Site and species dependent effects of offshore wind farms on fish populations

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ARTICLE INFO

ABSTRACT

The expansion of offshore wind energy capacity is changing the seascape with the large-scale introduction of turbines and associated infrastructure. Subsurface structures can influence the abundance, distribution and behaviour of some marine fish species by providing artificial habitat and food resources that supplements natural occurrence. At two of the highest latitude operational wind farms the abundance, biomass and size of haddock and flatfish was higher close to jacket turbine foundations, with the effect larger at the older and more complex foundations. The results provide further evidence of the fine-scale impacts of offshore wind turbines on demersal fish and illustrate their species and site-specific nature. Quantifying how these changes may have positive or negative effects on local ecosystems and scale up to networks of wind farms is a challenge, but will be required if potential future wind farm consenting policies are to be addressed.

1. Introduction

Offshore wind farms are changing the seascape by creating a patchwork of arrays, consisting of thousands of individual turbines with effects both above and below the waters' surface (Fig. 1a; ARUP, 2022; Lee et al., 2021; Ouro et al., 2024; The Crown Estate, 2021; Watson et al., 2024). The introduction of artificial structures into the offshore marine environment has been occurring for centuries in the form of shipwrecks (Hickman et al., 2023) and in recent decades through artificial reefs (Jensen, 2002) and extensive construction of platforms and pipelines for oil and gas extraction (Kaiser, 2018). The spatial extent of wind farm development and number of associated structures in the water, however, has already surpassed the fossil fuel industry (Paolo et al., 2024), and with projected global capacity to increase ~7 fold in the next 10 years (>60 GW: Williams et al., 2023).

The influence of artificial structures on marine species has been long studied (Fernandez-Betelu et al., 2022; Olsen and Valdemarsen, 1977; Paxton et al., 2019; Todd et al., 2009; Valdemarsen, 1979) but has become more pertinent with the expansion of offshore wind energy, and the debate surrounding decommissioning of oil and gas platforms at their end of productive life (Fortune et al., 2024; Knights et al., 2024). The distribution and abundance of fish has been found to be altered around subsurface structures, with certain species attracted to and aggregating around the hard substrate habitat they create (Birt et al.,

2024; Claisse et al., 2014; Egerton et al., 2021; Ibanez-Erquiaga et al., 2024; Paxton et al., 2019; Rosemond et al., 2018). Studies at offshore platforms that have been operating for many years provide evidence they can become some of the most productive fish habitats globally (Birt et al., 2024; Claisse et al., 2014). The effect of offshore wind farms on marine ecosystems has yet to be fully assessed, however, the response of individual animals and local or regional populations that utilise these waters will likely be species and scale dependent (Degraer et al., 2020, 2023; Inger et al., 2009; Ouro et al., 2024; Watson et al., 2024). Individual wind turbines may not have the spatial footprint of larger offshore oil or gas platforms but the aggregation/attraction, and possible production, of fish is understood to be analogous for some species (e.g. reef associated) with effects cumulative and changing over the life of the installations (Degraer et al., 2020; Mavraki et al., 2021; Reubens et al., 2011, 2013a, 2014). The variation in wind turbine sizes, designs and seabed attachment, e.g. fixed or floating (Mathern et al., 2021; Maxwell et al., 2022), are also considerations when assessing impacts on fish (Fernandez-Betelu et al., 2022; Watson et al., 2024). Fixed foundation type (e.g. jacket or monopile) and the presence or type of scour protection layer (SPL) have been found to alter the catch of a demersal species (Atlantic cod *Gadus morhua*: Werner et al., 2024), suggesting that design type influences the effect on certain fish species and requires further assessment to inform future wind farm planning.

