Science of the Total Environment 994 (2025) 179973

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Research Paper

Offshore wind farms act as de facto marine reserves

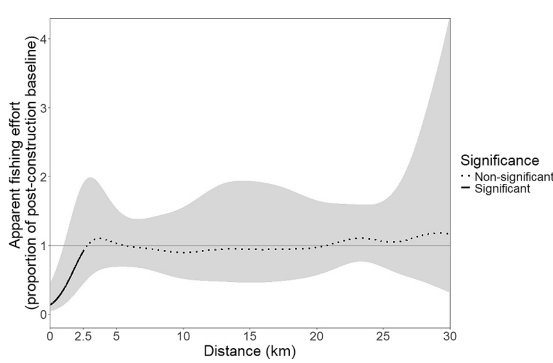
Benjamin Fitkov-Norris [1,*], Matthew J. Witt [2], Benno I. Simmons [1]

[1] Centre for Ecology and Conservation, University of Exeter, Penryn, Cornwall TR10 9FE, UK
[2] University of Exeter, Hatherly Laboratories, Prince of Wales Road, Exeter EX4 4PS, UK

HIGHLIGHTS

- Offshore wind farms function as de facto marine reserves, limiting fishing without formal legal protections
- Offshore wind farms reduce overall fishing effort up to 2.5 km beyond their boundaries
- Trawlers and seiners experience the most significant restriction, up to 3.7 km and 4.2 km respectively

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Olga Pantos

ABSTRACT

Marine biodiversity faces increasing threats, necessitating effective conservation strategies beyond just marine protected areas. As offshore wind farms (OWFs) expand to meet the demand for renewable energy, these could offer an additional benefit by restricting fishing, one of the greatest threats to marine ecosystems globally. However, this remains untested at scale. Here we assessed the impact of OWF construction on fishing effort across 34 European OWFs from 2016 to 2022. Our findings reveal a significant reduction in overall fishing effort up to 2.5 km beyond OWF borders. Seiners and trawlers are most restricted (up to 4.2 km and 3.7 km respectively), while fixed gear and dredge fisheries showed no significant reduction. These results highlight the de facto exclusionary effect of OWFs on fishing, extending well beyond their boundaries. This restrictive effect could be strategically leveraged to support marine conservation efforts, particularly in areas where conventional fisheries management has been insufficient.

1. Introduction

There is a considerable demand globally for Offshore Wind Farms (OWFs) to provide renewable energy. In Europe alone, 75 OWFs have been constructed over the past 10 years, representing an 89 % increase in footprint occupied by OWFs during that period (Centro Tecnologico del Mar - Fundación, 2024). The rate of expansion will only increase, with European offshore energy capacity forecast to more than double from 34 GW in 2024 to 83 GW by 2030 (Costanzo and Brindley, 2024). As OWF installations accelerate, a significant portion of these will

* Corresponding author.
E-mail address: bf327@exeter.ac.uk (B. Fitkov-Norris).

https://doi.org/10.1016/j.scitotenv.2025.179973
Received 10 April 2025; Received in revised form 13 June 2025; Accepted 19 June 2025
Available online 7 July 2025

unavoidably overlap with existing fishing sites (Stelzenmüller et al., 2022).

The area occupied by OWFs is largely incompatible with other uses. One particularly affected industry is fisheries. In some European countries, mandatory safety zones of up to 500 m around OWFs prohibit fishing (van Hoey et al., 2021; Püts et al., 2023), but even in countries where fishing is not legally restricted, there is considerable reluctance for fishers to fish near to, or inside, OWFs (Mackinson et al., 2006; Gray et al., 2016; Kafas et al., 2018). Thus, these OWFs are acting as de facto partial no-take zones. These can be seen as functionally equivalent to *de jure* Marine Protected Areas (MPAs) (Silva et al., 2023), albeit with the added complications arising from the wind farm structures inside (Jay, 2012). This aligns with the increasingly recognised concept of Other Effective area-based Conservation Measures (OECMs), where areas not primarily designated for conservation nonetheless deliver biodiversity benefits (CBD, 2018). Not only does this similarity with protected areas suggest the potential for a 'spillover' effect, where biodiversity benefits are apparent outside the protected area, but the structures within have been suggested to provide further benefits to biodiversity accumulation (e.g. Gill, 2005; Methratta and Dardick, 2019; Stephenson, 2023; Stelzenmüller et al., 2021; Halouani et al., 2020; Galparsoro et al., 2022). It has been proposed that fishers will find the optimal distance at which they can take advantage of the spillover while not contravening restrictions or exposing themselves to too much danger (Kellner et al., 2007; Silva et al., 2023).

However, the dynamics for how fishing effort is displaced, to what degree, to where and at what scale have yet to be explored in depth. Answering these questions would offer insights into whether OWFs act as de facto fisheries exclusion zones, and whether this reduction in threat is matched by an increase in threat elsewhere as fishing effort redistributes. Research in the UK has shown that there is a reduction in fishing intensity within OWFs (Gray et al., 2016; Dunkley and Solandt, 2022), but the dynamics of how this affects fishing outside the OWF are less clear. Vandendriessche et al. (2014) show that there is evidence that displaced fishing redistributes itself to surround OWFs in Belgian waters following construction, but a more recent analysis showed there was no increase in fishing in a 5 km pooled area outside newly constructed OWFs in the UK (Dunkley and Solandt, 2022). Ultimately, there is no clear picture of the behavioural response of fishers to the construction of OWFs.

With the advent of widespread AIS data as an increasing number of vessels carry transponders, and neural networks capable of classifying fishing behaviour based on this data, broad-scale analyses of fishing patterns are now possible (Kroodsma et al., 2018). Here we conduct a before-after gradient analysis to assess the impact of OWF construction on apparent fishing effort across all OWFs constructed in European marine waters between 2016 and 2022. We also investigate whether the impact of OWF construction on fishing differed by fishing gear type. We found that OWFs reduce fishing up to 2.5 km from their borders, with this restrictive pattern apparent in trawlers and seiners, but not static

