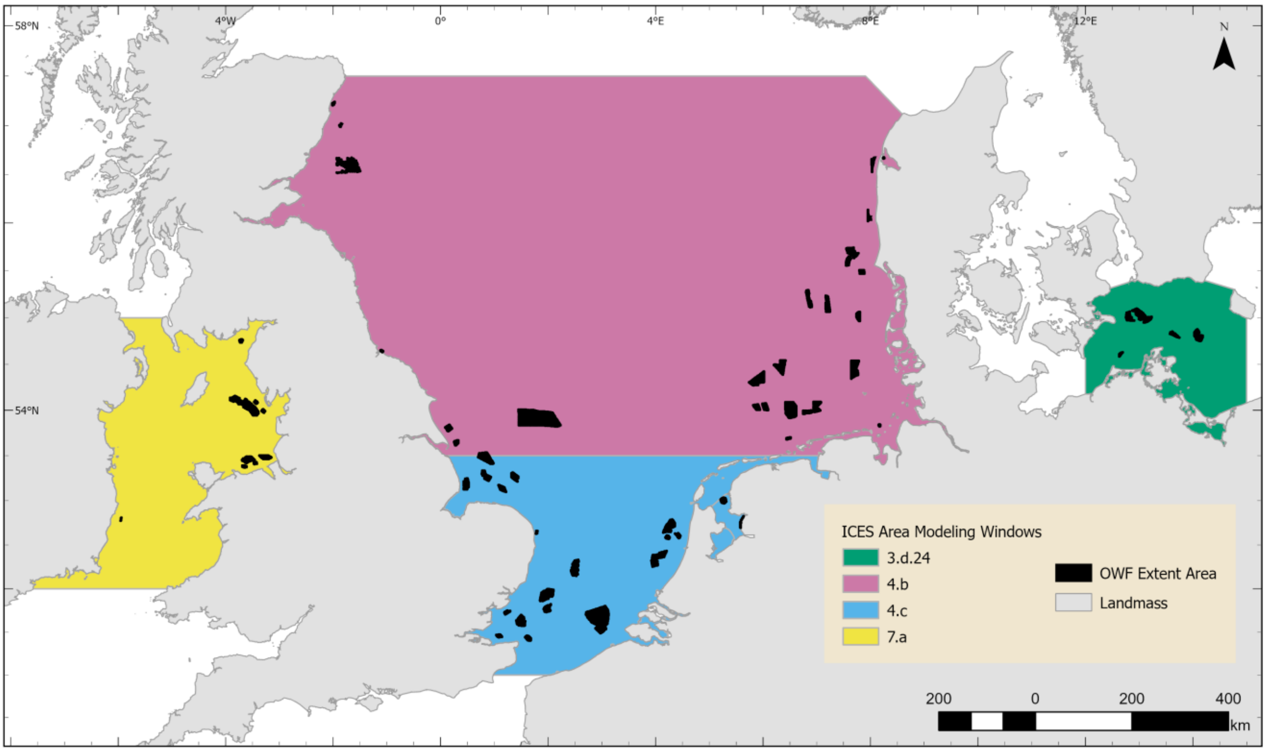
Interactions between Offshore Wind Farms and Fisheries in European waters



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Interactions Between Offshore Wind Farms and Fisheries in European waters

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Key findings and conclusions

- Detailed quantitative evidence of spatial overlap between static and towed-gear fisheries and 88 offshore wind farms (OWF) is provided over a twelve-year period in European waters.
- There were small reductions in static-gear effort in countries where such fishing is permitted e.g. 15% reduction in the UK and Netherlands.
- Study results suggest there is scope for coexistence between current OWF designs and static-gear fisheries although uncertainties remain over small vessel activities and effects on commercial fish species and landings.
- There were substantial reductions in towed-gear fishing effort across all countries including those where no mandatory exclusions occur e.g. 76% reduction in the UK.
- Study results are broadly in line with two recent peer reviewed publications.
- Codesign initiatives and early planning will be critical determinants of coexistence outcomes.
- Ongoing research in the US and France on codesign initiatives that aim to optimise coexistence potential can inform Irish OWF development.
- Minimising sectoral overlap at the outset is also key to avoiding significant impacts on fishing.

Introduction

The development of offshore renewable energy (ORE) is occurring at pace to combat the effects of climate change and improve energy security. Global ORE generation capacity of 68 gigawatts (GW) in 2023 is forecasted to reach over 400 GW by 2035 with European projects dominating the future plans (McCoy et al., 2024). The European Union (EU) recently agreed to update their goals for the deployment of ORE generation capacity to 88 GW by 2030, and around 360 GW by 2050.

Under its Climate Action Plan, Ireland aims to achieve 20 GW by 2040 and 37 GW by 2050 from offshore wind farms (OWF). New infrastructure will require substantial areas of sea resulting in competition for space with other sectors such as fishing. It is envisaged that 3.1 GW of this will come from phase one, developer-led projects, primarily in the Irish Sea. The remainder will be produced under a plan-led regime under designated maritime area plans (DMAP), the first of which, the south coast DMAP (SC-DMAP), has passed through a public consultation process (Government of Ireland, 2024) and is formally approved.

When establishing and implementing maritime spatial planning (MSP), the European Union framework for MSP (Directive 2014/89/EU) requires Member States to consider economic, social and environmental aspects to support sustainable development and growth in the maritime sector. This will be done by applying an ecosystem-based approach and promoting coexistence of relevant activities and uses. The Directive also states that MSP will contribute to the effective management of marine activities and the sustainable use of marine and coastal resources, by creating a framework for consistent, transparent, sustainable, and evidence-based decision making. The Maritime Area Planning Act was introduced in Ireland in 2021 to comply with the requirements of the EU directive.

The Irish National Marine Planning Framework (NMPF) (Government of Ireland, 2021) sets out planning objectives and policies in relation to sixteen different marine sectors or activities. The NMPF fisheries policy objectives include delivering a sustainable seafood sector focused on competitiveness, innovation and growth, that protects and enhances the social and economic fabric of rural coastal communities and sustains primary food producers in contributing to food security.

The NMPF fisheries policies include requirements that any planning proposals that may have significant adverse impacts on access for existing fishing activities, must demonstrate that they will in order of preference: avoid, minimise, or mitigate such impacts. If it is not possible to mitigate significant adverse impacts on fishing activity, the public benefits for proceeding with the proposal that outweigh the significant adverse impacts on existing fishing activity must be demonstrated.

The SC-DMAP outlines how the facilitation of coexistence between OWF and other maritime usages and activities was central to the preparation of the plan. The NMPF and SC-DMAP define coexistence as ‘where multiple developments, activities or uses exist together or close to each other in the same area and / or at the same time.’ The SC-DMAP provides that mandatory permanent exclusions on additional activities or usages within Maritime Areas identified for future ORE development should not be imposed save relating to safety or other exceptional circumstances. The plan recognises the need to establish possible navigational safety exclusion zones in proximity to ORE infrastructure while exceptional circumstances include survey and construction periods.

