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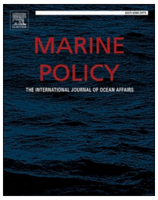

Windfarms, fishing and benthic recovery: Overlaps, risks and opportunities☆

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ABSTRACT

The UK is a leading nation in the development of large offshore wind energy installations (OWFs). Since 2000, the UK has installed 2610 turbines covering over 2000 km^2 of UK seas. As these sites overlap with historic fishing grounds as well as Marine Protected Areas it is important to understand the relationship between the presence of these OWFs and fishing activity to assess the extent to which OWFs could act as *de facto* MPAs with respect to fisheries management, providing other environmental impacts are mitigated. We assessed the extent to which the fishing activity of vessels using bottom-contacting mobile gears (trawls, dredges and demersal seines) were impacted by the construction of 12 offshore windfarms in the UK EEZ. Using publicly available Global Fishing Watch fishing effort data, we found fishing rate from vessels using bottom-towed gear was reduced by 77 % following OWF construction in 11 of the 12 sites studied. A decline in bottom-towed fishing activity was recorded in OWFs where turbines were constructed in a densely aggregated patch, and an increase in fishing activity where turbines were positioned as several distinct aggregated patches within the site. We conclude that bottom-towed fishing activity is affected by turbine layout, with OWFs likely offering some protection to the benthic environment from bottom-towed gear. We suggest this reduction in bottom-towed fishing provides space for co-location opportunities and note that consultations on domestic MPA designations should involve offshore wind stakeholders in terms of OWF 'co-location' with and 'avoidance' of MPAs.

1. Introduction

Offshore wind energy generation offers a vital route to decarbonising the UK's energy supply. Plans are in place in adjacent EU waters to develop 450 GW of energy from renewables by 2050 to meet carbon-neutral targets [1]. The UK Government are calling to increase supply from 10.5 GW to 40 GW by 2030 [2,3]. This 4-fold increase in the amount of power generated by windfarms offshore in order to meet current targets would potentially lead to greater areas of sea being compromised with respect to traditional industrial activity such as fishing – particularly in areas such as the North Sea [4–6] – raising concerns that displacement of fishing activity will further increase pressure on the seabed outside offshore windfarms (OWFs) [7,8]. However, the removal of bottom towed fishing pressures from within the UK's current and planned OWF boundaries could offer protection to some 21,000 km^2 of – albeit altered – seabed[1] [4,5] outside the UK's current Marine Protected Area (MPA) network.

Selecting conservation measures to reduce or ban fishing has historically been complex in offshore EU waters [9], and relies on a 'Joint Recommendation' process whereby fishing states must agree to the conservation measures outlined by the host member state of any MPA. However, the Marine Strategy Framework Directive (MSFD) process has urged ICES to provide advice to member states over the potential to 'trade-off' fishing vs achievement of 'seafloor integrity' at a macro-scale [10]. These developments all point to the potential to close significant areas of seafloor to bottom trawls that go beyond MPA boundaries for

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Abbreviations: MPA, Marine Protected Area; OWF, Offshore windfarm.

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[1] Total area of OWFs that are planned, under construction or active outside existing demersal Marine Protected Areas. Total area of inshore and offshore MPAs derived from JNCC, Natural England, Natural Resources Wales and NatureScot data.

