text{f}\left(\text{BA}\right) * \text{f}\left(\text{RI}\right) * \text{f}\left(\text{WF}\right) + \left(1|\text{f}\left(\text{top/gully}\right)\right) + \left(1|\text{f}\left(\text{station}\right)\right) + \left(1|\text{f}\left(\text{year}\right)\right).$$

An interaction analysis was conducted based on the pairwise comparisons of the estimated marginal means to test for a wind farm effect for both wind farms separately.

For both models, a thorough model validation based on visual plots of Pearson-residuals was carried out to check if all assumptions for linear regression were met (see Supplementary Material). All data exploration, modelling, and validation was carried out in R version 4.0.3 (R Core team, 2020)).

Results

Turbine-scale distribution patterns

A total of 31 plaice individuals were observed along the transects, of which 23 were spotted within the SPL-habitat (total searched area = 1028 m^2), while only 8 were found on the open sand surrounding the SPL (total searched area = 1436 m^2). The GLMM showed a highly significant effect for *habitat type* ($P = 0.0009$, $Z = -3.32$), whereby four times more individuals were found on the sand in between the rocks of the SPL (2.08 ± 0.55 ind. 100 m^{-2}, 95% confidence interval (CI) (1.24–3.49) compared to the surrounding open sand (0.53 ± 0.20 ind. 100 m^{-2}, 95% *CI* (0.25–1.11) (Figure 3a). Plaice abundances were high right next to the turbine, much lower a few metres farther away, increasing again with distance from the turbine up to the edge of the SPL, after which abundances significantly decreased. The observed numbers of plaice on the surrounding open sand, at distances between 24 and 40 m from the turbine, were much lower (Figure 3b).

Wind farm-scale distribution patterns

A total of 5186 plaice individuals were caught over 190 trawls ($\bar{x}$ = 0.18 ± 0.16 ind. 100 m^{-2}), covering a total trawled area of 3.37 km^2. The GLMM showed a significant three-way interaction (*BA∗RI∗WF*, $P = 0.002$, $Z = -3.06$), mainly explained by a significant difference in wind farm effect (BA∗RI) between both OWFs. For Belwind, no OWF effect was observed (BA∗RI, $P = 0.25$, $Z = 1.16$), with plaice abundances showing relatively similar patterns for reference and impact areas both before and after construction (Figure 4). For C-Power on the other hand, a significant wind farm effect (BA∗RI, $P = 0.0008$, $Z = -3.35$) was observed with 4.5 times higher plaice abundances in impacted samples [0.27 ± 0.09 ind. 100 m^{-2}, 95% *CI* (0.13–0.53)] after the construction compared to before the construction [0.06 ± 0.02 ind. 100 m^{-2}, 95% *CI* (0.03–0.12)] (Figure 4), while no difference in plaice abundance before and after construction was observed for reference samples ($P = 0.13$, $Z = -1.53$). Additionally, there was a significant difference in plaice abundances between reference and impact samples after construction ($P = 0.03$, $Z = 2.22$), while this was not the case in samples before construction ($P = 0.05$, $Z = -1.93$). Actually, this effect reflects a decrease in abundances in reference samples, which was not recorded in impact samples.

Discussion

We investigated the distribution patterns of plaice in the presence of OWFs at both turbine and wind farm spatial scales.