The scientific literature on OWF and fisheries interactions suggests that fishing vessels generally avoid OWF infrastructure due to safety issues, difficulties in manoeuvring vessels around infrastructure particularly in poor weather or strong tidal currents, and risk of entanglement (Blyth-Skyrme, 2011; Christie et al., 2014; Pardo et al., 2025; Rouse et al., 2020). Legal and insurance issues may cause additional barriers to vessel operations in proximity to OW infrastructure (Haggett et al., 2020).

Different types of fishing gears are affected in different ways. Dunkley and Solandt (2022) found a 77% reduction in bottom-towed gears following OWF construction across 11 out of 12 UK wind farms. Static gears such as potting for lobster may fare better but fisheries may be excluded from OWFs for extended periods during OWF construction, and site-specific issues should be accounted for (Roach et al., 2022) considering differences in ecosystem characteristics in different geographic locations.

National government and developer policies on safety zones in and around OWF infrastructure influence coexistence. Bonsu et al. (2023) describe the absence of mandatory safety zones but some provisions for developers to implement safety zones of 50 to 200 m in countries such as the UK, Sweden and Denmark. The authors also describe how Germany, the Netherlands and Norway have a variety of safety zones extending up to 500 m from OWF infrastructure in relation to different size vessels and/or fishing gears with experimental fisheries permitted in some cases. Bottom towed gears are not permitted in OWF in most EU countries apart from the UK and potentially France (Van Hoey et al., 2021). The German government excludes all forms of fishing other than static gears in OWF[1].

Technical characteristics of OWF infrastructure may also influence coexistence. For example, Austrheim et al. (2022) suggests that burying cables or increasing inter-turbine distance or 'turbine spacing' might provide more favourable conditions for fishing activities around OWF infrastructure although gears such as bottom trawling would need the most accommodation.

There is clearly a variety of obstacles but also potential opportunities around specific gear types, policies, and infrastructural design which can support coexistence between OWF and fisheries. In line with the ecosystem approach to marine management, there is a need to improve scientific knowledge on interactions between the two sectors to help ensure that the development of coexistence policies is based on the best available information.

Research to date includes Stelzenmüller et al. (2022) who used mean annual fishing effort in European fisheries preconstruction of OWF to broadly examine spatial overlap and conflict potential in current and projected OWF developments. Dunkley and Solandt (2022) compared mean annual fishing effort pre- and postconstruction of 12 OWFs to provide a snapshot of spatial overlap in UK bottom-towed fisheries between 2015 and 2021. More recently Fitkov-Norris et al., (2025) used a gradient analysis to assess the average response of fishing effort to 34 European OWF constructed between 2016 and 2022.

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[1] https://www.windindustry-in-germany.com/announcements/germany-s-association-for-offshore-wind-energy-on-the-final-report-of-the-fisheries-future-commission

An alternative approach is needed to assess longer-term trends and effects of potential explanatory variables on coexistence between two sectors which vary in space and time. The movement of fishing vessels can be highly dynamic when they operate on different fishing grounds at different times of the year. OWF development also varies in time and space with construction occurring on a phased basis, gradually expanding into new areas as groups of turbines are added over time (Rowe et al., 2017).

In this study, we aimed to assess changes in fishing effort in and around European OWF using a spatiotemporal modeling framework. We use post-hoc analyses to assess factors affecting fishing in OWF and discuss the findings in relation to challenges and opportunities around optimising coexistence potential between fisheries and OWF sectors.

Methods

Fishing data

We used publicly available data on fishing activity from Global Fishing Watch (GFW) (https://globalfishingwatch.org). GFW data are derived from Automatic Identification System (AIS) data which are mainly used for safety, navigation and communication purposes on board vessels. Vessels have the ability to turn off AIS which makes the resulting data unsuitable for absolute estimates of fishing activity (Shepperson et al., 2014) but better suited to assessing spatial or temporal trends in fishing effort (Kroodsma et al., 2018).

AIS has been mandatory for EU fishing vessels > 24 m since 2012 and > 15 m since May 2014. GFW distinguishes fishing vessels from other vessels such as cargo ships based on their behaviour and categorises them according to eight main fishing gears. For the purposes of this study, we further grouped these gears into towed, static, and mobile hook and line. We restricted analyses by fishing gear to towed and static gears due to minimal occurrence of mobile hook and line fisheries. Towed gears consisted of demersal and pelagic trawlers, seiners and dredgers while static gears consisted of pots or traps, set gillnets, and set longlines. Data at individual vessel level were not available during this study.

GFW data on vessel activities during construction of OWFs can generally be attributed to fishing vessels acting as guard vessels on behalf of OWF developers (Dunkley and Solandt, 2022) so we refrained from drawing inference on activities during construction.

OWF sites and spatial scope

We obtained data on OWF development from the global 4C Offshore proprietary dataset (https://www.4coffshore.com/) which includes details of individual OWFs, associated spatial polygons and information on each turbine group (TG) (Figure 1) located within each OWF. As of November 2024, there were 132 fully commissioned OWFs in European waters.

European fisheries are managed through the International Council for the Exploration of the Sea (ICES) which uses ICES Divisions and Subdivisions as distinct spatial areas for fisheries management rules such as species quota allocations and technical requirements for use of fishing gears. These management rules strongly influence the behaviour of fishing vessels. Hence, we used these areas as modeling windows to account for similar effects of management rules on vessel behaviour and broadscale changes in fishing effort in relation to OWF.