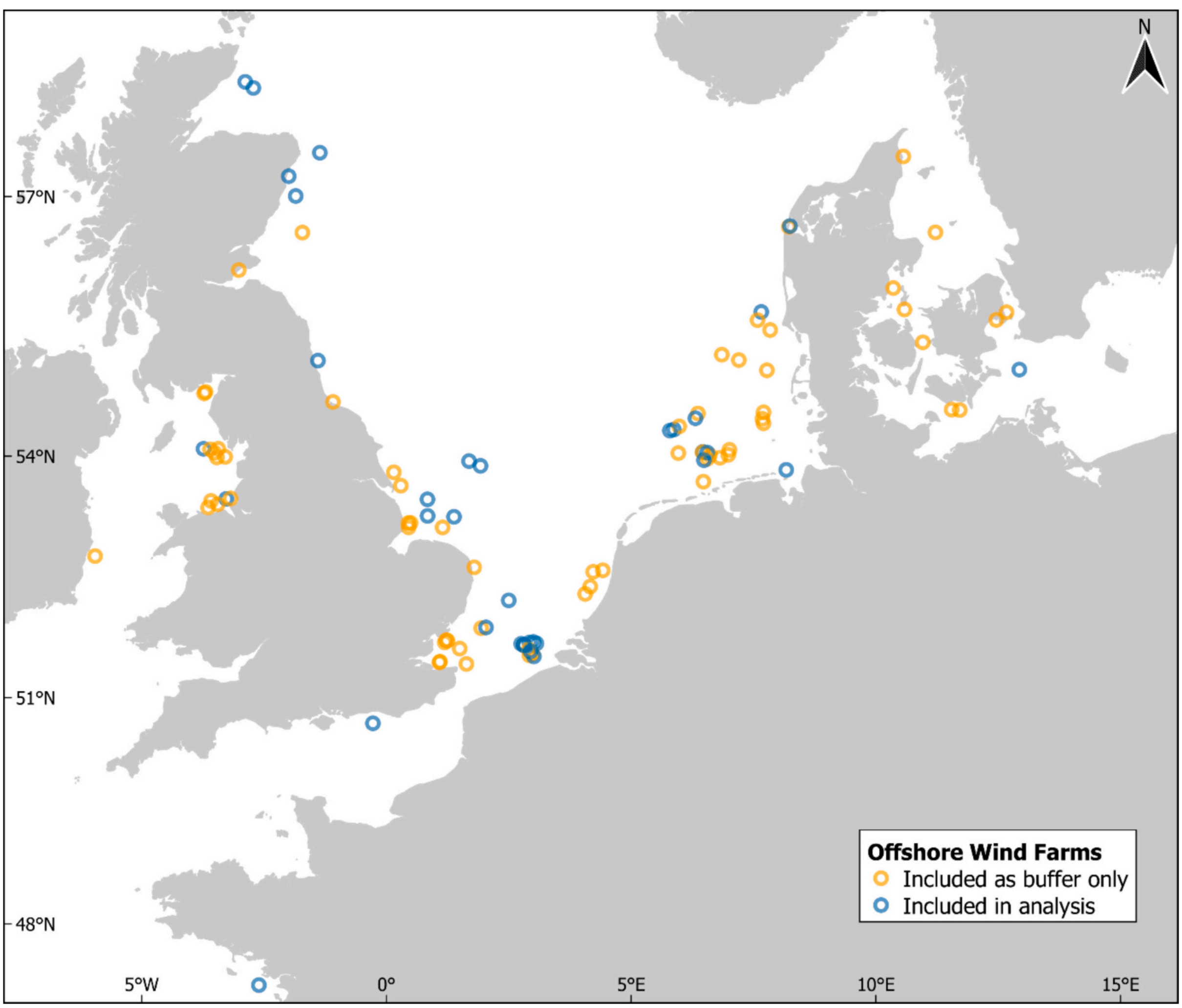


Fig. 1. A map of OWFs included in the analysis. Blue open circles represent OWFs included in the before-after gradient analysis, while orange open circles denote OWFs constructed before the study period, included to prevent misattribution of fishing effort to more distant OWFs.

gear or dredge fisheries.

2. Methods

2.1. Data acquisition

2.1.1. Offshore wind farms

European offshore wind farm (OWF) polygons as of 19/12/2022 were downloaded from the EMODnet Human Activities database (accessed 31/08/2023) (Centro Tecnologico del Mar - Fundación, 2023). All offshore wind farms in active production, along with those in construction, were included (Fig. 1).

OWFs were selected for inclusion in the before-after gradient (BAG) analysis by date. Only those that began construction after 01/01/2016 were included, in order to allow for at least one full year of high-quality fishing data pre-construction (explained further in section 2.1.2). Similarly, only those OWFs that had completed turbine installation by 27/10/2022 were included to allow for at least one full year of fishing data post-construction.

All polygons were checked and cleaned in QGIS 3.28 and R 3.4.1. Metadata on OWF first foundation installation and final turbine completion were gathered from press releases (Extended Data Table 1). OWFs that were constructed simultaneously were grouped as a single complex (e.g. MacColl, Stevenson & Telford comprising Moray East Offshore Wind Farm), but adjacent OWFs that were constructed at different times were considered separately in the analysis.

The final OWF dataset comprised 34 OWFs that were included in the BAG analysis.

2.1.2. Apparent fishing effort

Apparent fishing effort data were sourced from the Global Fishing Watch (GFW) AIS- and VMS-derived effort maps. These data were accessed via the GFW API using the 'gfwr' R package (Clavelle et al., 2023; Global Fishing Watch, 2025) and saved as raster files. Data were downloaded at a 0.01-degree resolution and were disaggregated by gear type into the following categories: Fixed Gear (fixed gear, set gillnets, set longlines, and pots & traps); Dredge Fishing (dredge fishing); Seiners (seiners, purse seines, other seines, other purse seines, and tuna purse seines); Trawlers (trawlers); Others (fishing, inconclusive, pole and line, and trollers).

Fishing effort data were obtained for the period 1 January 2015 to 27 October 2023. This choice of time window reflects a balance between ensuring data quality and maximising temporal coverage. AIS transponders only became mandatory for vessels >15 m in length in May 2014 (The European Commission, 2011) and, as such, pre-2015 GFW data were excluded from the analysis owing to lower AIS uptake and representativity during that time (Thoya et al., 2021).

2.2. Before-after gradient analysis

A BAG approach was used to examine changes in fishing intensity associated with OWF construction. The BAG method is a refinement of the before-after control-impact (BACI) framework, differing in its design by sampling at regular intervals along a distance gradient from the impact site, rather than defining discrete impact and control areas (Ellis and Schneider, 1997). Sampling across this gradient, extending beyond the anticipated impact zone, ensures the inclusion of both affected and unaffected areas while avoiding reliance on pre-defined impact zones, allowing data to reveal the extent of the affected area.

This design facilitates the construction of a statistical model to predict responses across the gradient for both pre- and post-construction periods, capturing the spatial extent and magnitude of the impact as it returns to a baseline. By sampling unaffected areas, a counterfactual baseline is established, with pre-existing patterns accounted for by comparing the shape of the response post-construction to the modelled response pre-construction. With this method, changes are identified even when absolute values shift. Regions of significant change in apparent fishing effort are determined by identifying distances where the gradient of the difference between the two curves is significantly different from zero. For further methodological details, see Ellis and Schneider (1997) and Methratta (2020, 2021).

2.2.1. Buffer creation

Fishing intensity was assessed along a distance gradient from each OWF using 1 km-wide buffer zones radiating outward from the OWF boundary (Fig. 2A). These sequential buffers captured fishing effort at increasing distance from the OWF, with the OWF polygon itself acting as the buffer with distance 0 km. Given the proximity of many OWFs to one another, a simple buffer creation approach could result in overlaps between the buffers of adjacent OWFs. This overlap poses a challenge because areas in the farther buffers of one OWF could be closer to a neighbouring OWF, potentially misrepresenting fishing effort as being far from any OWF when it is near a different one.

To resolve this, an adapted version of the regional_seas() function from the 'cartomisc' R package (Rochette, 2019) was used. This method uses Voronoi polygons to partition overlapping areas, ensuring that each buffer only extends to points where the originating OWF is the nearest OWF. Buffer areas overlapping with land were also excluded. This approach ensures that the buffers uniquely represent fishing effort at defined distances from the nearest OWF (Fig. 2B).

For pre-construction data, buffers were generated based on the OWF configuration at the time of each OWF's construction. This approach represents the maximum area where changes in fishing could be attributed to a specific OWF. Post-construction data, however, required recalculating buffers as new OWFs were commissioned. For each post-construction period, the buffer layout was updated to reflect the contemporary arrangement of OWFs to ensure comparability of data as new OWFs were constructed.

2.2.2. Fishing intensity calculation

Fishing intensity was calculated by summing the apparent fishing effort within each buffer region and dividing by the buffer surface area, for both the pre- and post-construction periods of OWFs (Fig. 2C, D). For the pre-construction period, where buffer layouts remained consistent, calculations were performed for the entire period as a single unit. In contrast, the post-construction period required separate calculations for each buffer layout, as new OWFs built nearby altered the spatial arrangement of buffers over time. The duration of each period was reserved as an offset term in the statistical model, rather than weighting fishing intensity during its calculation.

Fishing effort for each buffer was computed using the extract() function from the 'terra' (Hijmans, 2024) R package. This function calculates the percentage contribution of each raster cell based on the degree of overlap with the buffer strip. For instance, a raster cell entirely contained within a buffer contributes 100 % of its fishing effort to that buffer, while a cell that overlaps a buffer by 50 % contributes only half its value.

2.2.3. BAG model construction

A hierarchical generalised additive mixed-effects model (HGAMM) was selected to model the apparent fishing effort response to OWF construction (Pedersen et al., 2019). This approach was chosen because the additive component effectively captures non-linear patterns in fishing intensity across distances, while the mixed-effects component accounts for variability between individual OWFs. The hierarchical structure allowed for the inclusion of both pre- and post-construction periods within a single model, enabling the preservation of shared information across OWFs.