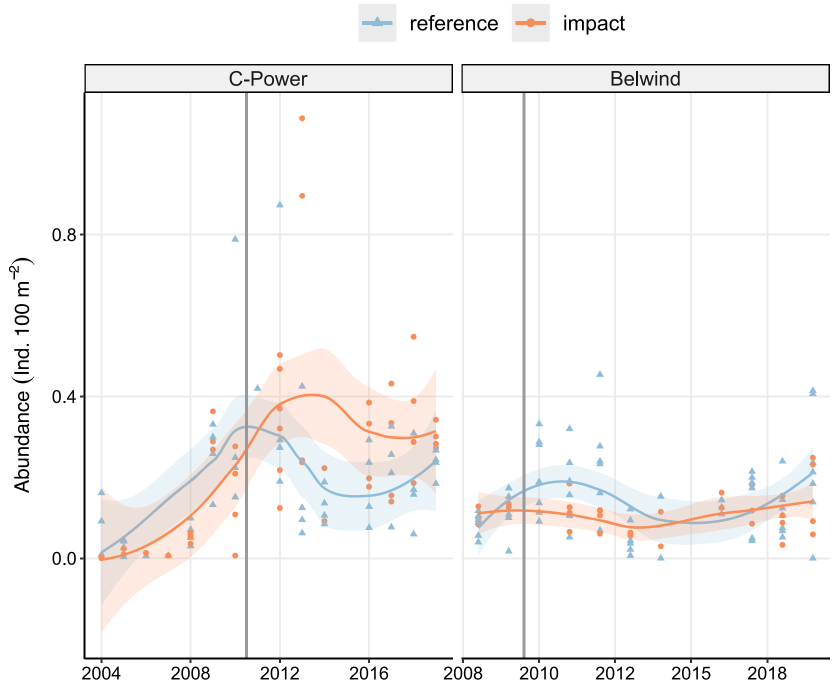

Figure 4. Plaice abundances in beam trawl samples (~ 200m from the turbines) for C-Power and Belwind in reference and impact areas over respectively, the time spans 2004–2019 and 2008–2019. Vertical dark grey lines indicate the BA period as considered in this study, which also coincides with the moment that fisheries activities were suspendend for the second and third phase of C-Power and for the construction of Belwind. The area around the six GBFs in C-Power (first construction phase) was closed in 2008. LOESS-smoothers with a span of 0.7 were fitted to the data to facilitate with the interpretation. Orange and blue bands indicate the standard error 95% *CI* for the impacted and reference areas, respectively.

At the turbine scale, we observed that plaice was attracted towards the sandy patches between the rocks of the SPL surrounding the wind turbines, with four times higher abundances compared to the surrounding open sand system. At the wind farm scale, higher plaice abundances were recorded for one of the two OWFs, indicating that OWFs not only attract hard substrate benthopelagic species, like pouting *Trisopterus luscus* (Reubens *et al.*, 2013b) and edible crab *Cancer pagurus* (Krone *et al.*, 2017), but also soft-sediment demersal species like plaice.

Attraction of plaice to the SPL surrounding the turbine

Man-made structures that are introduced deliberately into soft-sediment marine environments to increase local biodiversity for nature conservation or fisheries management purposes are generally referred to as "artificial reefs" (Bohnsack and Sutherland, 1985; Petersen and Malm, 2006). Although wind turbines, their scour protection and cable toppings are not constructed to serve this particular goal, research has shown that densities of fish and epibenthic invertebrates are higher close to wind farm structures (Degraer *et al.*, 2020). The extent of such an attraction effect is species-specific, but it can generally be observed up to a maximum distance of 100 m from the artificial reef structures with a sharp decline from around 50 m (dos Santos *et al.*, 2010; Reubens *et al.*, 2013a).

In our study, which specifically focused on flatfish, we recorded significantly higher abundances of plaice on the sand between the rocks of the SPL, compared to the surrounding open sand, indicating an attraction towards the SPL habitat. This is in contrast to other studies that did not find indications of an artificial reef effect for flatfish species in OWFs or even suggested avoidance behaviour in relation to the hard substrate (Hinz *et al.*, 2006; Krone *et al.*, 2017; van Hal *et al.*, 2017). This might partly be explained by the fact that their sampling design did not specifically focus on flatfish, whose passive behaviour is different from more active benthopelagic and pelagic species, resulting in a sampling bias (Gibson, 1997).

Apart from the sampling design, the configuration of the SPL seems to be an even more important explanation why we could show an attraction effect for flatfish, while this was not found in other studies. In the Belwind OWF, the rocks of the SPL are sufficiently spread and sedimentation sufficiently high to allow for the (natural) development of sandy patches in between the hard substrate. In contrast to the "open rock fields" observed in Belwind, Krone *et al.*, (2017) described the rocks of the scour protection around the monopiles in the Riffgat wind farm as "closed rock fields". Also, in other European wind farms, such as the Offshore Windpark Egmond aan Zee (OWEZ) (NL) and Horns Rev (DK), much higher densities of rocks without visible sediment patches are shown in video footage and pictures of the SPL (Leonhard and Pedersen, 2006; Lengkeek *et al.*, 2017). Krone *et al.* (2017) already suggested that the amount of rocks making up the scour protection may influence the distribution patterns of soft bottom fauna.

Our results showed that the spatial distribution of plaice is associated with the presence of sandy patches and thus the rock density of the SPL, which supports the idea that SPL configuration is important. High abundances of plaice were found in the immediate surroundings of the turbine where almost no rocks are present. A few metres away from the turbine, the rocks of the armoured layer are closely stacked on top of each other, leaving no patches of sand in between them, and low plaice abundances were observed. With increasing distance from the turbines, the number of rocks decreases until the edge of the SPL merges into natural sandy habitat, corresponding with a gradual increase in plaice abundance up till the edge of the SPL, followed by a decrease when moving farther away from the hard substrate. In conclusion, low abundances of plaice were recorded in areas without rocks and with very high densities of rocks, while higher plaice abundances were found in areas with a lower density of rocks.