Knowledge of how the large-scale development of wind energy will

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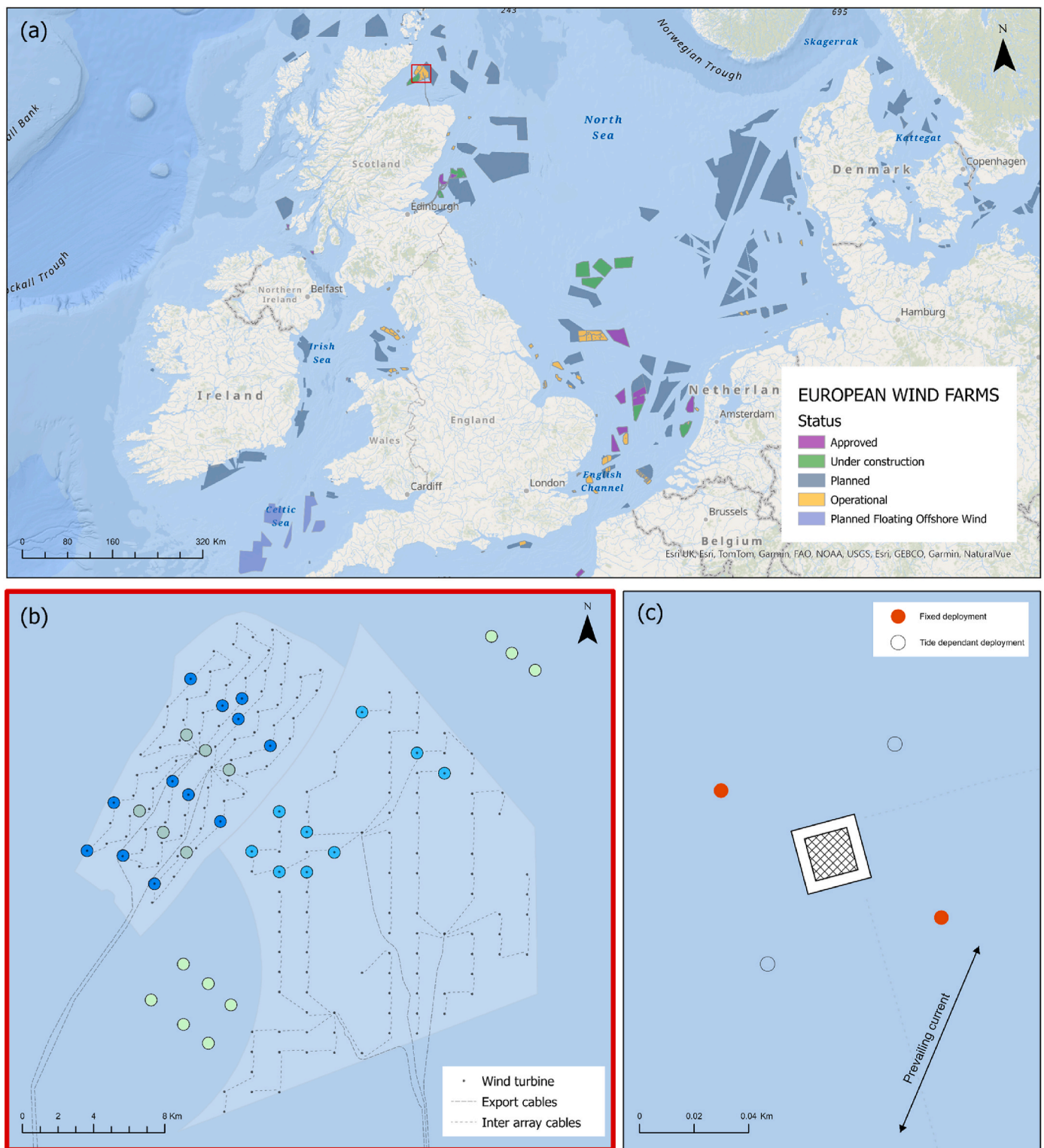
Fig. 1. (a) Offshore wind farm sites and status in northern Europe (EMODnet and Crown Estate data as of Nov 2023). **(b)** Baited remote underwater video system survey design at the Beatrice and Moray East operational wind farms in the Moray Firth, Scotland (red box in (a)). Grey blue polygons represent the boundaries of the wind farms. Each filled circle represents three simultaneous deployments around a wind turbine structure or a reference site. Dark blue = Beatrice turbine sites; light blue = Moray East turbine sites; dark green = inside wind farm reference sites; and light green = outside wind farm reference sites. **(c)** Illustrates an example of how 3 deployments were conducted around a turbine in the Beatrice wind farm but applies to all turbines (4 or 3 legged jackets). Two deployment sites in parallel to the prevailing tide (shown as red circles) were always used. The third location was chosen between two sites (shown as hollow circles), but always the site downstream of the current at the time of deployment to reduce risk of entanglement when close (<30m) to the structure. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

affect fish populations and communities is in its infancy but is benefitting from the application of contemporary research techniques, such as underwater videography, eDNA and bioacoustics (e.g. Bean et al., 2017; Bicknell et al., 2016; Hellström et al., 2022). Where studies have been conducted to assess fine-scale (sampling within 100m) effects of wind turbine foundations they have found aggregation and residency behaviour of demersal fish species, such as gadoids or flatfish (Buyse et al., 2022; Jech et al., 2023; Reubens et al., 2011, 2013a, 2013b). These studies have necessarily been concentrated in areas where some of the earliest offshore wind farms were built (i.e. southern North Sea) and were mostly monopile turbine foundations. As the industry expands, knowledge on how impacts may manifest and the species affected will expand through studies at sites with different characteristics (e.g. size, depth, distance from shore, latitude etc.), turbine foundation design and local fish communities. Moreover, governments globally have policies that aim to ensure no net loss (NNL) of biodiversity as a result of marine infrastructure developments, such as offshore wind (e.g. EU Environmental Impact Assessment, Habitat and Birds Directives), and this may soon extend further to net positive effects (Marine Net Gain) in some countries, such as the UK, France and Chile (Edwards-Jones et al., 2024; Hooper et al., 2021). It is still unclear how these policy changes might be implemented and assessed (Edwards-Jones et al., 2024) but highlights the need to consider how impacts on fish species (positive and negative) could be best quantified. Moreover, fish are a fundamental link within marine food webs affecting predator/prey interactions with often protected species groups such as cetaceans and pinnipeds, and ecosystem functioning (Raoux et al., 2017). Building evidence as to whether there are species-, taxa-, site- or foundation-specific generalisations that can be used to predict local or regional ecosystem effects of wind farms is an important step that will require studies across a broad geographic range and species distribution (Hooper et al., 2021).