The model was built iteratively through a process of stepwise forward selection, starting from a core structure:

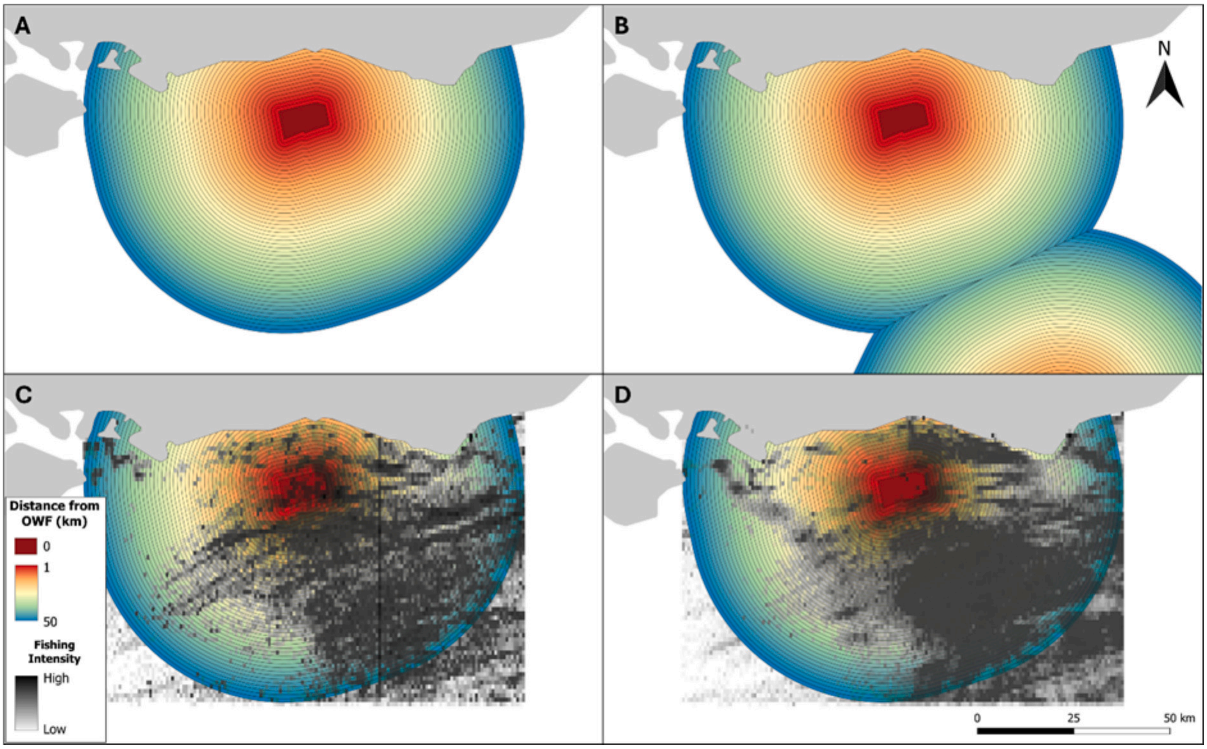


Fig. 2. (A) Map illustrating the arrangement of buffer strips around an OWF. (B) Map showing how buffer strips are affected by a nearby OWF. (C, D) Maps depicting fishing intensity across all buffer strips before (C) and after (D) OWF construction. Note: The vertical line in (C) is an artefact of GFW data at the prime meridian for one particular year.

$$
\begin{aligned}
E\left(FishingIntensity_j\right) &= \mu_j \\
log\left(\mu_j\right) &= \beta + Period_j + s\left(\mathrm{Distance}_j, by = Period\right) \\
&\quad + offset\left(\log\left(TimeDiff_j\right)\right) + e_j
\end{aligned}
$$

where s(x) represents a smooth term. To account for different sampling durations which vary based on the date of OWF construction, an offset term was included. The offset term acts as a constant rate while avoiding transforming our count data into rate data. This is preferable as it preserves information on the number of days sampled from and avoids changing the response variable distribution.where s(x) represents a smooth term. Building from the core structure, all potential additional covariates were tested one by one, with each term assessed for its impact on model performance based on changes in AIC. The term producing the greatest decrease in AIC was retained, and the process was repeated for the remaining covariates until AIC did not meaningfully decrease.

The response variable's statistical distribution was evaluated based on visual inspection of the data. Candidate distributions included the negative binomial, zero-inflated Poisson, and Tweedie distributions. Following residual diagnostics and Akaike Information Criterion (AIC) comparison, the Tweedie distribution was identified as the best fit.

The additional terms considered were: random intercepts by OWF complex name interacting with period; random effect smooths of distance interacting with OWF complex name (factor-smooth interaction); latitude; longitude; OWF Country; turbine commissioning date.

The model was constructed using the gam() function from the 'mgcv' (Wood, 2017) R package. To ensure sufficient flexibility in the smooth terms, the number of knots was validated using the gam.check() function. Residual plots were inspected visually to confirm appropriate model fit, and residual autocorrelation was assessed following the methods outlined in Zuur et al. (2009).

The final model selected was:

$$
\begin{aligned}
FishingIntensity_j &\sim tweedie\left(\mu_j\right) \\
ComplexName_j : Period_j &\sim N\left(0, \sigma_{ComplexName_j:Period_j}\right) \\
E\left(FishingIntensity_j\right) &= \mu_j \\
log\left(\mu_j\right) &= \beta + Period_j + s\left(\mathrm{Distance}_j, by = Period\right) \\
&\quad + ComplexName_j : Period_j \\
&\quad + s\left(\mathrm{Distance}_j, \mathrm{ComplexName}_j,\ by = Period\right) \\
&\quad + offset\left(log\left(TimeDiff_j\right)\right) + e_j
\end{aligned}
$$

where s(x) represents an additive smooth function and (by = Period) indicates that a separate smooth was estimated for each Period. A random intercept was estimated for each ComplexName and Period combination, and additionally factor specific smooths were fitted for each ComplexName and Period combination to account for individual variation. These factor smooths s(Distance, ComplexName, by = Period) were penalised more heavily to ensure a greater degree of variance was estimated by the global s(Distance, by = Period) term.

Using this model, the apparent fishing effort response to OWF construction over distance was quantified as the difference between the smooth of AFH as predicted by Distance for the post-construction period and the corresponding smooth for the pre-construction period. Regions of significant change in fishing intensity were identified by examining the first derivative of this difference and marking areas where the confidence interval for this first derivative did not overlap zero (Fig. 3B). This represents areas where the difference between the pre-construction and post-construction predictions were changing, with the understanding that areas where this was not changing represent areas where there is no change in apparent fishing patterns. This was calculated using adapted forms of the difference_smooths() and derivatives.gam() functions from the 'gratia' R package (Simpson, 2024), which take advantage of the linear predictor matrix alongside the covariance matrix to calculate the derivative and simulate confidence intervals.