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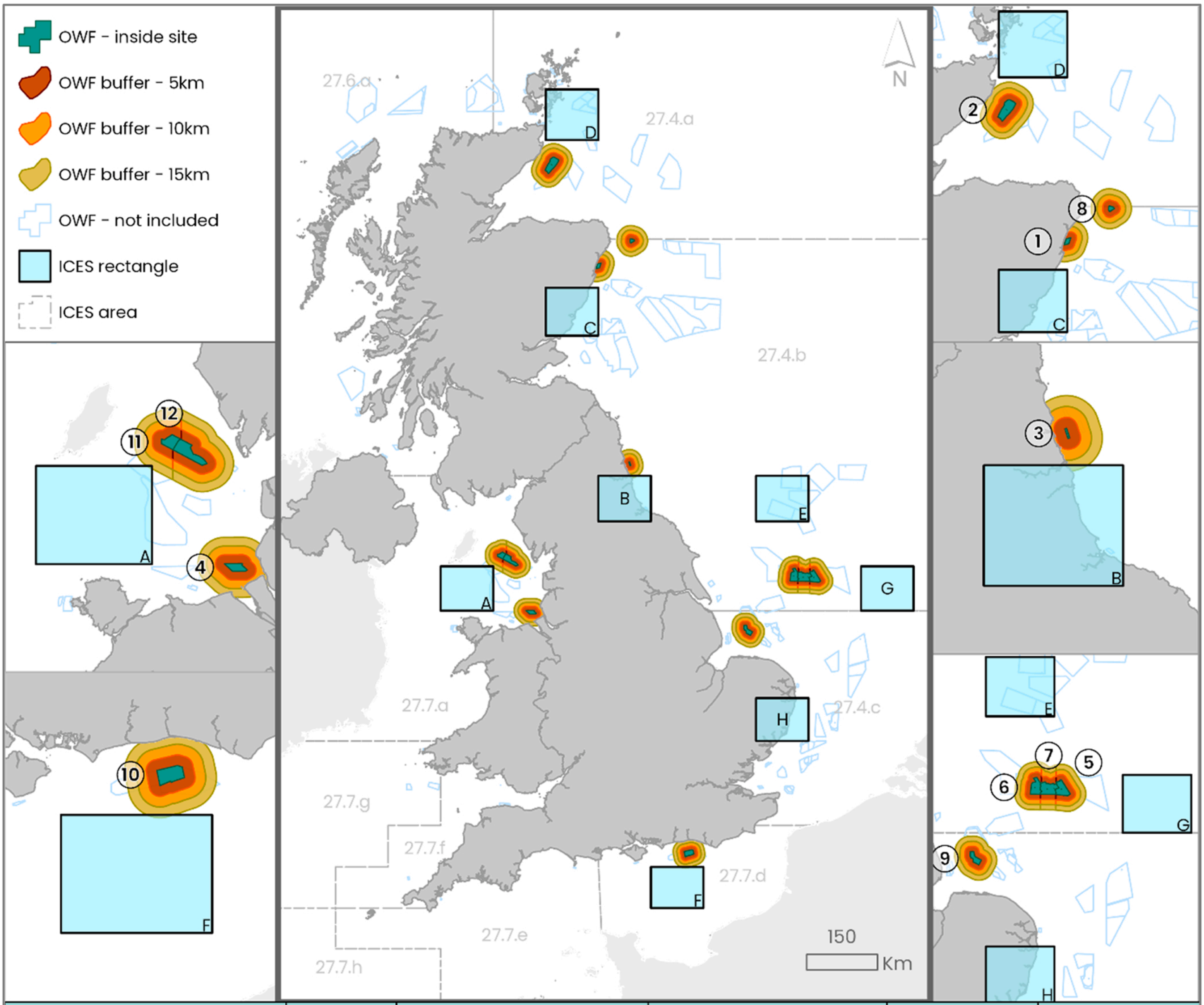
wider societal goals (e.g. Davies et al. [11]).

Offshore fishing in UK seas has tended to be fairly consistent in location since at least 2015 with fishers generally targeting 'core' areas at greater effort than less productive areas [10,12–14]. The presence of windfarm infrastructure and any resulting reduction in fishing pressure from vessels using bottom-towed gear has potential benefits for the marine ecosystem [15]. The cabling, turbine monopiles and surrounding rock armour change habitat dynamics from sedimentary to reef-like (or artificial reef) structures rich in bivalves, corals, bryozoa and hydroids [16–19]. The shift to these organisms provides a suspension feeding capacity (filtration by bivalves) in an otherwise depositional and 'scavenging' environment where flat sand and coarse gravel dominate (e.g. submerged worms, low biomass of invertebrate epifauna per unit area) [20]. However, studies show this could come at a cost with



OWF	OWF label	Year construction started	Year site commissioned	ICES rectangle	Rectangle label
Aberdeen Offshore W/F	1	2016	2018	42E7	C
Beatrice Offshore Wind Farm	2	2017	2019	46E7	D
Blyth Demo Phase 1	3	2017	2018	41E7	B
Burbo Bank Extension	4	2016	2016	36E7	A
Hornsea 1 (East)	5	2018	2020	36F3	G
Hornsea 1 (West)	6	2018	2020	38F1	E
Hornsea 1 (Njord)	7	2018	2019	38F1	E
Hywind Scotland Pilot Park	8	2017	2017	42E7	C
Race Bank	9	2016	2018	33F1	H
Rampion	10	2016	2018	29E9	F
Walney Extension 3	11	2017	2018	36E5	A
Walney Extension 4	12	2017	2018	36E5	A

Fig. 1. Twelve offshore windfarm sites included in analysis and the ICES statistical rectangles they were paired with. Contains data provided by The Crown Estate that is protected by copyright and database rights (2021) [4,5] and ICES [40].

abundance of a range of soft-bottom species declining, including dab (*Limanda limanda*), weaver fish (*Echiichthys vipera*) [21], and potentially lesser sandeels; an important forage fish for seabirds and marine mammals [22].

Such modification of 'sedimentary' habitat in natural 'sandbank' Special Areas of Conservation (under the UK Habitats Regulations), or 'circalittoral sand/mixed sediment' features in Marine Conservation Zones is controversial [15]. UK conservation advisors have assessed the impacts of shifts in habitat-type as to whether they significantly alter the ecological character of entire offshore MPAs that may require mitigation – for example to mitigate the change from sedimentary to rocky in physical and ecological characteristics [16]. The interactions between MPAs and windfarms has affected construction aspects such as cable routing around MCZs (e.g. Cromer Shoal Chalk Beds MCZ) [23]. That being the case, windfarms, the ecological communities they attract [17,24], and the effective restriction to bottom towed fishing gear brought about by safety issues could enable them to be considered as Other Environmental Conservation Measures (OECMs) [25]. That is providing any short- and/or long-term negative impacts on marine mammals, seabirds and other wide-ranging species are mitigated [26–28].