In this study, the fine-scale effect of wind turbine subsurface jacket foundations on the demersal fish distribution and size are directly assessed at two operating wind farms. The sampling was designed to focus on potential turbine foundation effects in a single year, rather than assessing interannual or seasonal variation in population and community metrics, although it is known these could be significant (Bicknell et al., 2019). In view of previous offshore wind farm studies (Bergström et al., 2013; Hillie et al., 2007; Leonhard et al., 2011; Wilhelmsson et al., 2006), it is predicted that the foundations will attract and aggregate species that prefer hard substrate habitat, therefore producing higher abundance and biomass close to them. Comparison between adjacent wind farms was also made to investigate whether any effects could be attributed to their different characteristics (age and jacket foundation type), given they are operating in proximity and subject to similar biotic factors.

2. Materials and methods

2.1. Sampling method

Baited Remote Underwater Video (BRUV) was used to survey fish abundance, biomass and diversity in this study. The method is commonly used to survey fish in temperate and tropical waters (see: Harvey et al., 2021; McGeady et al., 2023; Nalmpanti et al., 2023; Whitmarsh et al., 2016), with advantages over many traditional fish survey methods, including; non-destructive, no or limited observer bias, data reanalysis possible and unrestricted depth (cost-dependent) (Cappo et al., 2004; Lowry et al., 2012; Whitmarsh et al., 2016; Zintzen et al., 2012). As with other survey methods it has bias, e.g. differentially attracting species, bait type, plume effects or restricted view, and these have been investigated elsewhere (Dorman et al., 2012; Harvey et al., 2007; Stobart et al., 2007).

2.2. Study location

The study took place in and around the Beatrice and Moray East offshore wind farms in the Moray Firth, Scotland, North Sea (Fig. 1a) between 1st-23rd August 2022 during daylight hours. The wind farms are located between ~7.5 and 23 nautical miles offshore in water depth of between ~35 and 60 m. Beatrice operates 84 7 MW turbines with jacket foundations that have 4 legs giving each a square base (Fig. 2c), while Moray East operates 100 9.5 MW turbines with 3 legged jackets that create a triangle base (Fig. 2d). Neither jacket foundation designs had scour protection. Beatrice jacket foundations were installed between August 2017 and July 2018, and Moray East jackets between July and December 2020. Commercial fishing is still permitted within the wind farm boundaries, with scallop dredging, trawling and creel potting known to take place (Dunkley and Solandt, 2022), sometimes close to the turbines (<50m; pers comm). The seabed substratum across the wind farms comprised two biotopes: Medium to fine sands and muddy sands; or Cobbles and pebbles, gravels and coarse sands (Parry, 2019).

2.3. Sampling equipment

The BRUV systems used in this study were custom made calibrated deepwater submersible rigs built by Blue Abacus https://www.blueabacus.org/(Fig. 2a), each housing two cameras (Go-Pro Hero 9 Black) with LED lights mounted on the housing. The pole and bait box were attached to the housing and 15–20 kg of weight was fixed to the legs to temporarily secure the rigs to the seabed. The bait box contained 100 g of frozen Atlantic mackerel *Scomber scombrus* (mackerel) for each deployment.

2.4. Survey and design

BRUV systems were deployed close to 21 turbine jacket foundations (~30m) and at 15 reference sites either ~500 m from a jacket within a wind farm (the maximum possible displacement from a jacket) or >2 km away from a jacket outside the wind farms (Fig. 1b; Table S1). Three camera systems were simultaneously deployed to the seabed at each site for 45 min before retrieval to provide sampling replication and meant there was 108 deployments in total (Table S1). The turbine and reference sites were not paired and designed to be grouped into 4 sample groups (Beatrice turbines, Moray East turbines, inside wind farm references and outside wind farm references; Table S1) To reduce the likelihood of pseudo-replication due to fish movement between simultaneous deployments, the reference deployments were at least 150 m apart, and the turbine deployments were ~80 m apart and perpendicular to the prevailing current (i.e. bait plume). To avoid mooring entanglement risk, one of the jacket deployments was always on the opposite side of the structure in relation to the water current speed (Fig. 1c).