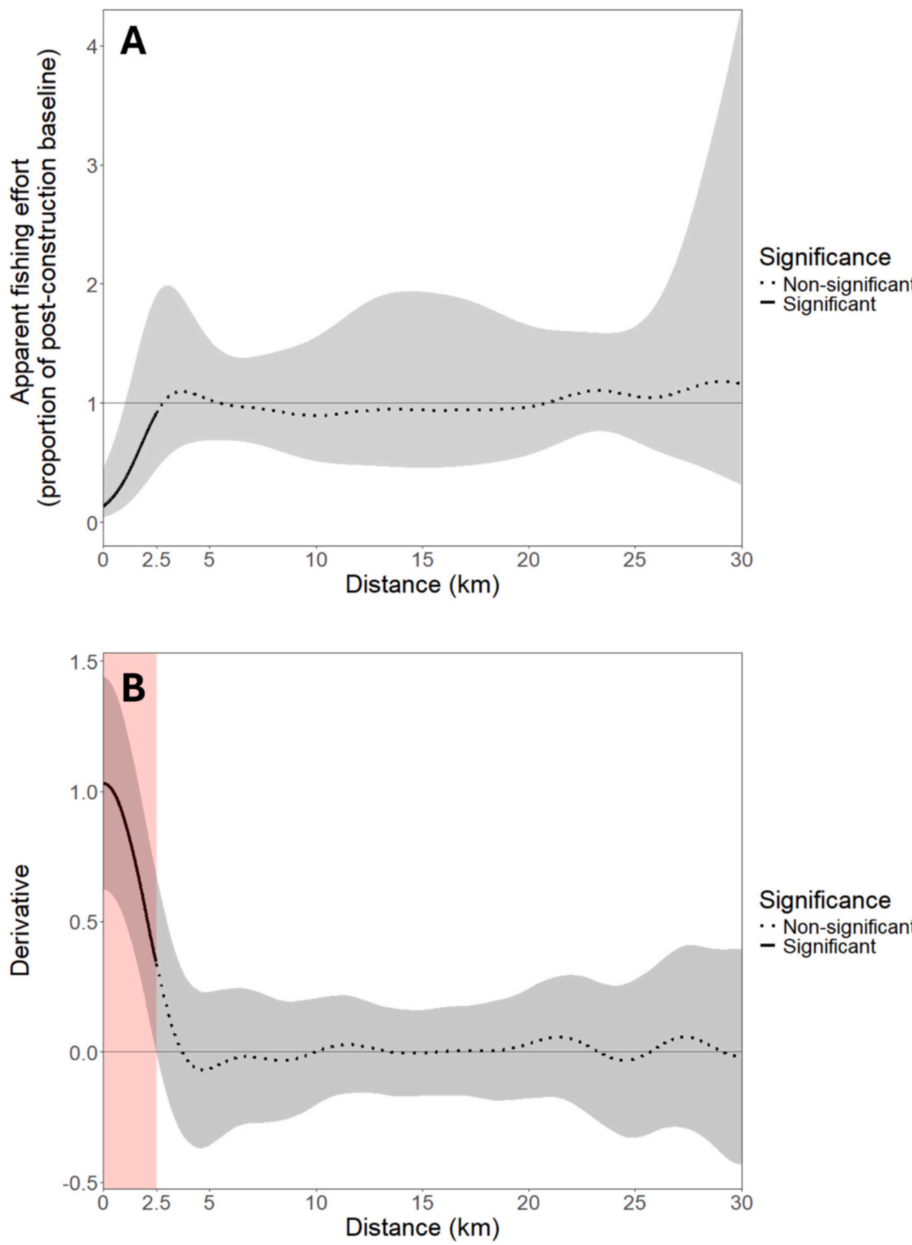


Fig. 3. (A) Predicted response of apparent fishing effort by distance from an OWF, expressed as a proportion of the estimated baseline. The solid line indicates regions where the derivative is significantly different from zero. Predictions are shown on the response scale. (B) Derivative of the predicted response, calculated from the response on the link scale.

To calculate final fishing intensity values, the intercept was taken from the post-construction period, while the smooth response over distance was derived from the difference between the post- and pre-construction smooths. Since these smooths are each centred around zero, the total fishing intensity reflected post-construction values (as derived from the intercept) but was spatially distributed in a way that directly attributed changes to the influence of OWF construction.

2.2.4. Gear type-specific models

Differences between gear types were assessed through a similar method to the overall BAG. Ideally, the gear type analysis would have been performed by including as a term within the overall model. However, distributions differed sufficiently between gear types owing to differing degrees of zero-inflation and so this was not possible. Instead, separate models were run for each gear type. Model selection was unchanged between the HGAMM for overall fishing and the HGAMM for individual gear types. As such, the final model for each gear type was:

$$
\begin{aligned}
&FishingIntensity_j &&\sim tweedie\left(\mu_j\right)\\
&ComplexName_j : Period_j &&\sim N\left(0, \sigma_{ComplexName_j:Period_j}\right)\\
&E\left(FishingIntensity_j\right) &&= \mu_j\\
&log\left(\mu_j\right) &&= \beta + Period_j + s\left(\mathrm{Distance}_j, by = Period\right)\\
& && + ComplexName_j : Period_j\\
& && + s\left(Distance_j, ComplexName_j, by = Period\right)\\
& && + offset\left(log\left(TimeDiff_j\right)\right) + e_j
\end{aligned}
$$

Regions of change were then calculated using the same approach as for the overall model.

2.3. Model interpretation

Following the identification of significant periods of change, a baseline fishing intensity was calculated as the mean of all values from non-significant periods of change. The effect was reported as the modelled apparent fishing effort response expressed as a proportion of this baseline. A confidence interval for the restrictive effect was calculated by simulating 10,000 posterior draws from the model and calculating the baseline predicted fishing intensity for each, and subsequently the fishing intensity as a proportion of the baseline at each distance. The confidence interval for each distance was then approximated by retaining only the central 95 % of values for this proportion.

3. Results

3.1. Total apparent fishing hours

Pre-construction apparent fishing effort was modelled from a total of 1.9 million apparent fishing hours and post-construction apparent fishing effort was modelled from a total of 2.6 million apparent fishing hours. Each individual gear type experienced more apparent fishing hours post-construction than pre-construction. Trawler fishing was the most common gear type, comprising 73 % of the total pre-construction effort and 68 % of the total post-construction effort. Seine fishing was the least common type at only 2 % of both the total pre- and post-construction effort.

3.2. Overall fishing effort response

There was a statistically significant reduction of fishing effort within and near to OWFs. Post-construction, the apparent fishing effort within OWFs was reduced by 87 % (95 % CI: 55 %, 96 %) of the baseline value (Table 1), with fishing effort significantly reduced up to 2.5 km from the site (Fig. 3A). After the statistically significant increase to the baseline, fishing effort remained relatively constant around the baseline up to the 30 km buffer, suggesting no impacts beyond 2.5 km. Although there is a slight 'hump' over the baseline at the point where the impact ends, as would be expected if fishers were 'fishing the line', this is not a statistically significant period of change so cannot be responsibly interpreted as such (Fig. 3A, B).

3.3. Gear type specific responses

Trawlers, accounting for the majority of apparent fishing effort, revealed a similar displacement pattern to the overall model, with a statistically significant restriction before a continuously non-significant baseline (Fig. 4B). Trawling effort within the OWF area declined by 93 % (95 % CI: 86 %, 97 %) relative to baseline levels, with significant reduction in apparent fishing effort extending up to 3.7 km from the OWF (Table 1), over a kilometre further than in the overall fishing effort model.

Seine fishing revealed a similar response to the overall model, with a statistically significant reduction near to the OWF then a return to a non-significant baseline (Fig. 4C). Seine fishing demonstrated the most pronounced 'hump' after the reduction, with a modelled increase to over double the baseline fishing value, however, the derivative is not significant and similarly should not be interpreted as 'fishing the line'. Fishing effort is reduced by 93 % (95 % CI: 65 %, 99 %) of the baseline value within OWFs and is significantly reduced up to 4.2 km from the OWF (Table 1).

In contrast, fixed gear exhibited no response, with no statistically significant reduction in fishing within and near to the OWF area (Fig. 4E, Table 1).

Dredge fishing similarly did not reveal significant effects within the OWF, though there was a period of significant change between 2.1 and 3.2 km (Table 1). This period of significance arises from a period of reduced uncertainty in the data at this distance rather than a pronounced change in the derivative (Extended Data Fig. 1), with the shape of both the derivative and the response curve mimicking other gear types but exhibiting much greater uncertainty over the return to the baseline.

Other fishing methods, encompassing either unclassified fishing effort or gear types that did not fit into any of the overarching gear type groupings, showed trends similar to overall fishing effort (Fig. 5F), with a significant reduction in effort by 78 % (95 % CI: 33 %, 93 %) of baseline levels within the OWF area, with the restrictive effect extending up to 3.3 km from the OWF (Table 1).

4. Discussion

4.1. Overall effect

The findings from this research, which look across 34 OWFs over a period of eight years, present compelling evidence of a spatial impact on fishing activities, extending approximately 2.5 km beyond the boundaries of OWFs. While there has always been an expectation that fishing is restricted by the presence of OWFs (Mackinson et al., 2006; Kafas et al., 2018; Silva et al., 2023), little work has been done to quantify this change. Recent research in the UK has established that effort from bottom-towed gear is significantly reduced within OWFs, but when sampled at a 5 km resolution could not resolve any effects beyond this (Dunkley and Solandt, 2022). However, our research suggests that the deterrent effect of OWFs on fishing is not strictly limited to their formal borders but extends into nearby areas, even further than the extent of any *de jure* safety zones, which can only extend 500 m under the United Nations Convention on the Law of the Seas article 60 (1982).