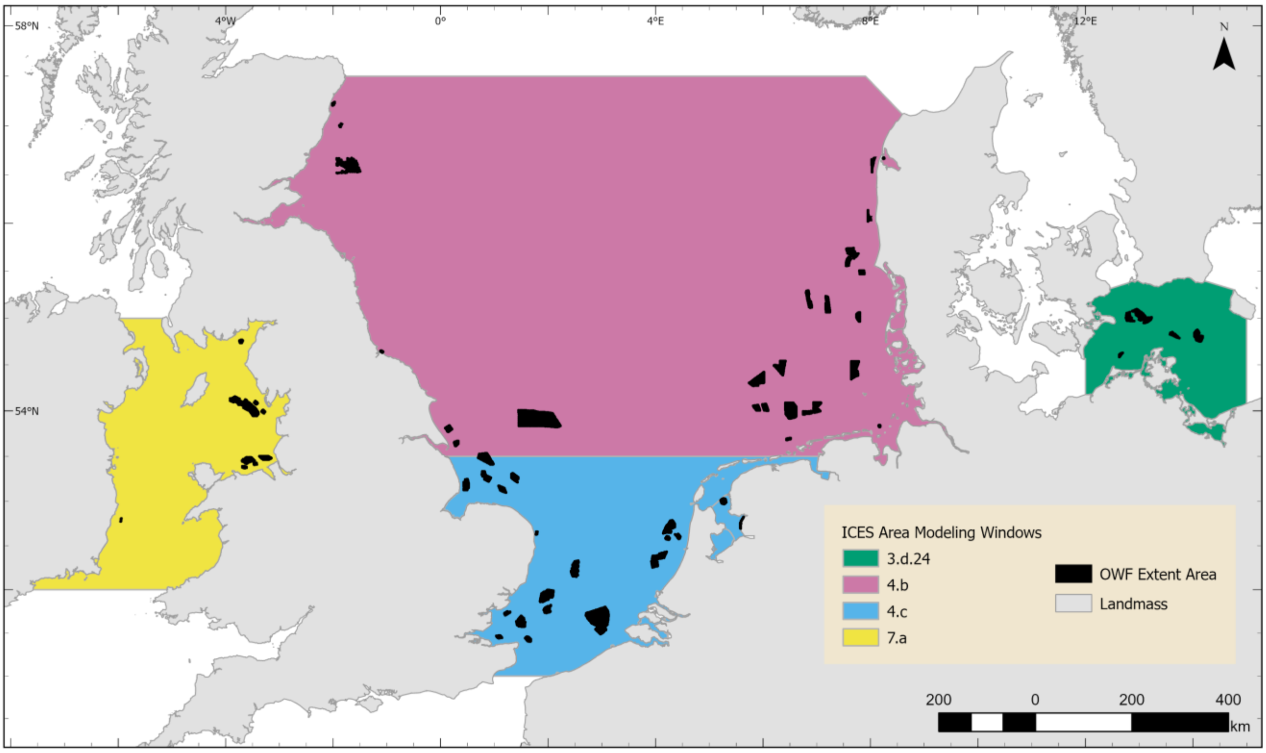

Figure 1. Map of ICES Divisions and Subdivisions used as spatiotemporal modeling windows

Some 101 (or 77%) of the fully commissioned OWF occurred in three ICES Divisions in the North (4b, 4c) and Irish Seas (7a), and one ICES Subdivision in the Baltic Sea (3d 24) (Appendix I). We used these four areas as our modeling windows to focus on key OWF development areas and optimise the accuracy of model outputs (Figure 1).

We categorised 10 of the 101 windfarms as demonstration sites based on: use of the term demonstration, pilot, test, or innovation to describe them in the 4C Offshore dataset; having an area < 1 km²; and/or having ≤ three turbines. These were retained as underlying features in modeling windows but excluded from analyses of the effects of OWF on fishing.

Post-hoc data exploration revealed that three OWF were in freshwater bodies. These were removed providing a total of 88 OWF retained in subsequent analyses. The predicted towed effort for the UK 44 OWF was considered a major outlier given an extremely high level of predicted post-construction fishing activity which far exceeded all other OWF despite having no observed towed effort postconstruction. This outlier was removed from model outputs. Ireland was removed from mean predicted outputs by country due to the occurrence of just one farm with very low levels of associated fishing effort.

UK 30 straddled two modelling windows so we simply split the farm in two and made inference in the separate areas. We considered additional OWF infrastructure such as cables as outside the scope of the current study. We used 1 km buffers (BUF) around TG to help provide a balanced overview on changes in fishing effort within and around OWFs (Figure 2).

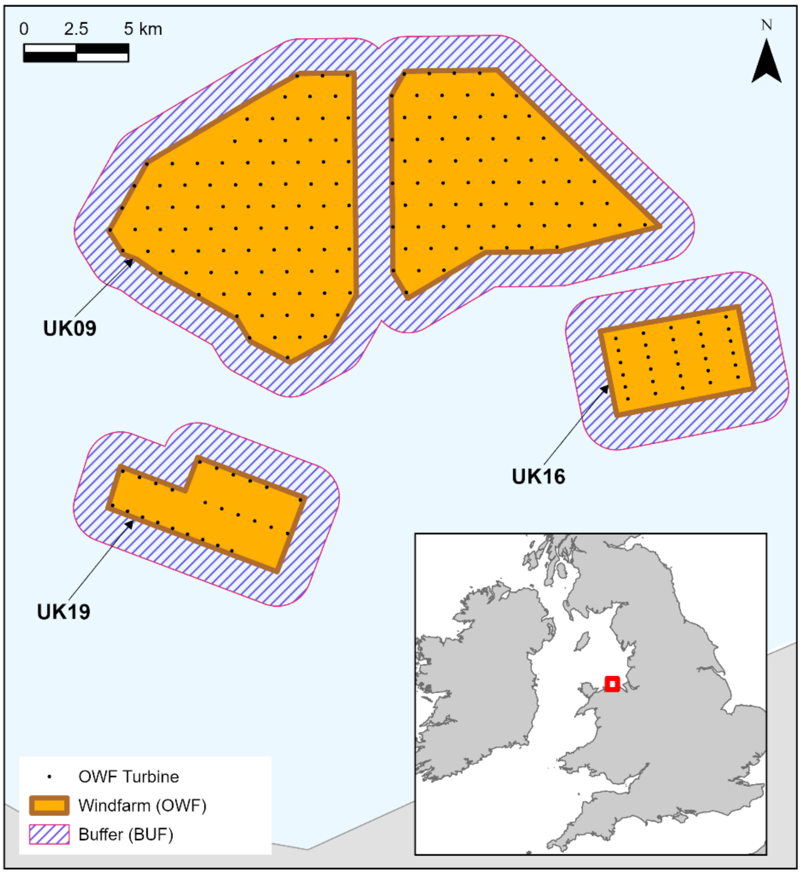

Figure 2. Example of 3 offshore windfarm (OWF) extents and buffer areas (BUF) used in this study. Each OWF extent consists of one or more turbine groups (TG), UK19 and UK16 (N = 1), UK09 (N = 2). BUF areas consist of 1 km areas around each turbine group in each OWF.

Data processing and analysis

We used a Microsoft Azure Windows 11 Pro Intel(R) Xeon(R) Platinum 8370C CPU @ 2.80GHz 2.79 GHz (Installed RAM 128 GB & 32 cores) virtual machine to conduct analyses and store project data in a PostgreSQL database. We analysed data using RStudio 2023.12.1+402 "Ocean Storm" Release (2024-01-28) (R Core Team, 2015) for windows using the packages; ggplot2 (Wickham et al., 2016), sf (Pebesma et al., 2018), and mgcv (Wood, 2017 and 2025).