2.5. Image and data processing

The survey provided ~81 h of video footage from 108 BRUV deployments (Table S1), which was analysed using EventMeasure software (www.seagis.com.au). The analysis produced: number of demersal fish species (richness), relative abundance (MaxN) and fish lengths. MaxN is the maximum number of individuals, of each species, that occurred in a single video frame (MaxN frame). The use of MaxN to provide species relative abundance is widely used for BRUVs and is considered a conservative estimate of abundance, especially when species occur at a high density as no individual can be counted more than once (Cappo et al., 2003; Willis and Babcock, 2000).

Analysis of the footage began once the BRUV landed on the seabed and the sediment settled and ended after 30 subsequent minutes (see Bicknell et al., 2019). The relative abundance was determined by recording the first instance of a species and then subsequently when the

Fig. 2. (a) Baited remote underwater video systems used for the offshore wind farm surveys. **(b)** Example image from BRUV video footage illustrating main species composition and abundance (haddock and flatfish). **(c)** Four leg turbine jacket at Beatrice wind farm, and **(d)** three leg turbine jacket at Moray East wind farm.

number of individuals for that species exceeded the previous MaxN.

All individuals were identified to the lowest taxonomic level, apart from Dab *Limanda limanda* and European flounder *Platichthys flesus,* which were grouped as *Pleuronectiformes* spp. (subsequently referred to as flatfish) since it is not possible to reliably distinguish between the two species on horizontal video footage.

Total length (snout to tip of tail) measurements were taken of individuals in the MaxN frame. Measurements of flatfish were taken manually using stereo images in EventMeasure, whereas length of the haddock were obtained using a semi-automated machine learning model in Automated Fish Identification (AFID), which is a plug-in for EventMeasure (Marrable et al., 2022). Haddock were labelled with a point in both videos which enables the AFID software to calculate a length measurement. All AFID measurements were checked for accuracy and re-measured manually where necessary. A Residual Mean Square (RMS) value was calculated for each measurement, to indicate the error between corresponding measurement points in the stereo images (Marrable et al., 2022). Only measurements with an RMS <20 were used in further analyses.

For individuals in a MaxN frame that could not be measured accurately (e.g. when animals were not sufficiently perpendicular to the BRUV rig, or in a higher density scenario when fish bodies obscured each other), the mean length for that species MaxN frame was applied. In circumstances where there were no other individuals of that species in the video, the following hierarchy was followed until a mean measurement could be applied: location; wind farm; treatment (turbine or reference) (see Andradi-Brown et al., 2016; Barley et al., 2017).

To estimate individual fish weight the following standard equation was used:

$$W = a*L^b \qquad \text{(Eq 1)}$$

where W is the total weight in grams, L is the total length in cm (taken from the MaxN measurements), and **a** and **b** are species-specific conversion factors (Froese and Pauly, 2023).

The conversion factors were taken from the English North Sea ground fish survey (IBTS3E) for all fish species, except pout (*Trisopterus luscus*) due to lack of data. Pout conversion factors were taken from the Eastern English Channel and Southern North Sea beam trawl surveys

(Silva et al., 2013).

A biomass estimate for each deployment was then calculated using:

$$rB = W*MaxN \qquad (Eq\ 2)$$

where *rB* is the total relative biomass in grams, W is the total weight in grams (Eq (1)) and MaxN is the relative abundance.

The video footage was used to assign a habitat type code for each deployment: 1-rocky reef, 2-large coarse sediment, 3-medium mixed sediment, 4-fine sediment (as detailed in Bicknell et al., 2019). Habitat type was used in the subsequent analyses, alongside seabed current speed data (m/s) that was taken from POLPRED seabed CS20 models, NOC (https://noc-innovations.com/services/tide-prediction-software/offshore-software/) for the time of each BRUV deployment.

2.6. Data analysis

Only data for haddock *Melanogrammus aeglefinus* and flatfish were used in relative abundance, biomass and length comparisons, due to their high proportion of the total fish observed (cumulatively >90%; Table 1). Community composition comparisons using all observed species were initially examined but due to the extreme skew in abundance for two species it was considered uninformative.

To test for potential differences among sample groups in abundance, biomass or fish length, (generalized) linear mixed models ((G)LMM) were fitted with sample group (4 levels: Beatrice turbines, Moray East turbines, inside OWF references, outside OWF references) as fixed effect. Additionally, water depth and current speed were added as continuous fixed effects and habitat type (3 levels) and sampling site (36 levels) as random effects. Habitat type was not included as a fixed effect since it was not being directly tested and therefore not integrated in the survey design. When there was little variability resulting in a highly unbalanced random term that cause model instability, habitat was removed from models. Response data distributions were checked to determine model structure for each metric and comparison (Fox and Weisberg, 2019), resulting in negative binomial, zero-inflated negative binomial or log transformed response with a normal distribution used for abundance and biomass models. All fish length measurements were log transformed to fit normal distribution models. Model selection from all combinations of fixed effects in the full model was performed based on lowest AICc value (best fit) using the MuMin R package (Bartoń, 2023). Models with

significant collinearity of fixed effect terms were removed from model selection. Model performance and diagnostics were performed using the residual simulation-based approach in the DHARMa R package (Hartig, 2022). Analyses were conducted in R version 4.4.0 (R Core Team, 2024) using glmmTMB (Brooks et al., 2017) and lme4 (Bates et al., 2015) packages. Model pairwise contrasts between sample groups were conducted using the emmeans R package (Lenth, 2024).