The higher plaice abundance on the sandy patches of the SPL can be explained by the presence of shelter and food. The SPL increases the environmental complexity and creates crevices (Bohnsack and Sutherland, 1985), which creates a shelter against currents and predators. Food is another reason, since it has been estimated that the introduction of hard substrates may lead to a 50-fold food increase (Leonhard and Pedersen, 2006). We therefore hypothesize that plaice benefits from the presence of hard substrate in relation to the associated increase in food and shelter, but only if sandy sediments are present to facilitate their natural burrowing behaviour. Additional studies, focusing on the behaviour and diet of plaice may further elucidate the reasons behind the observed attraction for this flatfish species.

Our findings, which demonstrate a flatfish species being present in higher abundances near hard substrates, are supported by Wright *et al.*, (2020), who showed a positive association of plaice in the western North Sea with the presence of oil and gas platforms, while Krone *et al.* (2013) found higher flatfish abundances near a research platform compared to natural soft sediments. Attraction towards an artificial reef island was also observed for marbled flounder *Pseudopleuronectes yokohamae* in Osaka Bay using acoustic telemetry (Mitamura *et al.*, 2021). Following the above-mentioned hypothesis, it is plausible that an attraction effect of flatfish to the hard substrate will appear in other wind farms over time where, up till now, no such effect was registered, at least if sedimentation rates and sinking rates of the rocks are high enough to allow for the formation of sandy patches in between the rocks. From our study, it is not fully clear if plaice uses the SPL only sporadically for foraging and shelter or if they spend longer time periods on the sandy patches in between the hard substrate. Including the use of acoustic telemetry in future studies might help to further elucidate the habitat use of plaice in OWFs (Winter *et al.*, 2010).

The fact that plaice is attracted to the sandy patches in between scour protection might be taken into account in the design of new SPLs in other wind farms. However, other species probably have other needs and so, eventually, choices on which species to attract or protect will have to be made. As this type of discussions have implications for nature conservation, the industry and local fisheries, they should take place already during the OWF design phase and should include as many stakeholders as possible (Gill *et al.*, 2020).

Increased abundances of plaice in between the turbines

Increased plaice abundances were also observed at the wind farm scale for one of the two studied OWFs. As no fisheries activities are allowed within any of the Belgian wind farm concessions due to safety restrictions, it is likely that the soft sediments in between the turbines serve as refuge areas for plaice, at least under specific conditions. Fisheries exclusion zones are widely used in nature conservation and fisheries management plans with the aim of enhancing biodiversity and biomass of certain key species, preferably leading to spillover effects in the surrounding areas (Fenberg *et al.*, 2012; Florin *et al.*, 2013; Abecasis *et al.*, 2014). The location of such fisheries exclusion zones is mostly based on the high intrinsic natural value or the presence of certain key species, which is not really the case for OWFs. Therefore, the potential of OWFs as refuge areas might be lower than for specifically designated areas. Notwithstanding, our study is one of the first to provide evidence that under certain conditions, *de facto* fisheries exclusion areas like OWFs can lead to increased abundances of certain commercial flatfish species.

Other studies that looked at flatfish abundances in between the turbines of OWFs found no significant wind farm effect (Lindeboom *et al.*, 2011; Wilber *et al.*, 2018). The average time for the first detection of a refuge effect on a target species in a fisheries exclusion zone is over 5 years (Babcock *et al.*, 2010). Most probably, the studied period in the mentioned publications was not long enough (<5 years) to detect subtle changes. This highlights the need for long-term monitoring strategies in OWFs.

Our study covered a period of >10 years, showing significantly higher plaice abundances in C-Power after construction. However, also here results were not consistent between both studied OWFs. Other factors might play a role in explaining the observed discrepancy. First of all, fishing pressure in the areas surrounding the OWFs differed. The fisheries exclusion zone surrounding C-Power is larger and has been closed for a longer time period both northwest and southeast of the OWF, related to the construction of the neighbouring Rentel (2017) and Norther (2018) OWFs. Belwind has been surrounded by the Nobelwind concession since 2016, but the construction of other neighbouring OWFs only started in 2019. A VMS (Vessel Monitoring System) analysis showed an increase in fishing effort in the vicinity of Belwind and other more offshore located wind farms in the period 2016–2017 compared to 2006–2007, probably due to fisheries displacement in combination with a potential increase in fish abundances due to spillover effects (De Backer *et al.*, 2019). The combination of higher fishing pressure at the edges and a smaller fishing exclusion area could have counteracted a potential refuge effect in Belwind.

Further, the foundation type and presence of an SPL probably also play an important role. The majority of turbines in C-Power (48) are jacket foundations without SPL, with an additional 6 gravity-based foundations with SPL, while all turbines in Belwind are monopile foundations surrounded by scour protection. The observed turbine-scale attraction towards the sandy patches of the SPL in Belwind may be the result of a displacement of individuals, as such creating fish hot spots near the hard substrate and thereby decreasing the detection probability in beam trawl samples at 200 m from the turbines. The effects at the wind farm scale in Belwind could thus be masked by the more pronounced smaller-scale attraction of plaice towards the scour protection around the turbines.