We aggregated GFW data available from January 2012 to October 2024 at a spatial resolution of 0.01 x 0.01 decimal degrees (~ 1 km^2) to total hours fished month^{-1}. We clipped the data to the four modeling windows and added zero values where no fishing effort was recorded for a given cell and month to facilitate modeling of effects on gear groups and associated buffers.

We used a generalized additive model for big data (BAM), a large-scale generalised modeling approach (Djouzi et al., 2023), to assess the effects of OWF on all available fishing effort. The largest preliminary model estimation contained > 120 million rows of data and did not succeed with available computing resources. To achieve convergence and complete model runs: we split the largest modeling window 4b into 4b east and 4b west at four degrees longitude. We subsampled larger model windows to 10 million rows, completed two model replicates for stability checks and retained mean predictions in outputs.

Our model response variable was the total effort in 1 km^2 grid cell i in month t (months indexed sequentially with 12 months per year) denoted $y_{i,t}$. We modelled total effort as a function of time and space using the generalized additive model with a Tweedie distribution denoted Tw which helped deal with large numbers of zero values where no fishing effort occurred:

$$y_{i,t} \sim Tw_p(\mu_{i,t}, \sigma) \qquad (1)$$

$$\ln(\mu_{i,t}) = \alpha_t + \delta_{j,0} I_0(i,j,t) + \delta_{j,1} I_1(i,j,t) + s(lat(i), lon(i)) + s(lat_i, lon_i, t) \qquad (2)$$

where:

- $y_{i,t}$: Effort response - total hours in grid cell *i* in month *t*
- α_t*:* Categorical month effect, which is the average log effort in the modeling window for a given month
- $\delta_{j,0}$ OWF during construction effect
- $I_0(i,j,t)$ Indicator variable that has a value of one if cell *i* is in windfarm *j* during the construction period and a value of zero otherwise
- $\delta_{j,1}$ OWF post-construction effect that is our main focus
- $I_1(i,j,t)$ Indicator variable that takes a value of one if cell *i* is in windfarm *j* postconstruction and a value of zero otherwise
- $s(lat(i), lon(i))$ Spatial smooth that captures persistent spatial patterns
- $s(lat_i, lon_i, t)$ Spatiotemporal smooth that captures how spatial patterns change through space and time
-

Also included were 1km buffer effects similarly to $\delta_{j,0}$ and $\delta_{j,1}$ but only within the buffer around the windfarm and not within the OWF extent. These are not included in Equation (1) for notational simplicity.

The month effect implicitly subsumed seasonal dynamics associated with fisheries such as differences in fish availability and quotas, and random variation such as weather. Every month in the model was also treated as unique so that monthly effects could differ between years.

The parameter $\delta_{j,1}$ captures the ratio of $y_{i,t}$ in OWF and BUF areas in the presence of OWF to that predicted in the absence of OWF postconstruction:

$$\hat{y}_{j,ratio} = e^{\delta_{j,1}} = \frac{\hat{y}_{j,OWF=on}}{\hat{y}_{j,OWF=off}} \qquad (3)$$

We plotted $\hat{y}_{j,ratio}$ on an individual OWF farm basis by gear type and summarised results across farms using mean values by gear types, OWF and BUF areas, and countries.

We used post-hoc regression tree analysis (Lewis, 2000) to model the relationship between key OWF technical and policy characteristics, and $\hat{y}_{j,ratio}$. The independent variables included area (km^2), the number of TG, median turbine spacing (m), turbine density (N.km^{-2}), mean depth (m), country, and OperatorID for each OWF. Turbine spacing was derived using a nearest-neighbour analysis in R (Figure 3). The regression tree analysis was restricted to static gear which was less likely to be subject to mandatory exclusion from OWF compared with towed gear.