To estimate age of measured fish, an age-length-key was constructed for haddock and flatfish using aged fish from the International Council for the Exploration of the Sea's (ICES) Database of Trawl Surveys (DATRAS: https://www.ices.dk/data/data-portals/Pages/DATRAS.aspx). For haddock, data from the west North Sea trawls for the 3rd quarter, 2015 to 2023 were included. Dab data was used to represent flatfish, from South-East North Sea trawls for the 3rd quarter of 2009, 2012, 2016 and 2021. Using the age-length keys, relative abundance and length data from the BRUVs were converted into fish percentage within each age class from 0 to 6 for each sample group (Ailloud and Hoenig, 2019).

3. Results

3.1. Survey sampling

A total of 108 BRUV deployments were completed (100% of design: Fig. 1b; Table S1). There were 17 deployments that occurred on the NE side and 15 that occurred on the SW side of the turbine sites (Fig. 1c). The depth range of deployments was 39–54 m, and current speeds between 0.03 and 0.31 m/s. Three habitat types were observed on the deployment footage: 81 (75%) fine sediment, 17 (15.75%) medium mixed sediment & 10 (9.75%) large coarse sediment.

3.2. Image and data processing

A total of 2614 length measurements were recorded for flatfish (n = 2048) and haddock (n = 566). For flatfish, 1265 (62%) lengths were directly measured, while 783 (38%) were derived from the mean measurements of the same deployment (n = 772) or location (n = 11). For haddock, 345 (61%) lengths were directly measured, and 221 (39%) were derived from the mean measurements of the same deployment (n = 200) or location (n = 21).

Table 1
Teleost species observed on baited cameras with number of individual fish and percentage of species shown by sampling group and overall total. * = High confidence of Dab *Limanda limanda* but may contain European flounder *Platichthys flesus*.

Common Name	Species	Teleost Fish									
		Beatrice Turbines		Moray East Turbines		Inside OWF References		Outside OWF References		Total no. of fish	% of total species
		No. of fish	% of species	No. of fish	% of species	No. of fish	% of species	No. of fish	% of species		
Flatfish*	Limanda limanda (Platichthys flesus)	1086	78.52	348	52.02	276	83.13	338	75.45	**2048**	**72.32**
Haddock	Melanogrammus aeglefinus	280	20.25	162	24.22	50	15.06	74	16.52	**566**	**19.99**
Poor cod	Trisopterus minutus	0	0.00	126	18.83	0	0.00	15	3.35	**141**	**4.98**
Grey gurnard	Eutrigla gurnardus	5	0.36	10	1.49	3	0.90	11	2.46	**29**	**1.02**
Whiting	Merlangius merlangus	7	0.51	2	0.30	0	0.00	3	0.67	**12**	**0.42**
European plaice	Pleuronectes platessa	2	0.14	5	0.75	0	0.00	4	0.89	**11**	**0.39**
Common dragonet	Callionymus lyra	2	0.14	4	0.60	0	0.00	3	0.67	**9**	**0.32**
Atlantic cod	Gadus morhua	0	0.00	6	0.90	1	0.30	0	0.00	**7**	**0.25**
Shorthorn sculpin	Myoxocephalus scorpius	0	0.00	3	0.45	1	0.30	0	0.00	**4**	**0.14**
Ling	Molva molva	0	0.00	2	0.30	0	0.00	0	0.00	**2**	**0.07**
Long-spined bullhead	Taurulus bubalis	0	0.00	0	0.00	1	0.30	0	0.00	**1**	**0.04**
Pouting	Trisopterus luscus	0	0.00	1	0.15	0	0.00	0	0.00	**1**	**0.04**
Red gurnard	Chelidonichthys cuculus	1	0.07	0	0.00	0	0.00	0	0.00	**1**	**0.04**
Totals		1383	100.00	669	100.00	332	100.00	448	100.00	**2832**	**100.00**

3.3. Species diversity and taxonomic composition

A total of 13 teleost fish species from 7 taxonomic families were observed on the BRUV footage across all deployments. This represented 2832 individual fish, the majority (>92%) were either flatfish or haddock (Table 1).