The socio-economic benefits resulting from the removal of fishing pressures from OWFs could also mimic those offered by MPAs. Spill-over of commercially important fish species (e.g. cod (*Gadus morhua*), sole (*Solea solea*), whiting (*Merlangus merlangus*) [21,29]), found to become more diverse and abundant within the arrays, provides opportunities for improved fishing outside the OWF sites, with vessels benefiting from a 'reserve effect' [11,30]. Furthermore, the OWFs themselves could present ample opportunity for co-location with a range of other marine activities if integrated via effective marine spatial planning [6,8]. Reduced-impact passive gear use (e.g. potting for crabs [31,32]), restoration of historic native oyster (*Ostrea edulis*) reefs [33,34] and sustainable mariculture (e.g. seaweed cultivation) [35] are but a few examples. Such activities especially strengthen the provisioning and regulating 'ecosystem services' provided by each OWF; improving fisheries, carbon sequestration, and water quality [36,37].

Whilst some nations (e.g. Denmark and the Netherlands) have outright bans on seabed trawling in windfarms [38], this is not the case in the UK. Nevertheless, fishing effort has been reported as being reduced around operational windfarms because of the risks of bottom-towed gear being snagged, and ship strike with monopiles [39], but quantification of this effect has been limited in the literature.

This study examines the extent to which the construction of offshore windfarms impacts fishing effort of vessels using bottom-towed gear (bottom trawls, dredges and demersal seines). We identify the risks and barriers OWF construction pose to fishing activity and explore the opportunities this presents for benthic protection and recovery.

2. Materials and methods

To assess the impact of windfarms on fishing activity, we analysed fishing effort before, during and after the construction of OWFs (Fig. 1) that became operational (i.e. were built and commissioned) between 2015 and 2021. Twelve windfarms met the criteria (Fig. 1).

We used fishing effort data from the Global Fishing Watch (GFW) Marine Manager online portal [41] specifically for vessels GFW categorised as 'trawlers', 'dredge_fishing' and 'other_seine'. GFW data is derived from Automatic Identification System (AIS) vessel tracks that are processed using "convolutional neural networks" to extract apparent fishing activity to a resolution of 0.01 × 0.01 decimal degrees (approximately 1 km × 1 km) [42]. This AIS derived data represents fishing activity to a greater level of precision than that derived from Vessel Monitoring Systems (VMS) due to its more frequent 'ping' rate and is also publicly available at a finer resolution than VMS (as used in other studies [6]) so was more appropriate for analysis using small OWF polygons. As the use of AIS has only been a legal requirement on vessels > 15 m in length fishing in EU waters since 2015 [43], data was selected for the period 1st January 2015–31st December 2021. Furthermore, GFW's 'trawler' category does not distinguish between demersal and pelagic gear, so we cross referenced all effort data with the EU fleet register [44] to extract fishing effort only for vessels registered using a demersal trawl, dredge, or demersal seine as their main gear as in Dunkley and Solandt [12].

Prior to analysis it was noted that some "fishing" activity GFW had recorded within the OWFs could be attributed to fishing boats acting as Guard Vessels (vessels engaged to deter fishing in and around the OWFs) during the construction of windfarms – their activity had been picked up as fishing due to similarities in the vessel behaviour. We excluded data attributed to these vessels from the dataset.

We then conducted an overlay analysis using windfarm polygon data provided by the Crown Estate [4] and Crown Estate Scotland [5] to extract the total fishing hours recorded within the twelve windfarm boundaries. We also extracted total fishing hours for 0–5 km, 5–10 km and 10–15 km buffer zones around these 12 sites to test for evidence of displacement. Where sites shared boundaries (Walney Extensions 3 and 4, and Hornsea 1 Heron East, Heron West and Njord), we considered the conjoined OWFs as a single site for the purpose of creating buffer zones. These buffer zones were then split along a line from the shared boundary of each site to a point directly due north. This was to minimise overlap between buffer zones thereby avoiding double-counting fishing effort. To provide a control for wider stock-dependent fishing effort, we also extracted total fishing hours for a selection of analogous ICES statistical rectangles [40]. We chose ICES rectangles that met the following criteria: 1. situated in the same ICES area as the relevant OWF so they are subject to the same fisheries advice and quota allocation; 2. contains no other OWF sites included in analysis; 3. has a pre-construction fishing rate closest to the ICES rectangle within which each OWF is located (Fig. 1).

We derived the fishing rate (h/km^2/year) by dividing the total hours by the polygon area (km^2) of each OWF and the respective buffer and control areas. Then, as data was not normally distributed, we used paired Wilcoxon signed rank tests to compare the mean fishing rate for the area inside the OWFs, their respective buffer zones and the control ICES rectangles before, during and after construction.

All statistical analysis was undertaken using R (version 4.0.2) [45] and spatial analysis was completed using ArcPro 2.5.026 and QGIS 2.8.327.

We grouped the OWFs according to the nature of their turbine layout in order to describe the effect of OWF construction on fishing activity. Three categories were used: 1. Nucleated – turbines constructed in a single compact patch; 2. Multi-nucleated – turbines constructed in several compact patches; 3. Linear – turbines constructed in a single line.