Apart from the differences in foundation type and fishing pressure, environmental conditions such as depth, sediment composition, turbidity, hydrology, and water temperature also differ between both concession areas in the BPNS, which also influence species distribution and food web interactions (Dannheim *et al.*, 2014). Macrobenthic monitoring within the WinMon.BE program in the same OWFs revealed more pronounced positive effects on the macrobenthic communities in C-Power (Lefaible *et al.*, 2018), corroborating the results observed for plaice in this study.

It remains a challenge to try and capture real refuge effects, as many factors are at play and sampling methods or designs might not be optimal, at least not for all species. Although we have shown that OWFs have the potential to act as refuge areas for plaice, results of this study are inconsistent, while several other studies reported no effects. Not being able to demonstrate an effect, however, does not mean that there is no effect. Moving away from a BACI-design towards a before–after gradient (BAG) design might help to overcome low statistical power in monitoring studies (Methratta, 2020). In the latter design, samples are taken over a distance gradient from the impact site, which has the advantage that no specific control areas need to be identified. As shown in our study, the inclusion of different spatial scales improves our understanding of how OWFs influence species distribution patterns, as refuge effects might be masked by an attraction towards the SPL-habitat (Bergström *et al.*, 2013). Finally, most OWF-studies focused on fish abundances, which are highly variable in space and time, while refuge effects may be more easily identified when looking at other fish life history or population parameters, such as age, fish length, and sex ratio (Miethe *et al.*, 2010; Florin *et al.*, 2013). For example, Di Franco *et al.* (2009) showed that the observed increase in biomass for many target species within a protected area in the Mediterranean was mainly due to an increase in fish size rather than fish abundance.

Conclusion

Our study showed that the presence of OWFs, together with the associated absence of fisheries activities, does affect soft-sediment fish species, *in casu* plaice, at both turbine and wind farm spatial scales. At the turbine scale, we observed higher plaice abundances on the sandy patches of the open-rock SPL habitat. We state that the SPL configuration has an important effect on the attraction and distribution patterns of plaice, especially the presence of sandy patches between the rocks, providing both food and shelter, and facilitating the natural burrowing behaviour of this flatfish species. Future studies should also focus on the diet and behaviour of soft-sediment fish near turbines and scour protection to further elucidate the potential functions of this introduced habitat for such species. Based on acquired scientific knowledge, SPL design could then be optimized to meet the ecological needs of certain target species (e.g. the presence of sand patches between rocks for plaice). However, choices in SPL design equally depend on the targeted species itself, related to different needs concerning habitat configuration and complexity.

At the wind farm scale, we observed increased plaice abundances for one OWF, suggesting that OWFs can act as refuge areas for flatfish. However, factors such as differences in environmental conditions, fishing pressure, and foundation type potentially play an important role as well, as they create specific circumstances that might influence fish species and communities in contrasting ways. Moreover, OWF-related refuge effects are difficult to pick up, due to the high year-to-year variability in fish abundances, compared to the relatively small differences between impact and control sites. Additionally to abundances, we recommend to monitor other fish life history or population parameters such as length, sex ratio, weight, and age to enhance the detection of potential refuge effects. We advise monitoring programs to take into account different spatial scales, as attraction at both turbine and wind farm scales might influence each other, thus creating a bias when focusing on only one scale. Alternative monitoring methods, such as acoustic telemetry, environmental DNA, and the deployment of ROVs can be useful for studying fish behaviour and distribution where traditional methods cannot be used due to safety regulations (Reubens *et al.*, 2013b; Lengkeek *et al.*, 2017; Ruppert *et al.*, 2019; Staehr *et al.*, 2022). The first Belgian wind farm zone of 238 km^2 has been completed in 2020 with nine OWF concessions, with no fisheries activities allowed within this entire area. We expect potential refuge effects to become more pronounced in the near future, enabling a better understanding of the effects of OWFs on fish distribution on an even larger scale.

Supplementary data

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

Data availability statement

All data underlying this article will be shared on reasonable request to the corresponding author. The video footage from the diving transects is owned by third parties and can be shared on request to the corresponding author with permission of the third parties, provided that a correct attribution is given to the authors of the files when they are being used or displayed (only non-commercial purposes, CC BY-NC).

Authors' contributions

JB, KH, SD, and ADB conceived the ideas and developed the methodology. JB, KH, and ADB participated in the data collection. JB analysed the data and wrote the manuscript. KH, SD, and ADB contributed to the original drafts and critically revised the manuscript. This manuscript was submitted with the approval of all the authors.

Conflict of interest statement

The authors declare no conflicts of interest.

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