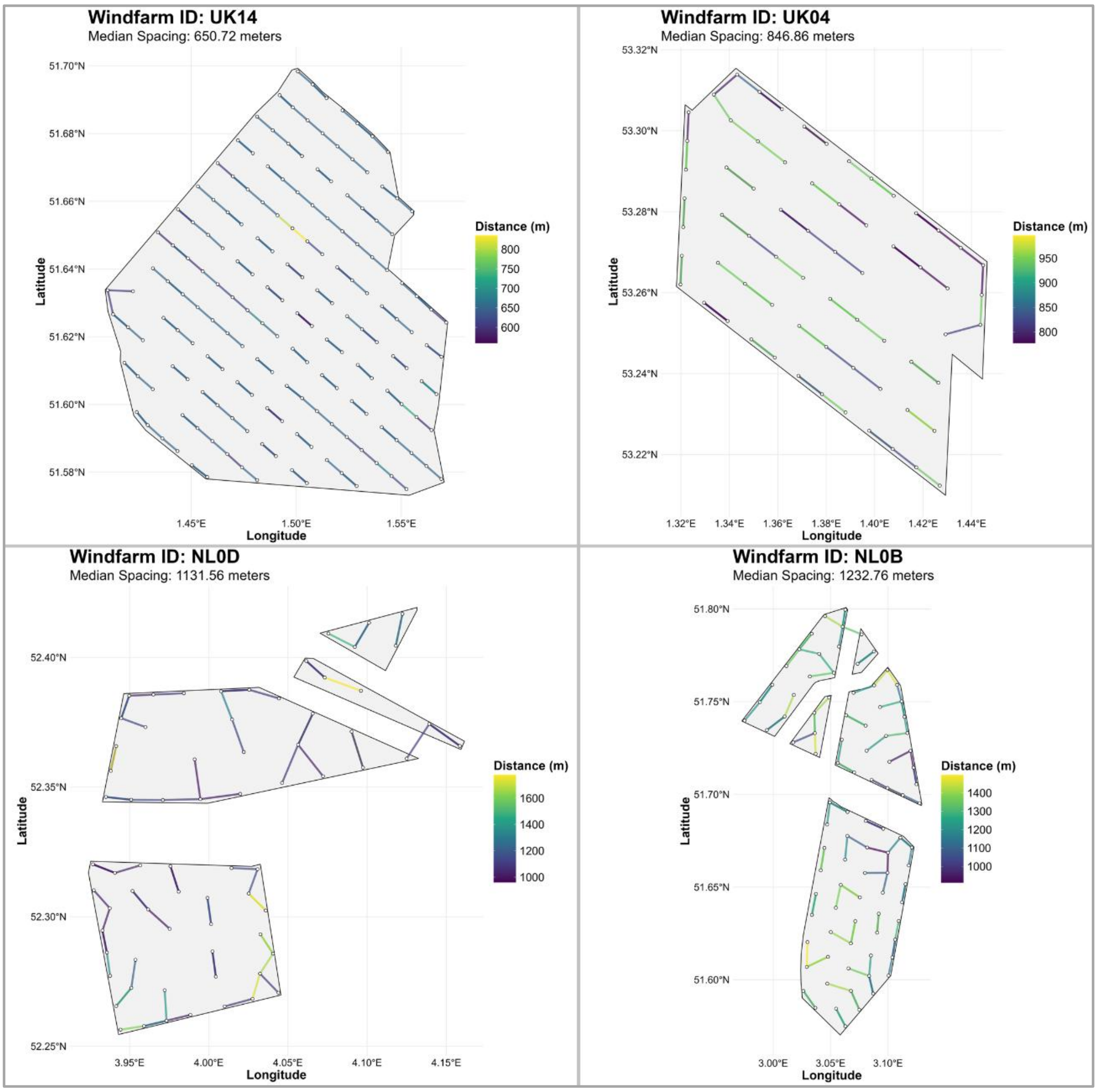

Figure 3. Demonstration of the nearest neighbour analyses on four offshore windfarms. The grey polygons are turbine groups (TGs); the white dots within these TGs are individual turbines; the colour scale illustrates the distance from a turbine to its nearest neighbour. Median turbine spacing within each OWF is provided and termed 'turbine spacing' in our post-hoc regression tree analysis.

Using an OWF with a reasonable amount of preconstruction fishing effort we produced line plots to illustrate differences in predicted post construction fishing effort in the presence and absence of the OWF post construction. We also used a cluster of 12 OWF located in close proximity to each other in the North Sea (ICES 4c) to demonstrate how the developed spatiotemporal modeling approach accounts for changes in fishing effort and OWF construction over time. We used an ISO standard Geographic information spatial schema to develop the latter visualisation (www.iso.org/obp/ui/en/#iso:std:iso:19107:ed-2:v1:en).

Results

Mean predicted static fishing effort was reduced by 52% in OWF extents and 24% in associated BUF areas postconstruction across all OWF. Mean predicted towed effort was reduced by 79% in OWF extents and 47% in associated BUF areas postconstruction across all OWF (Table 1).

At country level, predicted reductions in static effort in OWF ranged from 99% in Germany to 15% in the UK and Netherlands. Differences in static effort in associated BUF areas ranged from a 90% reduction in Belgium to an 84% increase in the Netherlands. The UK and Denmark also had 16% and 11% increases in predicted static fishing effort in BUF areas. Predicted reductions in towed effort in OWF extents ranged from 99% in Belgium to 76% in the UK, and in BUF areas from 79% in the Netherlands to 38% in the UK (Table 2).

Most $\hat{y}_{j,ratio}$ values for individual OWF were close to zero indicating low levels of fishing effort postconstruction (Figure 4). Few points were close to 1 indicating no change in expected fishing effort or > 1 indicating an increase in expected fishing effort in OWF areas. Notable exceptions include three German OWF with a reasonable amount of towed gear effort where minimal reductions in expected fishing effort occurred postconstruction. Mandatory towed gear exclusions in German OWF suggest that this activity was likely guard vessel activity rather than fishing effort.

Two UK OWF with a reasonable amount of static gear effort had increases in $\hat{y}_{j,ratio}$. The differences in predicted fishing effort in individual OWF were generally not as great in BUF areas compared with OWF extents for both towed and static gear with some notable increases in static effort in BUF areas in the UK and Netherlands (Figure 4).

Summarised technical characteristics of the 88 OWF are outlined in Table 2. Our base regression tree analysis for static gear in OWF extents including all variables found OperatorID was the most important variable, followed by country and year commissioned. The degrees of freedom (DF) for OperatorID were high, however, due to a large number of operators relative to the number of OWF with many of them responsible for a single OWF.

Table 1. Mean predicted differences in fishing effort ($\hat{y}_{j,ratio}$)

Gear	Area	Mean difference (%)
Static	OWF	-53
	BUF	-22
Towed	OWF	-79
	BUF	-47

Table 2. Mean predicted differences in fishing effort ($\hat{y}_{j,ratio}$) by country

Country	Gear	Area	Mean (%)
United Kingdom (UK)	Static	OWF	-15
		BUF	16
	Towed	OWF	-76
		BUF	-38
Germany (DE)	Static	OWF	-99
		BUF	-81
	Towed	OWF	-85
		BUF	-43
Belgium (BE)	Static	OWF	-83
		BUF	-90
	Towed	OWF	-99
		BUF	-71
Netherlands (NL)	Static	OWF	-15
		BUF	84
	Towed	OWF	-98
		BUF	-79
Denmark (DK)	Static	OWF	-60
		BUF	11
	Towed	OWF	-91
		BUF	-55

Table 3. Summarised technical characteristics of Offshore wind farms

Characteristic	Max	Min	Mean	(± SD)
Turbines (N)	175.0	5.0	60.8	37.9
Mean Depth (m)	74.9	3.9	23.7	11.9
Area (km2)	470.0	3.0	55.7	79.1
Median turbine spacing (m)	1409.4	338.2	743.3	225.0
Turbine density (N/km2)	7.5	0.2	2.1	1.4
Turbine groups (N)	5.0	1.0	1.3	0.7

An alternative regression tree model excluding operators showed that country was the most important predictor of effort change with more static-gear fishing occurring in the UK and Netherlands postconstruction. Within these countries more fishing occurred in deeper OWF ($\geq$ 27 m) while in shallower water depth (< 27 m), turbine density may have had an effect although contrasting values of >=2.9 or <1.8 make this difficult to interpret. Belgium, Denmark, Germany, and Ireland had lower predicted static fishing effort in OWF extents postconstruction (Figure 5).

Aside from the issues around DF and exclusion of certain variables, low R^2 values for both model runs suggest that a relatively low level of variance was explained. These caveats aside, OperatorID and Country were the main variables affecting fishing effort postconstruction.

The demonstration line plots of predicted fishing effort in UK62 outline how the model can predict fishing effort in the footprint of an OWF in the presence and absence of the OWF (Figure 6). In this example postconstruction static effort was predicted to increase in the OWF both in relation to preconstruction levels, and in relation to fishing effort if no OWF had been constructed. In contrast, towed effort was predicted to substantially decrease on both counts.

Figures 7 and 8 illustrate the developed modeling approach and changes in fishing effort and OWF construction in time and space. Substantial increases in post construction static fishing effort were predicted in the large Netherlands farms located to the east of the cluster, while very little static fishing effort was predicted in Belgian OWFs to the west (Figure 7). This is in line with model predictions by country (Table 2) and the existence of experimental static fisheries in the Netherlands (Bonsu et al., 2024). In contrast, towed gear fisheries were practically eliminated from this OWF cluster (Figure 8).

Figure 4. Predicted ratios of effort in offshore windfarm extents (OWF: blue circles) and 1 km buffer areas (BUF: yellow circles) to that expected in the absence of the OWF ($\hat{y}_{j,ratio}$). Effort data for each gear type are scaled to the total effort for that gear type.