3. Results

Demersal towed fishing rate before windfarm construction did not differ significantly to that of the control (ICES rectangle fishing rate; mean vs mean) (Fig. 2). However, fishing rate declined from an average of 1.32 h/km^2/year before OWF construction to 0.31 h/km^2/year after site completion. Fishing rate during construction and after the commissioning of OWFs is significantly lower than that recorded in the control ICES rectangle areas (mean vs mean; $p < 0.01$) and all buffer zones (mean vs mean; $p < 0.01$). Rampion Windfarm experienced the greatest decline in fishing rate with an average annual rate of 14.15 h/km^2/yr recorded prior to construction and 2.79 h/km^2/yr recorded after the site was commissioned (Fig. 3 and Map 8, Fig. 4).

Comparing bottom-towed fishing rate in the 3 buffer zones (0–5 km, 5–10 km and 10–15 km) we found that fishing effort remained largely consistent before, during and after OWF construction increasing slightly on average, during construction in the 5–10 km and 10–15 km buffer zones. Paired statistical analysis found this increase during construction to not be significantly different to the fishing rates recorded in each site's respective control area. This is therefore unlikely to be evidence of

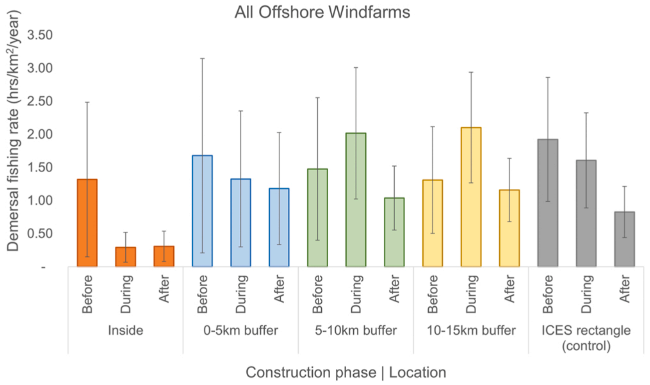


Fig. 2. Mean fishing rate for towed gear (± SE) inside windfarms, within the 0-5 km, 5-10 km and 10-15 km buffer zones and in the wider ICES control area (n = 12).

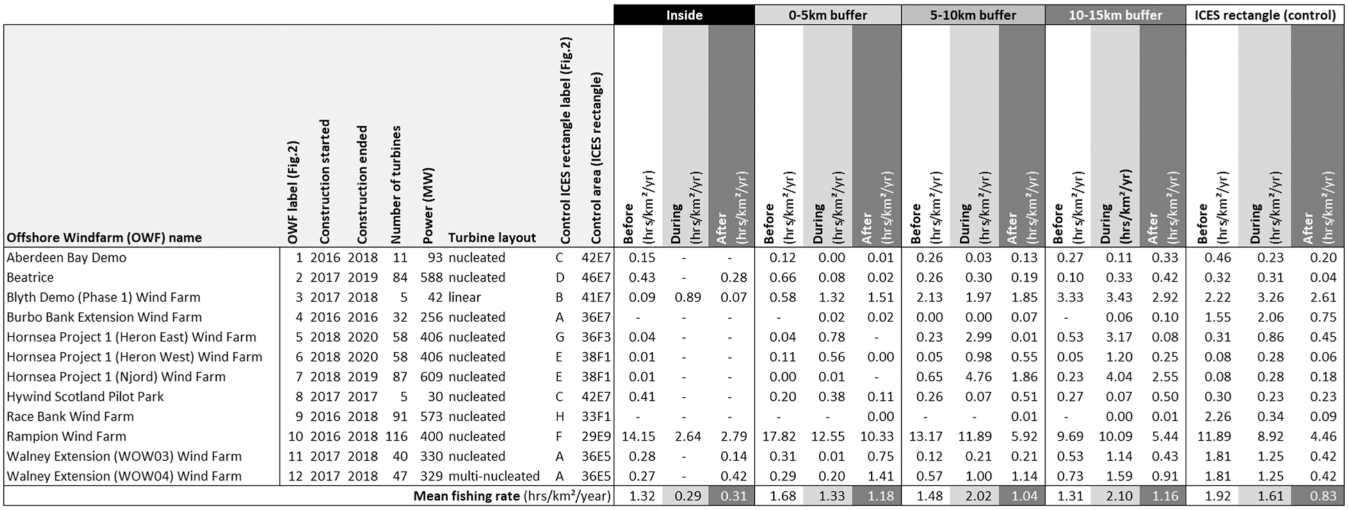
fishing effort displacement to areas immediately outside the OWF during construction. Whilst in general the presence of an OWF does appear to induce a significant drop in the fishing rate inside the windfarms, patterns did vary between sites with two of the 12 sites (Burbo Bank and Race Bank – Maps 4 and 7, Fig. 4) experiencing no fishing throughout the study period, and one site (Walney Ext. 4 – Map 9 in Fig. 4) experiencing an increase in towed demersal fishing rates after the windfarm became operational (Fig. 4). We note that the turbine layout within Walney Extension 4 site differed from the other sites studied. Rather than being constructed as a single 'nucleated' patch, the turbines in Walney Extension 4 are constructed in two distinct patches (i.e. multi-nucleated) (Map 9, Fig. 4).