This shows OWFs represent a de facto barrier to fishing. It is likely that this barrier arises primarily from safety concerns, which in interviews with fishers have been raised as a primary deterrent (Mackinson et al., 2006; Gray et al., 2016). It is unsurprising, therefore, that fishing activity is reduced not only within OWFs but also in surrounding areas. The risk of gear entrapment or turbine collision persists even when fishing outside the borders of the OWF much as it does within. Notably, at distances under 500 m outside the OWF, it is conceivable that a point may be closer to a turbine than when within the OWF, due to the typical spacing between turbines (based on an average rotor diameter of 100–150 m and the spacing between turbines being ~10 rotor diameters (Howland et al., 2019)).

Table 1
Key values from the data and models for both overall fishing activity and individual gear types.

Gear Type	Pre-construction Effort (hours)	Post-construction Effort (hours)	EDF Pre	EDF Post	Effort Within OWF (% of Baseline)	Region of Significant Change (km)
All Fishing	1,940,813	2,594,700	~1	~13	13 % (4 %, 45 %)	Up to 2.5 km
Trawlers	1,415,047	1,785,977	~1	~8	7 % (3 %, 14 %)	Up to 3.7 km
Fixed Gear	182,386	243,761	~2.7	~4	64 % (19 %, 214 %)	No significant reduction
Dredge Fishing	117,478	188,276	~2.4	~6.4	18 % (3 %, 125 %)	2.1–3.2 km
Seiners	33,312	62,573	~2.7	~7.1	7 % (1 %, 35 %)	Up to 4.2 km
Other Fishing	193,006	317,070	~2.9	~7.7	22 % (7 %, 67 %)	Up to 3.3 km

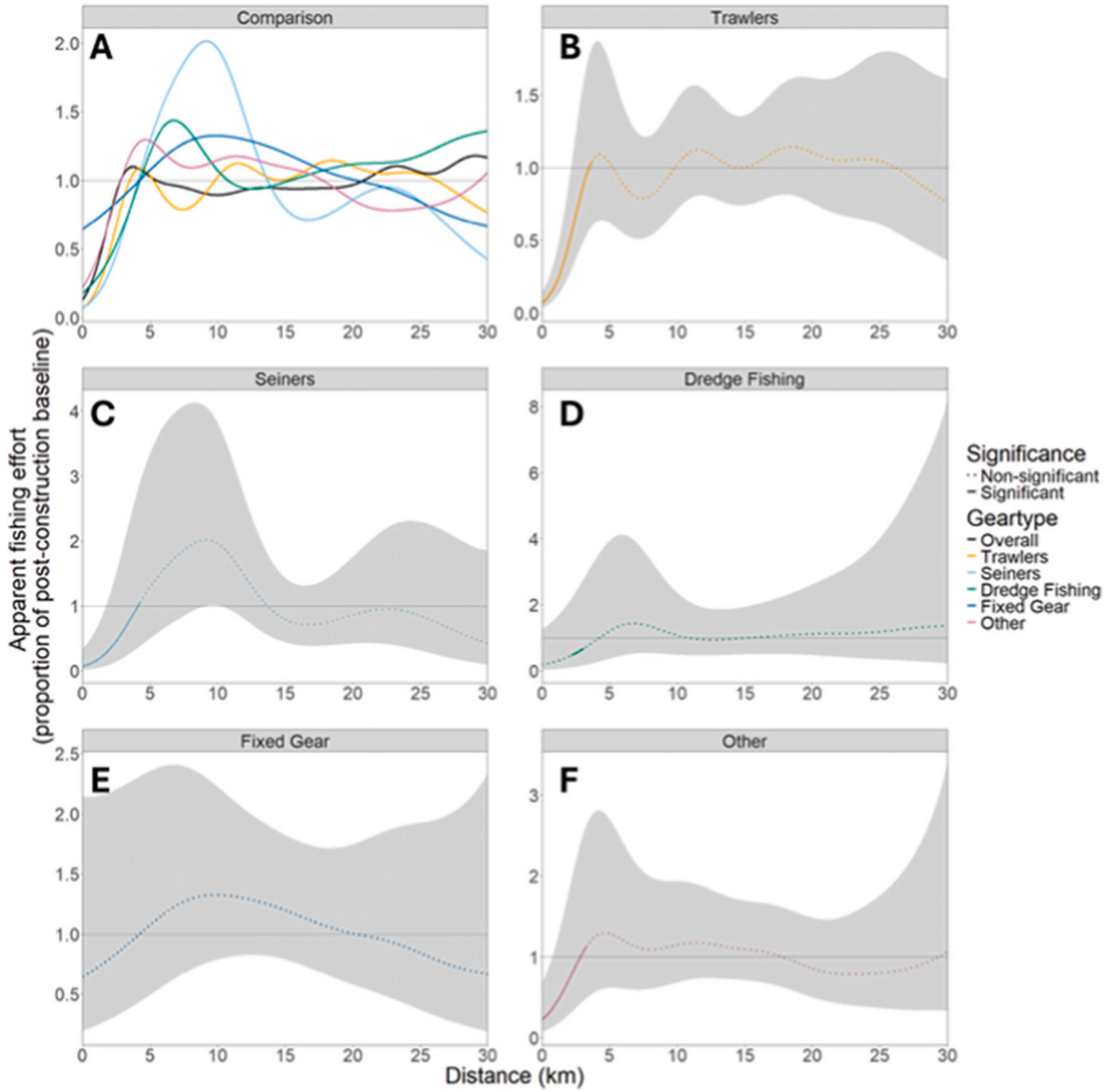


Fig. 4. (A) Comparison of predicted responses for each gear type with the overall model from Fig. 3A, all presented on the response scale. (B—F) Predicted responses for individual gear types, including associated uncertainty. Solid lines indicate regions where the derivative is significantly different from zero. Predictions are given on the response scale, with error bars and derivatives calculated on the link scale and transformed.

A reduction in fish stocks at OWF sites, whether actual or only perceived, could contribute to a decline in apparent fishing effort around OWFs. The expectation of reduced stocks alone, as is a repeated fear outlined by fishers (Gray et al., 2016; Hogan et al., 2023), would be sufficient to reduce apparent fishing effort as fishers avoid the grounds, even if not borne out in reality. Even an overall biomass increase could be driven by non-target species with a reduction in target species.

4.2. Individual gear types

The apparent fishing effort response to OWF construction varies by gear type. Broadly, this suggests that the effect is not a general response for vessels fishing near OWFs. Instead, it indicates that inherent characteristics of each gear type influence how fishing activity is affected, with some gear types being more or less willing to operate in the vicinity of OWFs due to the nature of their interaction with these structures. Alongside any threat to vessel safety from OWF presence, there is further risk of gear entanglement from any towed gear types (Alexander et al., 2013).

4.3. Fixed gear

Most notably different from the overall response is fixed gear fishing, which appears to be unaffected post-OWF construction. In our dataset, fixed gear was represented predominantly by static gillnets (71 % of identified apparent fishing effort for the gear type) and pots and traps (22 % of identified apparent fishing effort for the gear type). Fixed gear fisheries have been highlighted as a candidate for co-location with OWFs (Hooper et al., 2015), as there is no substantially increased risk of gear snags as compared to deployment in any other rocky area (Alexander et al., 2013), while the increase in hard substrates can increase target species abundance (Hooper and Austen, 2014). Despite this, vessel safety from entering the OWF is consistently raised as a concern in the context of fixed gear fisheries (Hooper and Austen, 2014; Hooper et al., 2015), despite there being no restrictive effect evident on fixed gear fishing. Conceivably, while this could indicate a simple lack of any impact of the OWF on apparent fishing effort, this could equally represent the counteracting impacts of a generalised reduction in effort from vessel safety concerns, alongside a specific increase in effort for fixed gear types within OWFs.

4.4. Dredge fishing

Dredge fishing revealed no significant periods of change within and near to the OWFs. It is surprising not to detect a reduction in apparent fishing effort for dredge fishing, a bottom-contacting gear type that would be expected to be considerably impacted by OWF infrastructure.

It is worth considering that the shape displayed by the response is similar to that of the overall model and there is a period of significant change between 2.1 and 3.2 km. This presents an alternative interpretation of the response of dredge fishing, suggesting a reduction in apparent fishing effort within and near to the OWF, with the fishing effort only beginning to return to baseline values at 2.1 km from the OWF, in contrast to the immediate returns to baseline in all other gear types with significant periods of change.