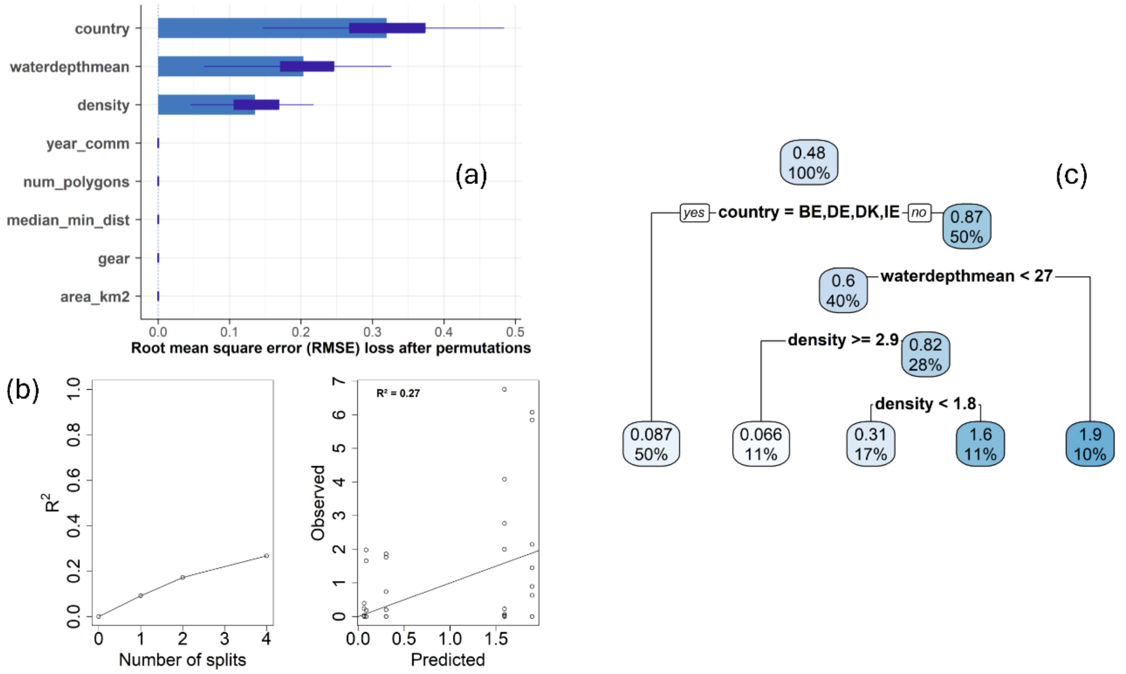

Figure 5. Regression tree model outputs for static gear fishing within OWF extents (n=88): (a) variable importance plot; (b) R-square plot; (c) regression tree plot

Figure 6. Time series plots demonstrating predicted post construction static fishing effort (left) and towed gear effort (right) in the presence (OWF on) and absence (OWF off) of UK62 OWF. Effort is the total predicted hours fished in the OWF by month. The orange line is the predicted fishing effort if the OWF had not been built, and the blue line is the predicted fishing effort with the farm in existence.

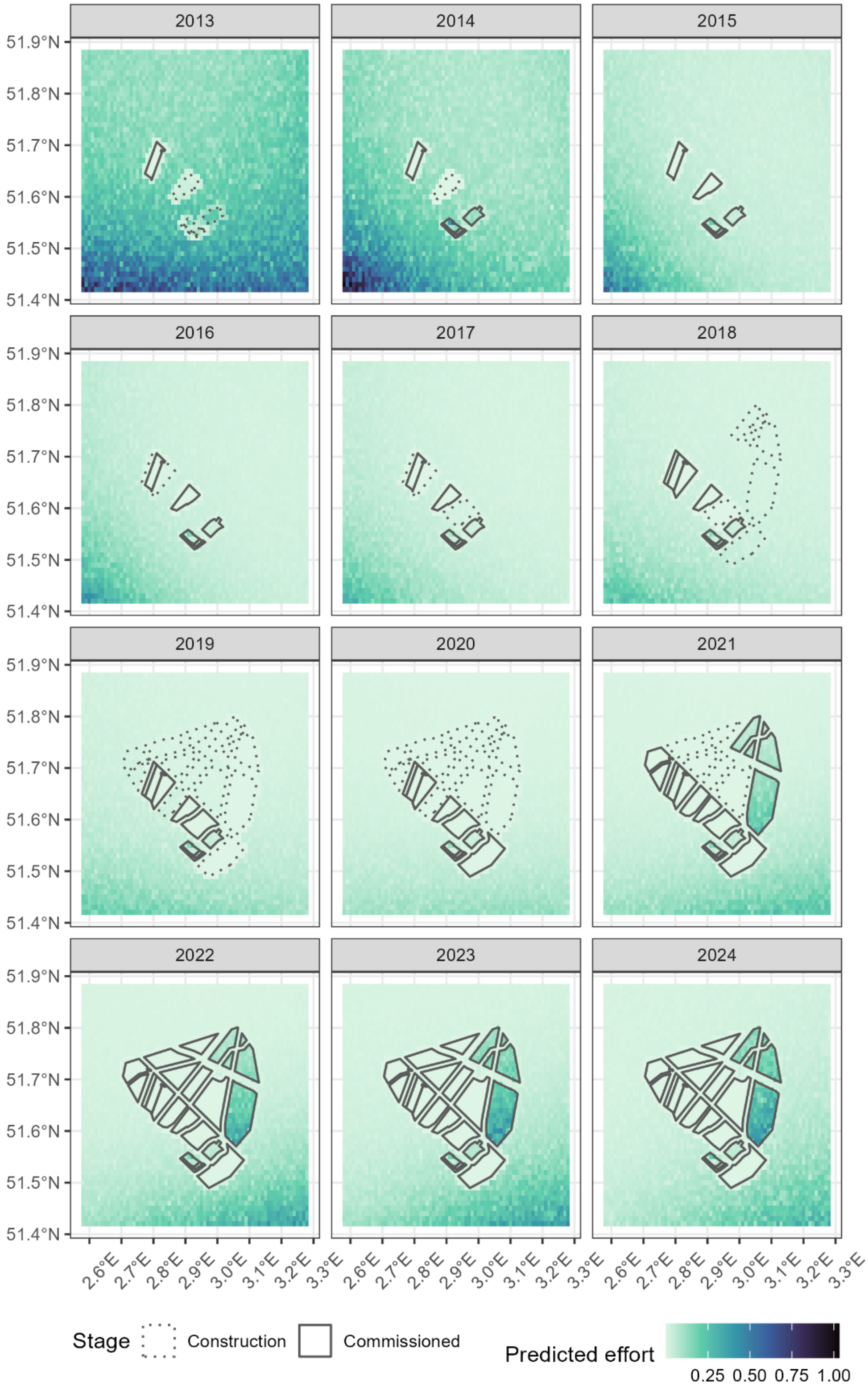

Figure 7. Demonstration of spatiotemporal modeling of OWF and static gear fisheries interactions using a cluster of 10 Belgian and 2 Netherlands OWF in the North Sea (ICES 4c). Predicted fishing effort is presented as total hours per km^2 per year.