In Walney 4, fishing rate prior to construction was relatively low (0.27 h/km^2/year), dropping to zero during construction, then rising to 0.42 h/km^2/year following site activation (Fig. 5A). By comparison, the fishing rate in the associated control area (ICES rectangle 36E5) shows a gradual decline in fishing rate over the course of construction (1.81 h/km^2/year before, 1.25 h/km^2/year during, and 0.42 h/km^2/year after) (Fig. 5A). Whilst the vessels active within Walney Extension 4 were all beam trawlers, fishing effort in the control area prior to construction can be attributed predominantly to vessels using dredge or bottom otter trawl gear. It is the activity of these vessels that gradually declined over the building phases rather than beam trawling (Fig. 5B). Extracting activity solely for beam trawlers in the control area shows a similar pattern of change to that recorded within Walney Extension 4 and up to 10 km outside the site (Fig. 5B). Beyond the 10 km buffer, the pattern of change reflects that of the otter trawl and dredge dominated control area. Future research should compare fishing activity defined by specific gear type and, if possible, target species to gain further insight.

By contrast, Blyth Demonstration OWF (Map 3, Fig. 4) had a linear turbine layout with 5 turbines placed in a single line, however no rise in fishing effort was recorded following the site being commissioned despite background fishing effort increasing. There was, however, a steep increase in fishing rate during the construction of Blyth Demonstration OWF (from 0.09 h/km^2/year to 0.89 h/km^2/year) similar to that seen in the control area. The activity within the windfarm can be attributed to a single UK vessel using otter trawl gear that fished within the site for 12 h between January and February 2018 (the site was commissioned in June 2018 – Fig. 3). This was after turbine installation had been completed, but before the site was commissioned.

4. Discussion

There is considerable anecdotal information of lost fishing opportunities in and around fixed offshore windfarm installations [39], and UK fisher surveys have historically claimed loss of fishing opportunity and displacement from within windfarms putting increased pressure into surrounding grounds [46]. However, we saw no significant trends to indicate any displacement effect compared to background fishing levels in nearby 'buffers' or wider ICES (control) areas once the OWFs had been commissioned. We do note, however, that our findings suggest considerable variability in the amount of towed fishing activity within and around windfarms before and after construction and operation. This, in part may be due to the length of time for which we had suitable data from the Global Fishing Watch database. As the use of AIS (from which GFW data is derived) has only been a legal requirement on vessels > 15 m in length fishing in EU waters since 2015 [43], we were restricted in the timeframe for which appropriate data was available. Our sample size is therefore limited to a small number of windfarms in UK waters where we have fishing activity information for 'before and after operation'. Many are still being constructed during the time of writing, and such an increase in number may provide more of a consistent pattern of fishing activity change, including displacement, in due course. Our use of AIS derived data also means vessels under 15 m in length are underrepresented in our data, although as smaller vessels represent only around 25 % of the EU bottom-towed gear fleet [12] the effect of this will be less than that found in other studies focusing on fixed gear usage. Despite the limitations of the data, we found that of the



									Inside			0-5km buffer			5-10km buffer			10-15km buffer			ICES rectangle (control)		
Offshore Windfarm (OWF) name	OWF label (Fig.2)	Construction started	Construction ended	Number of turbines	Power (MW)	Turbine layout	Control ICES rectangle label (Fig.2)	Control area (ICES rectangle)	Before (hrs/km²/yr)	During (hrs/km²/yr)	After (hrs/km²/yr)	Before (hrs/km²/yr)	During (hrs/km²/yr)	After (hrs/km²/yr)	Before (hrs/km²/yr)	During (hrs/km²/yr)	After (hrs/km²/yr)	Before (hrs/km²/yr)	During (hrs/km²/yr)	After (hrs/km²/yr)	Before (hrs/km²/yr)	During (hrs/km²/yr)	After (hrs/km²/yr)
Aberdeen Bay Demo	1	2016	2018	11	93	nucleated	C	42E7	0.15	-	-	0.12	0.00	0.01	0.26	0.03	0.13	0.27	0.11	0.33	0.46	0.23	0.20
Beatrice	2	2017	2019	84	588	nucleated	D	46E7	0.43	-	0.28	0.66	0.08	0.02	0.26	0.30	0.19	0.10	0.33	0.42	0.32	0.31	0.04
Blyth Demo (Phase 1) Wind Farm	3	2017	2018	5	42	linear	B	41E7	0.09	0.89	0.07	0.58	1.32	1.51	2.13	1.97	1.85	3.33	3.43	2.92	2.22	3.26	2.61
Burbo Bank Extension Wind Farm	4	2016	2016	32	256	nucleated	A	36E7	-	-	-	-	0.02	0.02	0.00	0.00	0.07	-	0.06	0.10	1.55	2.06	0.75
Hornsea Project 1 (Heron East) Wind Farm	5	2018	2020	58	406	nucleated	G	36F3	0.04	-	-	0.04	0.78	-	0.23	2.99	0.01	0.53	3.17	0.08	0.31	0.86	0.45
Hornsea Project 1 (Heron West) Wind Farm	6	2018	2020	58	406	nucleated	E	38F1	0.01	-	-	0.11	0.56	0.00	0.05	0.98	0.55	0.05	1.20	0.25	0.08	0.28	0.06
Hornsea Project 1 (Njord) Wind Farm	7	2018	2019	87	609	nucleated	E	38F1	0.01	-	-	0.00	0.01	-	0.65	4.76	1.86	0.23	4.04	2.55	0.08	0.28	0.18
Hywind Scotland Pilot Park	8	2017	2017	5	30	nucleated	C	42E7	0.41	-	-	0.20	0.38	0.11	0.26	0.07	0.51	0.27	0.07	0.50	0.30	0.23	0.23
Race Bank Wind Farm	9	2016	2018	91	573	nucleated	H	33F1	-	-	-	-	-	0.00	-	-	0.01	-	0.00	0.01	2.26	0.34	0.09
Rampion Wind Farm	10	2016	2018	116	400	nucleated	F	29E9	14.15	2.64	2.79	17.82	12.55	10.33	13.17	11.89	5.92	9.69	10.09	5.44	11.89	8.92	4.46
Walney Extension (WOW03) Wind Farm	11	2017	2018	40	330	nucleated	A	36E5	0.28	-	0.14	0.31	0.01	0.75	0.12	0.21	0.21	0.53	1.14	0.43	1.81	1.25	0.42
Walney Extension (WOW04) Wind Farm	12	2017	2018	47	329	multi-nucleated	A	36E5	0.27	-	0.42	0.29	0.20	1.41	0.57	1.00	1.14	0.73	1.59	0.91	1.81	1.25	0.42
Mean fishing rate (hrs/km²/year)									1.32	0.29	0.31	1.68	1.33	1.18	1.48	2.02	1.04	1.31	2.10	1.16	1.92	1.61	0.83