3.4. Relative abundance and biomass

The haddock relative abundance and biomass models revealed the metrics to be significantly higher at Beatrice and Moray East turbines compared to reference sites (all model contrasts: p < 0.05; Fig. 3; Tables S2 and S3). The effect size was larger at Beatrice turbines than Moray East turbine sites (Fig. 3; Tables S2 and S3). There was no significant difference between reference sites (>0.05; Tables S2 and S3). Current speed was retained in both models, but no interactions, and where significant showed a weak decline in abundance and biomass with increasing speed (Table S2).

The flatfish relative abundance and biomass models revealed the metrics to be significantly higher at Beatrice turbines compared to reference sites (all model contrasts: p < 0.05; Fig. 4; Tables S4 and S5). No significant difference for either metric was found at Moray East turbines compared to reference sites, or between reference sites (all model contrasts: p > 0.05: Fig. 4; Tables S4 and S5). Depth and/or current speed were retained in some models, but no interactions, and where significant the effect was a decrease in abundance or biomass with an increase in depth or current speed (Table S4).

3.5. Length and age

Length measurements taken from 345 haddock ranged between 20.5 and 40.3 cm, and from 1265 flatfish ranged between 10.3 and 30.7 cm. The overall mean was 29.1 cm ($\pm$2.9 SD) for haddock and 16.8 cm ($\pm$2.7 SD) for flatfish. These lengths indicate a mix of mature adults and juveniles for both species (Mature haddock L_{50} > 28 cm, age 1–2; Mature dab >11–14 cm) (Marty et al., 2014; Rijnsdorp et al., 1992).

The haddock length model revealed significantly larger fish at Beatrice and Moray East turbines compared to reference sites (model contrasts: p < 0.05; Tables S6 and S7). It also revealed no significant difference between Beatrice and Moray East turbines (p > 0.05; Tables S6 and S7). The turbines sites were grouped together to create and run a reduced model with 3 sample groups (OWF Turbines, inside OWF reference and outside OWF references). When turbine sites were grouped, the haddock length model revealed significantly larger fish at the turbines compared to reference sites (model contrasts: p < 0.01; Fig. 5a; Tables S8 and S9). The model estimated individual haddock were 1.4 cm and 2 cm larger at the turbines compared to inside and outside the wind farm, respectively. The flatfish model revealed a small but significant difference in size, with larger fish at turbines compared to the reference sites outside the wind farms (~0.75 cm; p = 0.03; Fig. 5c; Tables S8 and S9), but not to sites inside the wind farms (Fig. 5c; Tables S8 and S9).

Most haddock and flatfish measured were found to be age classes 1, 2 and 3 years, across all sample groups (>93%; Fig. 5b & d). The spread over these age classes differed between the sample groups, with a higher percentage of older fish (Age 3 or over) found around turbines and higher percentage of younger fish at reference sites (Age 1 or under) (Fig. 5b & d).
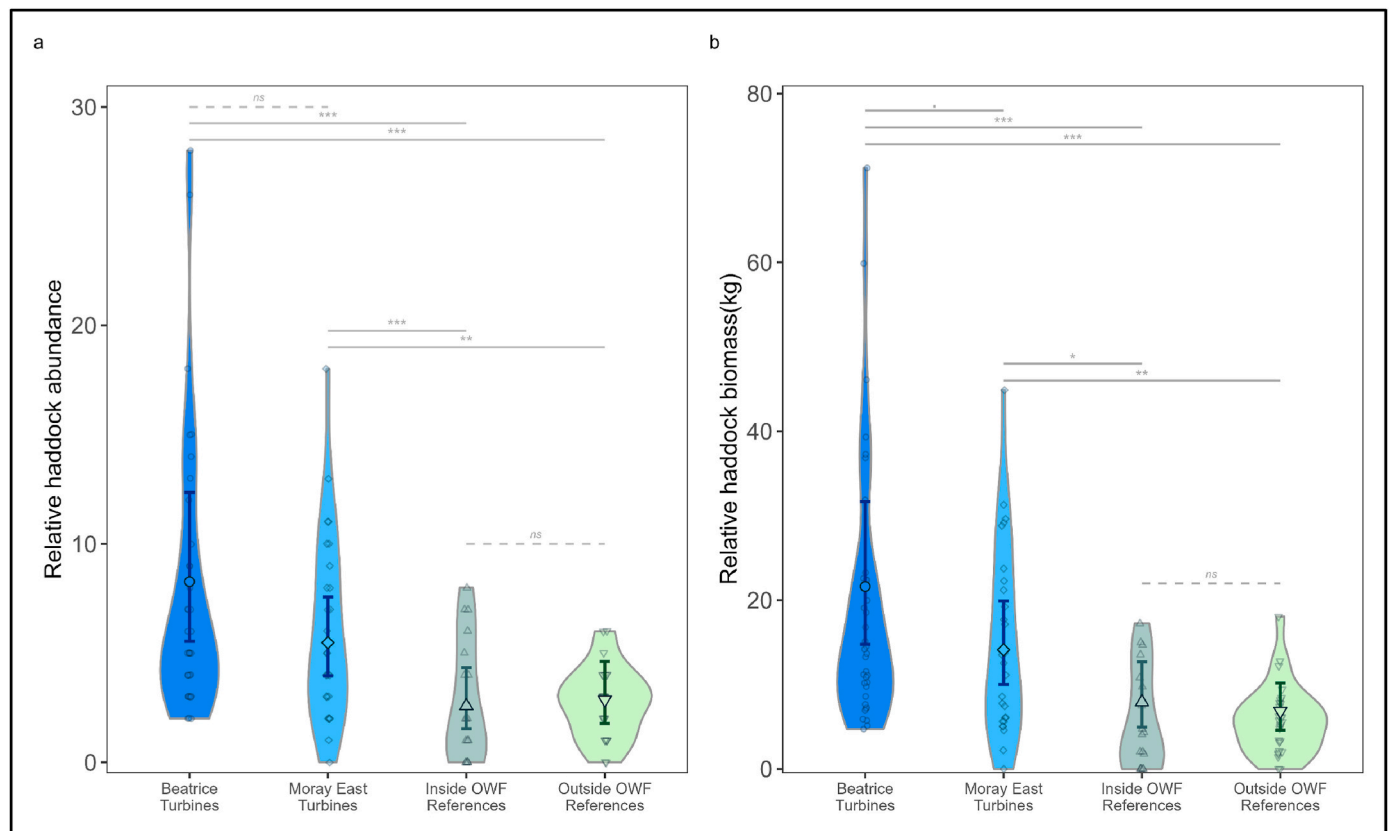