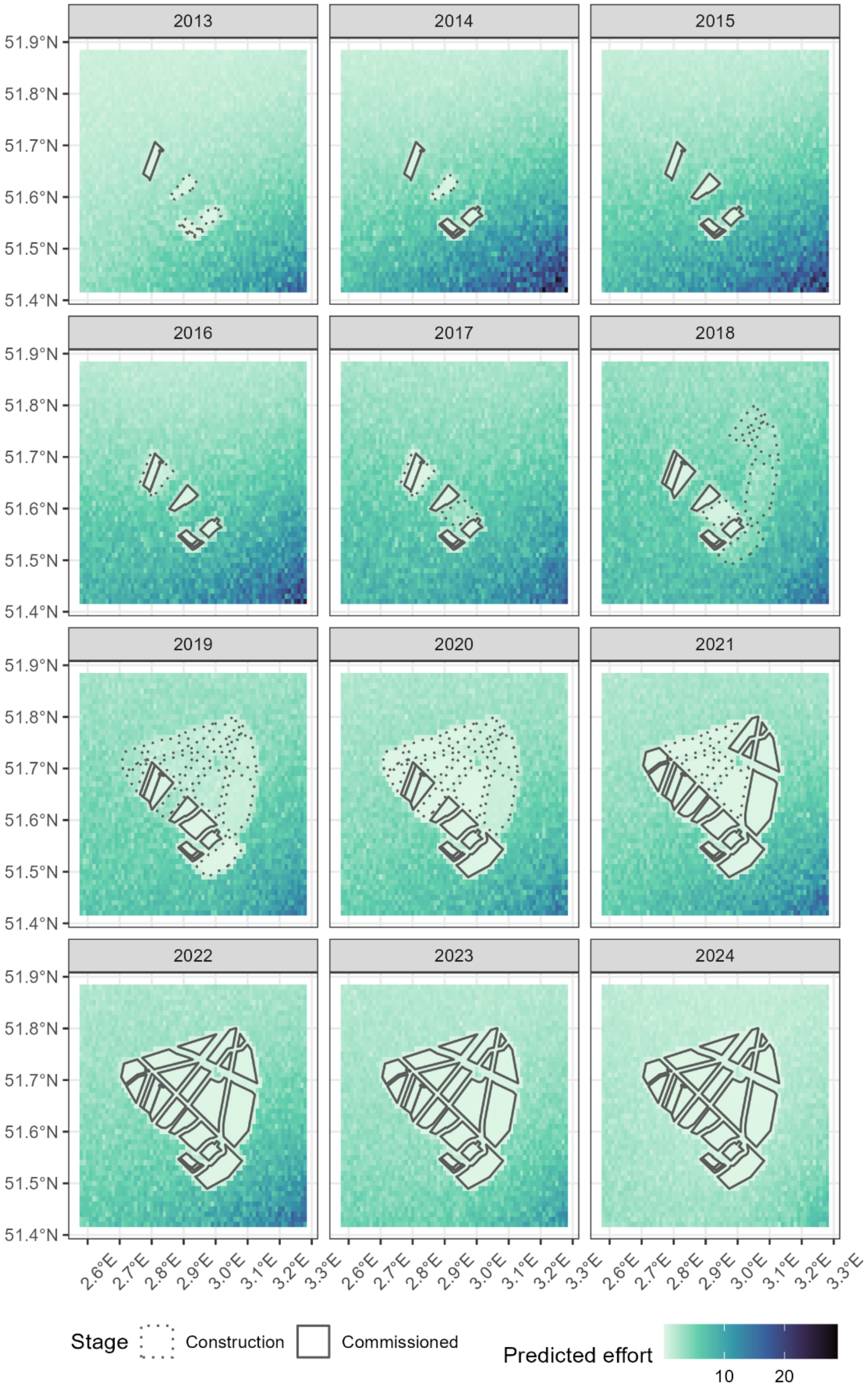

Figure 8. Demonstration of spatiotemporal modeling of OWF and towed gear fisheries interactions using a cluster of 10 Belgian and 2 Netherlands OWF in the North Sea (ICES 4c). Predicted fishing effort is presented as total hours per km^2 per year.

Discussion

There were major differences in postconstruction static effort in OWF extents across countries. Substantial reductions were predicted in Belgium, and Germany but smaller reductions were predicted in the Netherlands and UK. Indeed, increased static effort was predicted in buffer areas in the latter countries and Denmark. Increased effort does not equate to increased fish landings, however, and there is little evidence to support greater abundance of fish species in areas adjacent to OWF due to spillover effects (Bonsu et al., 2024; Gill et al., 2020).

Post-hoc regression tree analysis results should be treated with caution given model uncertainty. That said, the country effect is plausible given that predicted reductions in fishing effort for the UK and Netherlands were relatively minor (Table 2). The UK does not have mandatory safety zones, and the Netherlands permits experimental fisheries which suggests that national policies are potentially facilitating continued fishing activity. Potential Operator effects may also be plausible given that different operators may have different policies around implementation of safety zones. The results also suggest that deeper-water farms may be more conducive to static fishing in countries where the activity permitted.

Although we generally refrained from making inference on individual OWF, substantial increases in predicted static effort in two UK OWF (Figure 3) merit follow-up investigations around potentially positive coexistence case studies.

Smaller static gear vessels are poorly represented in this study as AIS is not mandatory for vessels under 15 m. There is little difference in fishing techniques for static gears such as pots or gillnets regardless of vessel size, and smaller vessels are more manoeuvrable which suggests potentially reduced OWF impacts. However, smaller vessels are less resilient to displacement effects (Szostek et al., 2025) and additional assessment would be needed to determine OWF impacts.

Our model predictions of OWF effects on static fishing gear are broadly similar to (Fitkov-Norris et al., 2025) who estimated a 36% reduction in static effort within OWF extents and no significant difference in static effort outside OWF extents.

Our estimated 76% reduction in towed fishing effort in UK farms was similar to the previously observed 77% reduction in bottom-towed gears (Dunkley and Solandt, 2022). However, the current study included pelagic as well as bottom towed gears. Pelagic-towed gears may be less susceptible to snagging on OWF foundations and cables, but vessels tend to be large potentially making manoeuvrability around OWF infrastructure more difficult.

Our towed-gear results were also broadly similar to Fitkov-Norris et al. (2025) who estimated 82% to 93% effort reductions in towed-gear fisheries within OWF extents and significant reductions in fishing effort up to 4.2 km outside OWF extents.