Fig. 3. Summary data for the 12 Offshore windfarm sites included in the study. Contains data provided by The Crown Estate and The Crown Estate Scotland that is protected by copyright and database rights (2021) [4,5].

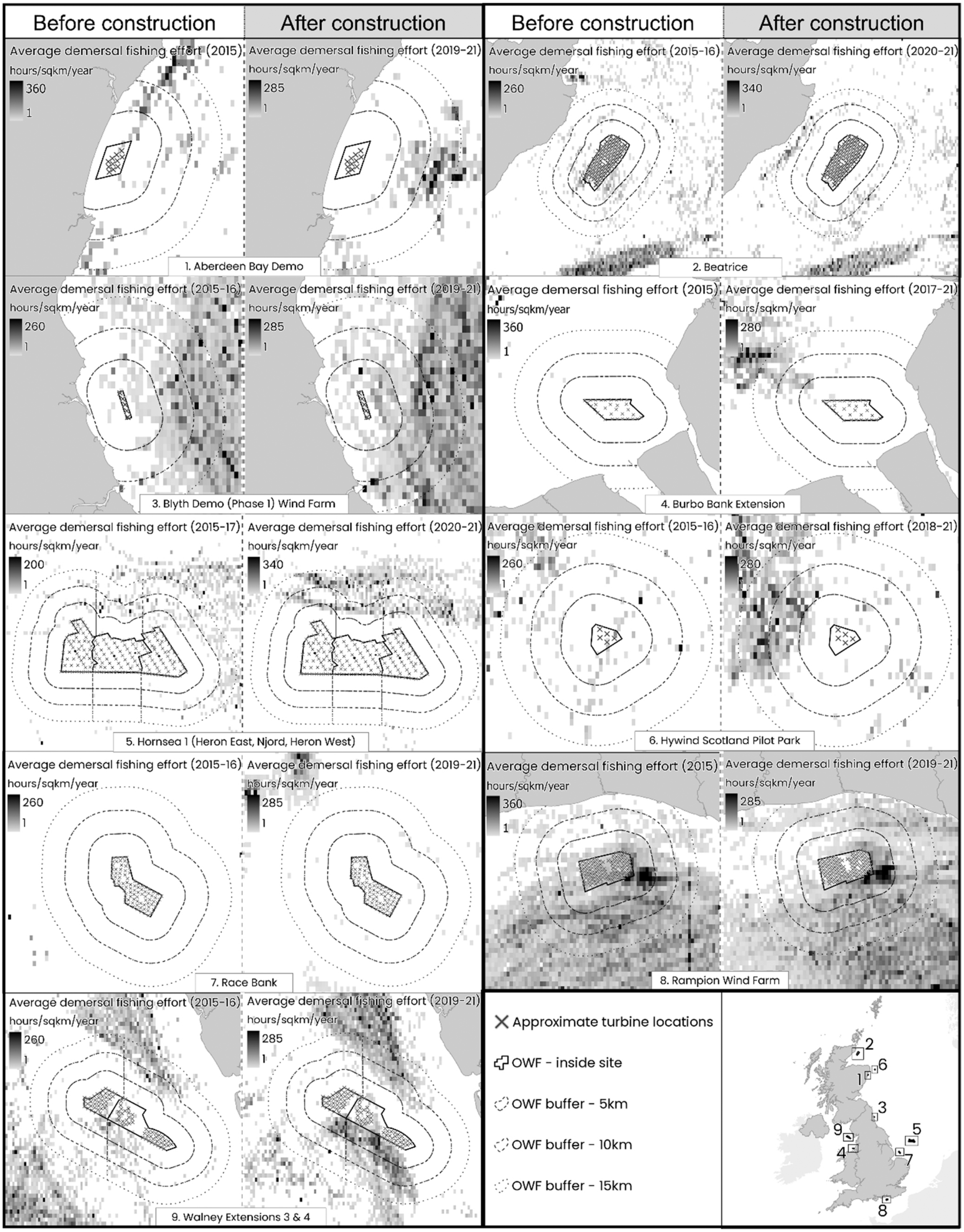


Fig. 4. Towed fishing effort before and after the construction of the windfarms. Burbo Bank and Race Bank are not shown as no fishing was recorded within their respective boundaries before or after construction. Contains data provided by The Crown Estate that is protected by copyright and database rights (2021) [4,5] and data from GFW [41].