Fig. 3. Violin plots for haddock abundance (a) and biomass (b) data from survey sites at turbines and reference sites inside and outside the offshore wind farms (OWF), with model predictions (empty shapes ± confidence intervals). Solid grey bars indicate the paired comparison that are significantly different and dashed grey lines where they are not. Significance labels: *ns* = not significant, **.** = 0.05, * = p-value <0.05, ** = p-value <0.01 & *** = p-value <0.001.
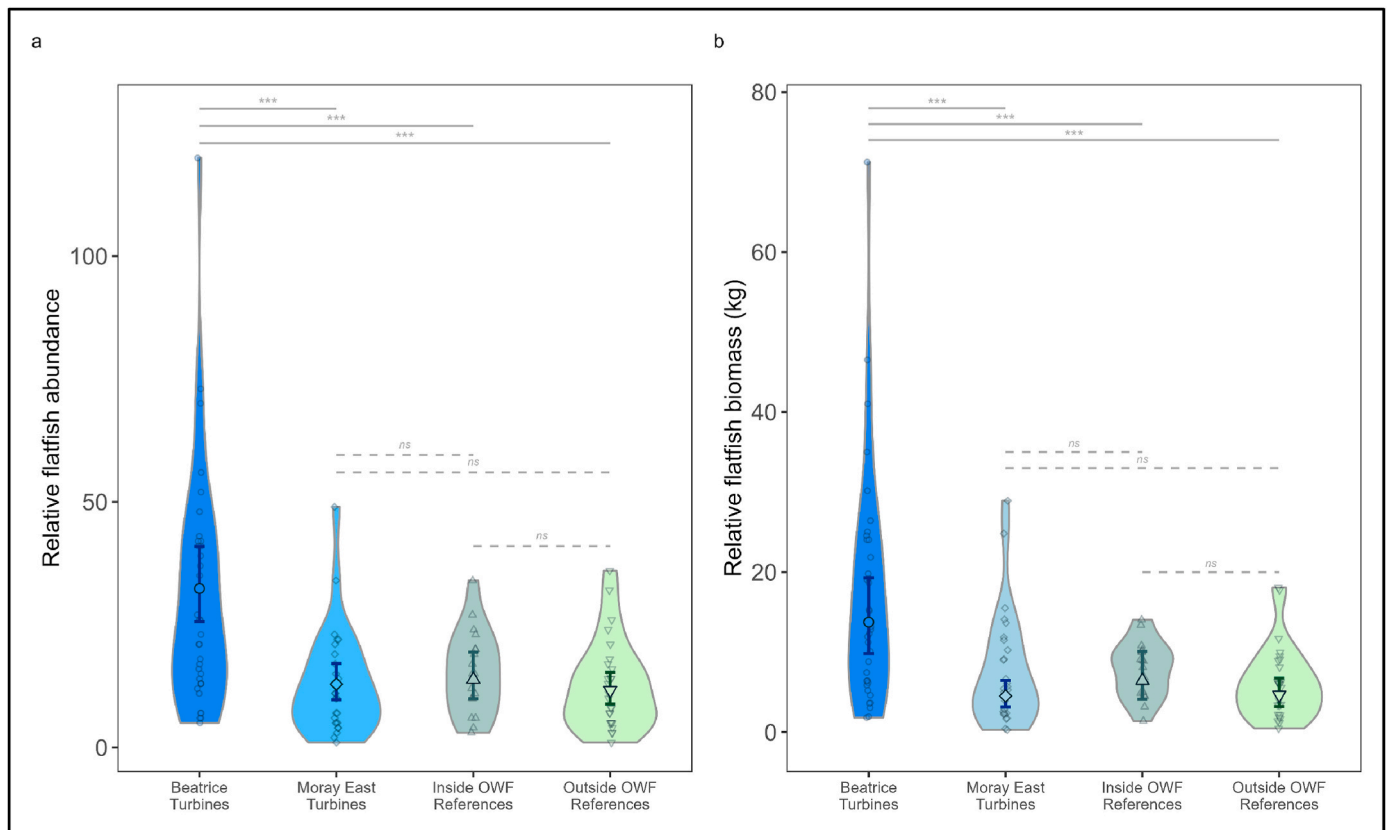
Fig. 4. Violin and point plots for flatfish abundance (a) and biomass (b) data from turbines and reference sites inside and outside the offshore wind farms (OWF), with model predictions (empty shapes ± confidence intervals). Solid grey bars indicate the paired comparison that are significantly different and dashed grey lines where they are not. Significance labels: *ns* = not significant, * = p-value <0.05, ** = p-value <0.01 & *** = p-value <0.001.