However, given the error bars in the derivative (Extended Data Fig. 1), there is considerable uncertainty around the model and the statistically significant period of change is a consequence of reduced uncertainty for that period and not from any increase in the predicted derivative at those points. Notably, dredge fishing was observed at the fewest OWFs, as shown in the relative abundance figures in the extended data (Extended Data fig. 2).

This pattern is likely influenced by how dredge fishing is classified in GFW data. Unlike some of the other gear types, dredge fishing is classified primarily by matching vessels to known registers, rather than inferring the gear type from movement patterns (Taconet et al., 2019). While this does not inherently affect the ability to uncover patterns, it may contribute to a higher proportion of zero-values in the data for certain regions or countries where vessel and gear type information is unavailable. This prevalence of zero-values limits the capacity of some OWFs to demonstrate reductions in dredge fishing activity, particularly as sites with no recorded fishing before construction are not able to exhibit declines. As such, at this stage we instead cautiously choose to interpret this as showing no reduction in apparent fishing effort as a response to OWF construction.

4.5. Trawlers and 'other'

It is not surprising to see trawlers, comprising the majority of all apparent fishing effort sampled, display a very similarly shaped response to that from the overall model. However, the period of significant change is recovered over a kilometre further out than the overall model. The most likely explanation for this is that the overall model's effect is diluted by the inclusion of the fixed gear and dredge fishing gear types with no significant impact. 'Other' fishing also showed a very similar pattern to trawler fishing, suggesting that much of the effort classified as 'other' is more trawler fishing that was not correctly attributed in the GFW dataset.

4.6. Seiners

Seiners exhibited the greatest degree of fishing effort restriction in response to OWF construction. As a highly mobile gear type requiring large operational areas for net encircling of target shoals, it is unsurprising that this gear type is most impacted by OWF construction. Seiners rely on both sufficient space and flexibility with their surroundings to effectively track target shoals, and as such any safety considerations are amplified by the mobile nature of this fishing method.

4.7. Spillover effect and 'fishing the line'

A spillover effect is seen where area-based restrictions on catches lead to higher target species abundances outside the restricted area (Roberts et al., 2001). 'Fishing the line' is a concept introduced as a response to this spillover effect, describing the tendency for fishers to concentrate effort at the boundary of a no-take reserve to maximise yield from the spillover effect (Kellner et al., 2007). Given this research demonstrates OWFs act as areas of restricted fishing effort, and OWFs have been proposed to have positive effects on target species abundance, we might expect to see a spillover effect and consequently similar pattern of 'fishing the line'. However, any biomass spillover is not necessarily an immediate consequence of a fisheries closure, and may take time to develop (Barceló et al., 2021).

As such, it is interesting to see a repeated motif of the 'hump' after the return to the baseline (Fig. 3A; Fig. 4B-D, F). However, in no case is this hump recovered as a statistically significant period of change (i.e. neither the climb above the baseline, nor the return to the baseline from the peak were statistically significant). Although we do not want to dismiss the idea of 'fishing the line' applying to OWFs, we do not recover any substantive evidence and the repeated motif could simply be an artefact of spline formation overshooting the baseline value following a steep climb.

It is important to note that apparent fishing effort is not a perfect proxy for total catch. For example, an increase in catch per unit effort, as might result from spillover effects, could allow fishers to meet catch targets with less time spent fishing. Therefore, a reduction in fishing effort, whether inside or outside the OWF, does not necessarily indicate a decrease in total catches. Additionally, individual variations in behaviour may obscure any overall pattern. The 'line' where fishers choose to concentrate their efforts may vary between individuals, wind farms and numerous other factors meaning the 'hump' in fishing activity may not occur at a consistent distance from the OWF.

4.8. Interpretive caveats

It is important to note that this analysis, which is based on interpretation of patterns of apparent fishing effort derived from AIS data, is restricted by limitations of this methodology. Within the EU, AIS transponders are only mandatory on vessels over 15 m in length (The European Commission, 2011). With over 80 % of the fishing fleet in the Northeast Atlantic comprising vessels under 12 m (Taconet et al., 2019), there is a considerable degree of fishing effort that is likely unrepresented in the data used in this analysis.

While we expect that the patterns we uncover in larger vessels are transferable to smaller vessels, it would be logical to expect that smaller vessels are less affected by turbine presence. While the risk of collision still applies, smaller vessels would be less vulnerable owing to their size and greater manoeuvrability and so may have fewer reservations of fishing nearby to OWFs. However, most smaller vessels are not expected to operate in offshore areas and vessels under 15 m in length may still voluntarily use AIS transponders (Taconet et al., 2019; Gray et al., 2016).

AIS data are also dependent on both signal reception and compliance, both affecting representativity of the AIS data. AIS reception is poor in the North Sea, particularly far offshore, but also at distances from shore where OWFs are sited (Taconet et al., 2019). Furthermore, gaps in AIS data can arise from vessels disabling AIS (Shepperson et al., 2018).

An important nuance in interpreting these results is that this approach cannot differentiate between a uniformly moderate response and a bimodal response, where avoidance of OWFs is highly pronounced under certain conditions (e.g. during poor weather) and significantly reduced in others. This means that the observed pattern may, in reality, represent a time-weighted average of diverse, context-specific responses. As such, while our research shows the average response of fishing effort to OWF construction, this cannot be used to inform on the mechanisms behind this restriction.

We emphasise that these caveats do not undermine the validity of our results. For these factors to substantially impact our findings, they would need to introduce a systematic bias that disproportionately affects either control or impact areas, and only during either the pre- or post-construction period. A uniform decrease in activity would still preserve the overall pattern observed, merely altering the absolute values calculated. Indeed, we propose that these results emerge despite these limitations, rather than as a consequence of them.

4.9. OWFs as conservation tools

It has been proposed to varying degrees that OWFs could, as a consequence of reducing fishing pressure along with potential habitat creation benefits, act beneficially for conservation, potentially as MPAs or OECMs (e.g. Punt et al., 2009; Inger et al., 2009; Ashley et al., 2014; Hammar et al., 2016). While there is considerable hesitancy about affording OWFs an official area-based conservation designation across a number of concerns (e.g. Blyth-Skyrme, 2011; Rees et al., 2015; Ashley et al., 2018; Stephenson, 2023), our research confirms that OWFs do reduce fishing, the largest threat to marine ecosystems in Europe (Gascuel et al., 2016; Mazaris et al., 2019), within and nearby. While it has been understood that OFWs have the potential to reduce fishing, this is typically framed through the lens of encouraging careful siting that minimises displacement (DECC, 2009). We propose a more nuanced approach, which involves taking advantage of this restrictive effect to amplify marine conservation efforts.

As a large number of new OWFs are considered, discussions about siting must take into account other relevant parties to ensure equitable outcomes (Stokesbury et al., 2022). However, simply minimising the footprint of OWFs is not the only option. The capacity for OWFs to reduce fishing is clear de facto protection from a threat, which is a powerful tool given the lack of real *de jure* restrictions on fishing in many existing protected areas (Dunkley and Solandt, 2021). OWFs alone are not sufficient as MPAs or OECMs (Stephenson, 2023) but OWFs have already been used to support efforts to reduce destructive fishing on a site ostensibly under existing protection (Ashley et al., 2018). Leveraging this de facto restrictive effect can bolster existing protections, or if placed appropriately, improve connectivity between other protected sites to amplify coherence (Adams et al., 2014).

5. Conclusion

OWFs have been likened to marine reserves in their potential to restrict fishing activity. Our research confirms that OWF construction significantly reduces fishing effort, but we find no evidence that this displaced effort is redistributed to areas immediately surrounding OWFs, nor is there a local increase in fishing activity to exploit potential spillover effects. Instead, we demonstrate that highly mobile gear types, such as trawlers and seiners, experience reduced fishing effort up to 4.2 km beyond OWF boundaries.

This impact on fishing grounds has important ramifications for fishers as key marine resource users. However, rather than solely focusing on mitigating the footprint of OWFs on fisheries, we argue for a more nuanced approach that considers OWFs as a possible tool to manage fishing pressure in targeted areas. With the rapidly increasing rate of OWF construction, it is vital that OWFs are carefully sited through effective marine spatial planning, but a key aspect of this could include consideration of the de facto fisheries exclusions to support marine conservation objectives and the developing discussions of marine net gain that might arise from human introduced structures in the sea.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2025.179973.