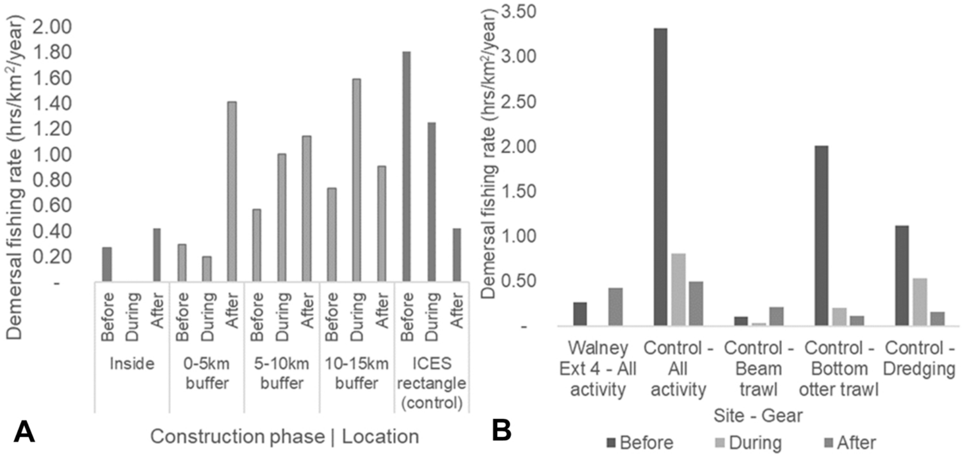


Fig. 5. A. Change in fishing rate inside Walney Extension 4, 0–5 km, 5–10 km and 10–15 km buffer zones and the control area. B. Fishing rate defined by gear type recorded within Walney Extension 4 and fishing effort recorded in the associated ICES control rectangle.

12 sites analysed, 9 sites showed declines in bottom towed fishing activity, whilst 1 showed an increase, and 2 no change due to a complete absence of fishing throughout.

One of the sites (Walney Extension 4) experienced an increase in towed gear activity in the site. This is likely due to the unconventional turbine layout within the site. In Walney Extension 4, turbines have been constructed in two distinct patches allowing vessels to move around and fish the site without entering into the turbine arrays (Fig. 4). The boats visiting the Walney 4 Extension windfarm were mainly Belgian beam trawlers as also noted in Gray et al. [39] and Giammichele et al. [47]. We found that towed gear effort was already low prior to construction likely due to a low Total Allowable Catch (TAC) for sole (*Solea solea*) in the Eastern Irish Sea established in 2000 [39,48]. The increase in fishing rate then coincides with an increase in TAC for sole from 40 t in 2018 to 414 t in 2019 (although the MSY approach was recommended with catches advised be minimal) [48] with Belgian fleets awarded a TAC of 192 t in 2019 up from 10 t (allowing for sole to only be caught as bycatch) in 2018 [49,50]. Whilst it is not possible to draw conclusions about sole stocks specifically within the site, though they have been found to become more abundant in OWFs [51,52], this increase in fishing activity is most likely a reflection of this change in TAC facilitated by the nature of the turbine distribution. The construction of the arrays in distinct patches appears to allow vessels to safely continue fishing within the boundary of the OWF in line with background fishing rates without having to navigate between individual turbines.

By comparison, Rampion – a windfarm off the south coast of England comprising 116 turbines - experienced a precipitous decline in towed fishing activity. The boats operating in this region were also predominantly beam trawlers likely targeting flatfish [53,54]. Whilst vessels targeting similar species in Walney Extension 4 were able to continue fishing within the site due to the distribution of turbines, turbines within the Rampion OWF are in a single compact nucleated patch. This means therefore that vessels are required to navigate between turbines to fish within the site. The large decline in fishing activity during the construction of Rampion together with the small recovery in effort almost entirely restricted to the edges of the site following commissioning indicates that vessels are avoiding the area due to the presence of the turbines. A decline in fishing effort was recorded in all three buffer zones after construction indicating an absence of displacement. This could be associated with the offer of ‘disruption payments’ to compensate loss of income during the construction and transitional phase of the site in principle to allow the fishing industry to reduce their activity without losing income [55,56].