There is no substantial increase in risk of static gears such as gillnets becoming entangled in OWF infrastructure compared with normal fishing grounds (Alexander et al., 2013). Towed gears such as bottom trawls are heavier than static gears and, due to the nature of the fishing method, are more susceptible to snagging on OWF infrastructure which is hazardous for fishing vessels and OWF operators. This likely explains the substantial reductions in predicted towed-gear fishing effort in OWF across all countries regardless of policies around mandatory exclusion.

Effective coexistence between towed fishing gears and OWF is unlikely to occur using traditional OWF infrastructure but there are opportunities to learn from ongoing research in this regard. For example, the US National Offshore Wind Research and Development Consortium aims to work with commercial fishermen to codesign novel infrastructural concepts that optimise coexistence potential[2].

In France, the Regional Committee for Maritime Fisheries and Marine Aquaculture is working on coexistence solutions[3]. They've shown coexistence can work under specific conditions and highlight that technical specifications need to be integrated from the outset of OWF development. This research is producing tangible tools for coexistence including a matrix of fishing practices and OWF technical components, and a digital tool that visualises interactions between fishing gear and OWF infrastructure.

Most of the fishing effort in German OWF postconstruction was likely by fishing vessels acting as guard vessels given mandatory exclusions of towed gears in OWF in that country (Van Hoey et al, 2021). Examination of available fisheries management strategies for these OWF provided no evidence to the contrary. We cannot discount the possibility that other mis-categorisation of guard vessel activities may have occurred in the AIS dataset potentially resulting in inflated estimates of post-construction fishing effort in other OWF.

Incorporating other forms of fishing effort data in the modeling framework would address this issue. Vessel monitoring systems (VMS) are currently legally required on vessels > 12 m in length and due to be phased in for all vessels by 2029 under EU regulation 2023/2842. Fisheries scientists and managers typically combine VMS data and vessel logbook data to provide spatiotemporal catch and effort data (Gerritsen and Lordan, 2011). Using these data in the developed approach would improve the accuracy of underlying effort data in relation to guard vessels by filtering out fishing activities with no associated logbook data. This could also help examine effects on catch rates of commercial fish species as well as economic impacts through incorporation of catch value in model predictions.

ICES which has access to European VMS and logbook data through national authorities of its member countries, may have scope to conduct such analyses. The ICES Roadmap for Offshore Renewable Energy goals include the further development and application of models and long-term observations supporting analysis of impacts from ORE on fishing activities and coastal economies (ICES, 2024a) with the Working Group on Offshore Wind Development and Fisheries (WGOWDF) specifically focused on fisheries interactions.

Not included in the current study, subsea cables in and around OWF are also likely to affect fishing effort (Szostek et al., 2025). Spatial information on cables is available in the 4C

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[2] https://nationaloffshorewind.org/projects/co-design-solutions-for-u-s-floating-offshore-wind-farms-and-fishing-compatibility/

[3] https://www.bretagne.bzh/actions/grands-projets/energies-marines-renouvelables/etude-de-coactivite-peche-eolien-en-mer/

Offshore dataset so these could be included in future analyses, ideally based on VMS and logbook data.

We dealt with changes in reporting behaviour and seasonal dynamics by adding within and across year month effects. Incorporating temporal effects in spatiotemporal modeling is commonly used in medical research on disease prevention to deal with seasonal variation and changes in reporting rates due to factors such as media attention (Held and Paul, 2012; Sofianopoulou et al., 2017).

In contrast to other studies which are limited to post 2015 when AIS became mandatory (Dunkley and Solandt, 2022; Fitkov-Norris et al., 2025), our spatiotemporal modeling framework greatly extended the time series and number of OWF included in the analysis, while also facilitating post-hoc analysis of potential explanatory factors.

Fitkov-Norris et al. (2025) assessed changes in fishing effort in 1km increments up to 50 km from OWF extents. We restricted this to 1 km buffers but the spatiotemporal modeling approach could be used to explore changes in fishing effort over much wider areas which would be useful given high mobility of larger vessels (Holmes et al., 2020).

Dunkley and Solandt (2022) used adjacent geographic areas which were analogous from a fisheries management perspective as experimental controls. Choosing representative controls is challenged by the dynamic nature of fishing effort in time and space. Our model incorporates experimental control implicitly by using all observations to define a spatiotemporal distribution of expected fishing effort and then estimating the difference from this distribution within the footprint of the ORE. Specifically, the spatial and spatiotemporal smooth terms capture underlying patterns in effort across modelling windows, accounting for persistent spatial structure and evolving temporal dynamics such as redistribution of fishing activity and random variability. The categorical month effect further controls for seasonal and system-wide temporal variation (e.g., owing to quota changes).

Within our framework, the OWF effect is estimated as an intervention effect (Box and Tiao, 1975) that evaluates the impact of the OWF on the expected effort within its footprint. This estimates the departure from the expected distribution of effort solely within the windfarm while accounting for dynamic effort. The effects attributed to OWFs represent differences between observed effort inside OWFs and the modelled counterfactual expectation derived from the full distribution of effort over space and time in and around the OWFs. In this way, areas outside OWFs function as a robust statistical control, allowing inference on OWF impacts without requiring explicitly designated control sites that may or may not be comparable to the windfarm.

In conclusion, this study provides detailed quantitative evidence of spatial overlap between static and towed-gear fisheries and 88 OWF over a twelve-year period in European waters. Broadly, our findings suggest that there is scope for coexistence between current OWF designs and static-gear fisheries although uncertainties remain over small vessel activities and effects on commercial fish species and landings. Novel OWF infrastructure would likely be needed to enable coexistence with towed-gear fisheries.

Ongoing research in the US and France on codesign initiatives that aim to optimise coexistence potential can greatly inform Irish OWF development. This is very much in line with the terms of reference of the Irish Seafood/ORE Working Group which include identification of opportunities for mutually beneficial co-existence between Irish seafood and ORE sectors. Regardless of technological advances in support of coexistence, monitoring of catch rates pre- and postconstruction of OWF is essential to provide plausible evidence of OWF impacts on commercial fisheries species (Gill et al., 2024) and fisheries.

Experience in the UK has shown that minimising sectoral overlap from the outset is the optimal way to avoid significant impacts on fisheries[3]. In addition to ORE, Marine Protected Areas (MPAs) are due to be incorporated into the existing Irish maritime spatial planning framework through DMAPs. Designated spatial areas should also be considered for important fishing grounds to safeguard key seafood production areas (ICES, 2024b; Szosteck et al., 2025) and ensure that NMPF objectives for Irish fisheries are realised.

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[3] https://www.nffo.org.uk/celtic-sea-offshore-wind-development-picks-up-pace/

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