CRediT authorship contribution statement

Benjamin Fitkov-Norris: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation. **Matthew J. Witt:** Writing – review & editing, Validation, Supervision, Project administration. **Benno I. Simmons:** Writing – review & editing, Validation, Supervision, Project administration, Formal analysis.

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.

Acknowledgements

BF-N was funded via a doctoral training grant awarded as part of the UKRI AI Centre for Doctoral Training in Environmental Intelligence (UKRI grant number EP/S022074/1).

Data availability

Data will be made available on request.

References

Adams, T.P., Miller, R.G., Aleynik, D., Burrows, M.T., 2014. Offshore marine renewable energy devices as stepping stones across biogeographical boundaries. J. Appl. Ecol. 51 (2), 330–338. https://doi.org/10.1111/1365-2664.12207.

Alexander, K.A., Potts, T., Wilding, T.A., 2013. Marine renewable energy and Scottish west coast fishers: exploring impacts, opportunities and potential mitigation. Ocean & Coastal Management 75, 1–10. https://doi.org/10.1016/j.ocecoaman.2013.01.005.

Ashley, M., Austen, M., Rodwell, L., Mangi, S.C., 2018. Co-locating offshore wind farms and marine protected areas. In: Yates, K.L., Bradshaw, C.J.A. (Eds.), Offshore Energy and Marine Spatial Planning, 1st ed. Routledge. https://doi.org/10.4324/9781315666877.

Ashley, M.C., Mangi, S.C., Rodwell, L.D., 2014. The potential of offshore windfarms to act as marine protected areas – A systematic review of current evidence. Mar. Policy 45, 301–309. https://doi.org/10.1016/j.marpol.2013.09.002.

Barceló, C., White, J.W., Botsford, L.W., Hastings, A., 2021. Projecting the timescale of initial increase in fishery yield after implementation of marine protected areas. ICES J. Mar. Sci. 78 (5), 1860–1871. https://doi.org/10.1093/icesjms/fsaa233.

Blyth-Skyrme, R.E., 2011. Benefits and disadvantages of Co-locating windfarms and marine conservation zones; report to Collaborative Offshore Wind Research Into the Environment Ltd., London, December 2010, p. 37.

Centro Tecnologico del Mar - Fundación (CETMAR), 2023. EMODnet Human Activities, Energy, Wind Farms [Dataset]. EMODnet. https://ows.emodnet-humanactivities.eu/geonetwork/srv/api/records/8201070b-4b0b-4d54-8910-abcea5dce57f?language=all.

Centro Tecnologico del Mar - Fundación (CETMAR), 2024. EMODnet Human Activities, Energy, Wind Farms [Dataset]. EMODnet. https://ows.emodnet-humanactivities.eu/geonetwork/srv/api/records/8201070b-4b0b-4d54-8910-abcea5dce57f?language=all.

Clavelle, T., Joo, R., Miller, N., 2023. Gfwr: interactions with GFW APIs providing data Tibbles. [computer software]. https://github.com/GlobalFishingWatch/gfwr.

Commission Directive 2011/15/EU of 23 February 2011 Amending Directive 2002/59/EC of the European Parliament and of the Council Establishing a Community Vessel Traffic Monitoring and Information systemText with EEA Relevance, 2011/15/EU (2011).

Convention on Biological Diversity, 2018. Decision adopted by the conference of the parties to the convention on biological diversity 14/8. Protected areas and other effective area-based conservation measures. (CBD/COP/DEC/14/8).

Costanzo, G., Brindley, G., 2024. Wind Energy in Europe—2023 Statistics and the Outlook for 2024–2030. WindEurope.

DECC, 2009. UK Offshore Energy Strategic Environmental Assesment (OESEA): Environmental Report. Department of Energy & Climate Change.

Dunkley, F., Solandt, J.-L., 2021. Marine unprotected areas: A case for a just transition to ban bottom trawl and dredge fishing in offshore marine protected areas (p. 50) [Unpublished]. Marine Conservation Society.

Dunkley, F., Solandt, J.-L., 2022. Windfarms, fishing and benthic recovery: overlaps, risks and opportunities. Mar. Policy 145, 105262. https://doi.org/10.1016/j.marpol.2022.105262.

Ellis, J.I., Schneider, D.C., 1997. Evaluation of a Gradient Sampling Design for Environmental Impact Assessment.

Galparsoro, I., Menchaca, I., Garmendia, J.M., Borja, Á., Maldonado, A.D., Iglesias, G., Bald, J., 2022. Reviewing the ecological impacts of offshore wind farms. Npj Ocean Sustainability 1 (1), 1. https://doi.org/10.1038/s44183-022-00003-5.

Gascuel, D., Coll, M., Fox, C., Guénette, S., Guitton, J., Kenny, A., Knittweis, L., Nielsen, J.R., Piet, G., Raid, T., Travers-Trolet, M., Shephard, S., 2016. Fishing impact and environmental status in E uropean seas: a diagnosis from stock assessments and ecosystem indicators. Fish Fish. 17 (1), 31–55. https://doi.org/10.1111/faf.12090.

Gill, A.B., 2005. Offshore renewable energy: ecological implications of generating electricity in the coastal zone: ecology and offshore renewable energy. J. Appl. Ecol. 42 (4), 605–615. https://doi.org/10.1111/j.1365-2664.2005.01060.x.

Global Fishing Watch, 2025. updated daily. 4Wings API V3, 2015-01-01 to 2023-10-27. Data set accessed 2023-11-06 at. https://globalfishingwatch.org/our-apis/. Disclaimer: Global Fishing Watch has made every attempt to ensure the completeness, accuracy and reliability of the information provided on this Site. However, due to the nature and inherent limitations in source materials for information provided, Global Fishing Watch qualifies all designations of vessel fishing activity, including synonyms of the term “fishing activity,” such as “fishing” or “fishing effort,” as “apparent,” rather than certain. And accordingly, the information is provided “as is” without warranty of any kind.

Gray, M., Stromberg, P.-L., & Rodmell, D. (2016). Changes to fishing practices as a result of the development of offshore windfarms—phase 1 (revised) (p. 121). The crown estate. ISBN: 978-1-906410-64-3 https://www.thecrownestate.co.uk/media/2600/final-published-ow-fishing-revised-aug-2016-clean.pdf.

Halouani, G., Villanueva, C.-M., Raoux, A., Dauvin, J.C., Ben Rais Lasram, F., Foucher, E., Le Loc'h, F., Safi, G., Araignous, E., Robin, J.P., Niquil, N., 2020. A spatial food web model to investigate potential spillover effects of a fishery closure in an offshore wind farm. J. Mar. Syst. 212, 103434. https://doi.org/10.1016/j.jmarsys.2020.103434.

Hammar, L., Perry, D., Gullström, M., 2016. Offshore wind power for marine conservation. Open Journal of Marine Science 06 (01), 66–78. https://doi.org/10.4236/ojms.2016.61007.

Hijmans, R.J., 2024. Terra: spatial data analysis [computer software]. https://CRAN.R-project.org/package=terra.

Hogan, F., Hooker, B., Jensen, B., Johnston, L., Lipsky, A., Metratta, E., Silva, A., Hawkins, A., 2023. Fisheries and Offshore Wind Interactions: Synthesis of Science. Northeast Fisheries Science Center.

Hooper, T., Austen, M., 2014. The co-location of offshore windfarms and decapod fisheries in the UK: constraints and opportunities. Mar. Policy 43, 295–300. https://doi.org/10.1016/j.marpol.2013.06.011.

Hooper, T., Ashley, M., Austen, M., 2015. Perceptions of fishers and developers on the co-location of offshore wind farms and decapod fisheries in the UK. Mar. Policy 61, 16–22. https://doi.org/10.1016/j.marpol.2015.06.031.

Howland, M.F., Lele, S.K., Dabiri, J.O., 2019. Wind farm power optimization through wake steering. Proc. Natl. Acad. Sci. 116 (29), 14495–14500. https://doi.org/10.1073/pnas.1903680116.

Inger, R., Attrill, M.J., Bearhop, S., Broderick, A.C., James Grecian, W., Hodgson, D.J., Mills, C., Sheehan, E., Votier, S.C., Witt, M.J., Godley, B.J., 2009. Marine renewable energy: potential benefits to biodiversity? An urgent call for research. J. Appl. Ecol. 46 (6), 1145–1153. https://doi.org/10.1111/j.1365-2664.2009.01697.x.