We note that whilst the Blyth Demonstration site experienced a decline in towed gear activity within the site after it was commissioned, we did record an increase in fishing during the construction phase. The activity is attributed entirely to one otter trawler active following the completed installation of the turbines, but before the site was formally commissioned. As this change in effort is also shown in the control area, it would suggest that Blyth Demonstration OWF too presents less of a barrier to fishing than other study sites likely aided by its unusual linear turbine layout [57]. This layout allows trawler tow paths from west-southwest to eastnortheast to occur close to the turbines. However, as fishing did not increase in the long-term within this site in line with the control area it is likely that the behaviour exhibited by this particular vessel is unusual. Fishing within this site would still require any skipper to navigate between individual turbines and therefore the risk and dangers of tide and wind drifting vessels and gear towards infrastructure above and below the water (e.g. cabling and scour protection bouldering on the seabed) would still be present. This vessel did not return in the proceeding years despite being active within the site soon after turbine installation. This could indicate that the OWF was deliberately targeted to take advantage of a ‘reserve-effect’ offered by the site whilst it was effectively closed to fishing during turbine installation [30], although further investigation would be required to confirm this.

The reduction in demersal towed gear fishing activity as a result of OWF construction particularly where turbine arrays are contiguous and compact could present opportunities for seabed protection and recovery within windfarms [58] akin to that offered by MPAs where fishing restrictions are in place, although the seabed is somewhat modified. OWFs have been reported to be associated with increasing local densities of demersal finfish populations [29] and will allow (over the operational lifetime of the windfarm) areas of seabed to recover from abrasion from bottom towed fishing gears that were towed over prior to construction.

Consideration of windfarms as ‘Other Effective area-based Conservation Measures’ (OECMs) is, however, debatable given the effect they have on cetaceans, seabirds and some fish species during the construction and operational phases [26,59]. Furthermore, the placement of OWFs within MPAs raises further questions mainly due to the preordained definition of the features for which MPAs are designated. These tend to be for sediment-related features in the locations of offshore windfarms (e.g. circalittoral muds, sands and gravels) [60]. Substantial proportions of the seabed where OWFs have or will be placed in offshore MPAs established for the protection of sediment features will change in physical character. The ecological ‘footprint’ effect of the ecosystems on turbine monopiles and surrounding rock armour has been recorded up to 50 m from the monopile base, mainly a result of shell-fall and scatter of predated bivalves and crustaceans [25,61], and from faecal pellets predominantly from the mussels [19]. These changes in the overall ecosystem go beyond that of the species alone, but to the additional ecosystem services offered by the windfarms (e.g. improved fisheries, better water quality, carbon sequestration) [16,37].

When viewed in the historical context illustrated in Olsen's 1883 Piscatorial Atlas [34], the habitat-modifying character within OWF could be considered as something of a recovery of a historical habitat. Before the advent of bottom trawling in the late 19th century [62], large swathes of bivalve reefs with associated fauna, and fish spawning habitat were reported in the southern North Sea, and in estuaries in the UK (e.g. Firth of Forth, Thames and Humber) [34,63]. So, at times of significant offshore MPA designation (from 2000 to 2021) studies posit that the ecological 'baseline' of MPAs has shifted to such a degree that the seas in the footprints of offshore windfarms have already been significantly modified by pervasive bottom trawling [64].

This factor is of particular relevance when considering the decommissioning of installations to ensure that the 'new' and restored habitats are not lost. Full natural capital asset accounting, and ecosystem services quantification of OWF infrastructure removal, subsequent incursion of fishing opportunities relative to the accumulated ecosystem services and biomass that the 'new' ecological habitats will provide within 'old' OWF arrays (> 20 years) should be applied in order to assess the societal value of installation removal [11]. We recommend that such accounting should all be set into the context of wider seas natural capital asset management in order to understand the ecological value that they will have accrued for the entirety of our marine environment in a view that echoes effective Marine Spatial Plans [8,65].

The restoration of habitats such as native oyster reefs (*Ostrea edulis*) within OWFs is just one opportunity for positive co-location initiatives. Others include low-impact fishing activities using potting and line gear likely improved by the absence of bottom-towed fishing [29,32], and sustainable mariculture activities such as seaweed cultivation. Further research is needed to quantify the extent of soft-sediment ecosystems that will be modified by current and future OFW development at a national scale. The impact of constructing sites in MPAs designated for benthic features should also be assessed to inform consultations on domestic MPA designations. Initial findings here that OWFs reduce bottom-towed fishing activity within turbine arrays suggest such consultations should involve offshore wind stakeholders in terms of the 'co-location' and 'avoidance' of MPAs and OWFs.

5. Conclusion

The construction of Offshore Windfarms significantly reduces demersal towed gear use within the arrays, likely a result of vessels deliberately avoiding turbine arrays due to safety concerns. OWFs where turbines have been constructed in compact nucleated patches posed the greatest barrier to fishing activity. Due to the presence of the turbines reducing bottom-towed fishing effort within the sites, OWFs are likely to offer the marine ecosystem within the arrays some protection from towed fishing gear. Whilst the construction of OWFs has been shown to cause functional shifts in the ecosystems around the turbine bases, this should be considered in a historical ecology context in order to assess the scope for OWFs to restore biogenic reef habitats lost to years of industrial trawling, and opportunities for co-location with bivalve reef restoration work (e.g. the native oyster & blue mussels).

CRediT authorship contribution statement

Frith Dunkley: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft, Project administration. **Jean-Luc Solandt:** Conceptualization, Funding acquisition, Supervision, Validation, Writing – original draft, Project administration.

Declarations of interest

None.

Data Availability

Data will be made available on request.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2022.105262.

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