Jay, S., 2012. Marine space: Manoeuvring towards a relational understanding. Journal of Environmental Policy & Planning 14 (1), 81–96. https://doi.org/10.1080/1523908X.2012.662383.

Kafas, A., Donohue, P., Davies, I., Scott, B.E., 2018. Displacement of existing activities. In: Yates, K.L., Bradshaw, C.J.A. (Eds.), Offshore Energy and Marine Spatial Planning, 1st ed. Routledge. https://doi.org/10.4324/9781315666877.

Kellner, J.B., Tetreault, I., Gaines, S.D., Nisbet, R.M., 2007. Fishing the line near marine reserves in single and multispecies fisheries. Ecol. Appl. 17 (4), 1039–1054. https://doi.org/10.1890/05-1845.

Kroodsma, D.A., Mayorga, J., Hochberg, T., Miller, N.A., Boerder, K., Ferretti, F., Wilson, A., Bergman, B., White, T.D., Block, B.A., Woods, P., Sullivan, B., Costello, C., Worm, B., 2018. Tracking the global footprint of fisheries. Science 359 (6378), 904–908. https://doi.org/10.1126/science.aao5646.

Mackinson, S., Curtis, H., Brown, R., McTaggart, K., Taylor, N., Neville, S., Rogers, S., 2006. A Report on the Perceptions of the Fishing Industry into the Potential Socio-Economic Impacts of Offshore Wind Energy Developments on their Work Patterns and Income. CEFAS, pp. 1–62.

Mazaris, A.D., Kallimanis, A., Gissi, E., Pipitone, C., Danovaro, R., Claudet, J., Rilov, G., Badalamenti, F., Stelzenmüller, V., Thiault, L., Benedetti-Cecchi, L., Goriup, P., Katsanevakis, S., Fraschetti, S., 2019. Threats to marine biodiversity in European protected areas. Sci. Total Environ. 677, 418–426. https://doi.org/10.1016/j.scitotenv.2019.04.333.

Methratta, E.T., 2020. Monitoring fisheries resources at offshore wind farms: BACI vs. BAG designs. ICES J. Mar. Sci. 77 (3), 890–900. https://doi.org/10.1093/icesjms/fsaa026.

Methratta, E.T., 2021. Distance-based sampling methods for assessing the ecological effects of offshore wind farms: synthesis and application to fisheries resource studies. Front. Mar. Sci. 8, 674594. https://doi.org/10.3389/fmars.2021.674594.

Methratta, E.T., Dardick, W.R., 2019. Meta-analysis of finfish abundance at offshore wind farms. Reviews in Fisheries Science & Aquaculture 27 (2), 242–260. https://doi.org/10.1080/23308249.2019.1584601.

Pedersen, E.J., Miller, D.L., Simpson, G.L., Ross, N., 2019. Hierarchical generalized additive models in ecology: an introduction with mgcv. PeerJ 7, e6876. https://doi.org/10.7717/peerj.6876.

Punt, M.J., Groeneveld, R.A., van Ierland, E.C., Stel, J.H., 2009. Spatial planning of offshore wind farms: a windfall to marine environmental protection? Ecol. Econ. 69 (1), 93–103. https://doi.org/10.1016/j.ecolecon.2009.07.013.

Püts, M., Kempf, A., Möllmann, C., Taylor, M., 2023. Trade-offs between fisheries, offshore wind farms and marine protected areas in the southern North Sea – winners, losers and effective spatial management. Mar. Policy 152, 105574. https://doi.org/10.1016/j.marpol.2023.105574.

Rees, S., Foster, N., Langmead, O., Griffiths, C., 2015. Assessment of the Ecological Coherence of the MPA Network in the Celtic Seas: A Report for WWF-UK by the Marine Institute. Plymouth University and The Marine Biological Association of the United Kingdom, Marine Institute, Plymouth University.

Roberts, C.M., Bohnsack, J.A., Gell, F., Hawkins, J.P., Goodridge, R., 2001. Effects of marine reserves on adjacent fisheries. Science 294 (5548), 1920–1923. https://doi.org/10.1126/science.294.5548.1920.

Rochette, S., 2019. Cartomisc: miscellaneous tools for spatial data manipulation and analysis. [computer software]. https://statnmap.github.io/cartomisc/.

Shepperson, J.L., Hintzen, N.T., Szostek, C.L., Bell, E., Murray, L.G., Kaiser, M.J., 2018. A comparison of VMS and AIS data: the effect of data coverage and vessel position recording frequency on estimates of fishing footprints. ICES J. Mar. Sci. 75 (3), 988–998. https://doi.org/10.1093/icesjms/fsx230.

Silva, A., Chaji, M., Ten Brink, T., Ebbin, S., Trumbull, N., Smythe, T., Thunberg, E., 2023. Fishing Operation Effects. Synthesis of Science. Northeast Fisheries Science Center, In Fisheries and Offshore Wind Interactions.

Simpson, G., 2024. Gratia: graceful ggplot-based graphics and other functions for GAMs fitted using mgcv. [computer software]. https://gavinsimpson.github.io/gratia/.

Stelzenmüller, V., Gimpel, A., Haslob, H., Letschert, J., Berkenhagen, J., Brüning, S., 2021. Sustainable co-location solutions for offshore wind farms and fisheries need to account for socio-ecological trade-offs. Sci. Total Environ. 776, 145918. https://doi.org/10.1016/j.scitotenv.2021.145918.

Stelzenmüller, V., Letschert, J., Gimpel, A., Kraan, C., Probst, W.N., Degraer, S., Döring, R., 2022. From plate to plug: the impact of offshore renewables on European fisheries and the role of marine spatial planning. Renew. Sust. Energ. Rev. 158, 112108. https://doi.org/10.1016/j.rser.2022.112108.

Stephenson, P. (2023). Maritime spatial planning in Europe. Discussion Paper on the Challenges and Potential Opportunities around the Colocation of Offshore Wind Energy with Marine Protected Areas. Report for the Renewables Grid Initiaitive, Berlin, Germany.

Stokesbury, K.D.E., Fay, G., Griffin, R., 2022. A framework for categorizing the interactions of offshore windfarms and fisheries. ICES J. Mar. Sci. 79 (6), 1711–1718. https://doi.org/10.1093/icesjms/fsac118.

Taconet, M., Kroodsma, D., Fernandes, J.A., 2019. Food and Agriculture Organization of the United Nations, Global Fishing Watch, AZTI-Tecnalia, & Seychelles Fishing Authority. Global atlas of AIS-based fishing activity, Challenges and opportunities. http://www.fao.org/3/ca7012en/CA7012EN.pdf.

Thoya, P., Maina, J., Möllmann, C., Schiele, K.S., 2021. AIS and VMS ensemble can address data gaps on fisheries for marine spatial planning. Sustainability 13 (7), 3769. https://doi.org/10.3390/su13073769.

United Nations General Assembly, 1982. United Nations convention on the law of the sea. https://www.un.org/depts/los/convention_agreements/texts/unclos/unclos_e.pdf.

Van Hoey, G., Bastardie, F., Birchenough, S., De Backer, A., Gill, A., De Koning, S., Hodgson, S., Mangi Chai, S., Steenbergen, J., Termeer, E., van den Burg, S., Hintzen, N.T., 2021. Overview of the effects of offshore wind farms on fisheries and aquaculture. European Commission 1–99. https://data.europa.eu/doi/10.2826/63640.

Vandendriessche, S., Hostens, K., Courtens, W., Stienen, E., 2014. Fisheries Activities Change in the Vicinity of Offshore Wind Farms.

Wood, S., 2017. Mgcv: generalized additive models: an introduction with R [computer software]. https://cran.r-project.org/web/packages/mgcv/.

Zuur, A. F., Ieno, E. N., Walker, N. J., Saveliev, A. A., & Smith, G. M. (2009). Violation of Independence—Part I. In A. F. Zuur, E. N. Ieno, N. Walker, A. A. Saveliev, & G. M. Smith, Mixed Effects Models and Extensions in Ecology with R (pp. 143–160). Springer New York. doi:https://doi.org/10.1007/978-0-387-87458-6_3.