4. Discussion

Offshore wind turbine foundations were found to alter the distribution of demersal fish at two adjacent operational wind farms in the Moray Firth, Scotland during the summer 2022. Haddock abundance and biomass was higher close to turbines compared to references sites, with the effect size larger at the Beatrice wind farm. Flatfish abundance and biomass was higher close to turbines in the Beatrice but not in Moray East wind farms. Turbine foundations in both wind farms had larger haddock aggregated close to them, with a small increase in flatfish size close to turbines compared to outside wind farm reference sites.

4.1. Species and communities

The prediction of higher abundance close to jacket foundations of species that prefer hard substrate habitat could not be assessed, since there were so few counts of species with this trait to conduct a robust analysis e.g. pouting *Trisopterus luscus*, poor cod *Trisopterus minutus* or Shorthorn sculpin *Myoxocephalus scorpius* (Table 1) (Stenberg et al., 2015). The baited camera systems used to sample the foundation community were deployed within 30m of the turbine foundations, however, this may not be close enough to attract and/or observe species that are intimately connected to the habitat and will not venture short distances from the structures. The hard substrate habitat offered by the foundations is confined to the jacket footprint since there is no scour protection that could extent the habitat further, unlike most monopile foundations. For these species, complimentary sampling (e.g. remote underwater vehicles or scuba diving) or different deployment methods (e.g. structure attachment) could be more suitable but would require further safety and logistical considerations. The proportion of teleost fish observed during the survey was heavily skewed toward haddock and flatfish,

>92% by abundance, supporting evidence from catch data gathered during Moray Firth pre- and post-wind farm construction trawl surveys (March 2019 & March 2021) of the importance of these species in the local demersal fish community (Beatrice Offshore Windfarm Limited, 2021; Moray Offshore Windfarm Limited, 2019). Seabed trawl survey data gathered in and around both wind farms also supported dab *Limanda limanda* being the most likely species within the assigned flatfish group, since very few flounder *Platichthys flesus* were caught across all trawl surveys (Beatrice Offshore Windfarm Limited, 2021; Moray Offshore Windfarm Limited, 2019). The small proportion of plaice *Pleuronectes platessa* and whiting *Merlangius merlangus* recorded on the BRUV footage compared to their relatively large presence in the trawl surveys (range 1–30% and 8–14%, respectively) (Beatrice Offshore Windfarm Limited, 2021; Moray Offshore Windfarm Limited, 2019) may be indicative of annual or seasonal variation in the Moray Firth, or possibly the baited technique not being optimal for attracting and observing these species. Whiting, however, has been observed regularly on previous camera surveys with the same bait (Bicknell et al., 2019; Elliott et al., 2017a, 2017b; Griffin et al., 2016), and plaice are known to respond to olfactory cues in a similar way to dab (de Groot, 1969, 1971), so might be expected to show comparable attraction. Bait type and quantity can influence species and feeding guilds observed on BRUV footage, but oily fish (as used in this study) are often used for their good olfactory plume and persistence (reviewed in Whitmarsh et al., 2016). Further study would be required to assess whether mackerel bait is unattractive for plaice, but it was used in this study to be consistent and allow comparison with additional survey years and other locations that have been assessed using the method (e.g. Bicknell et al., 2019; Davies et al., 2021).
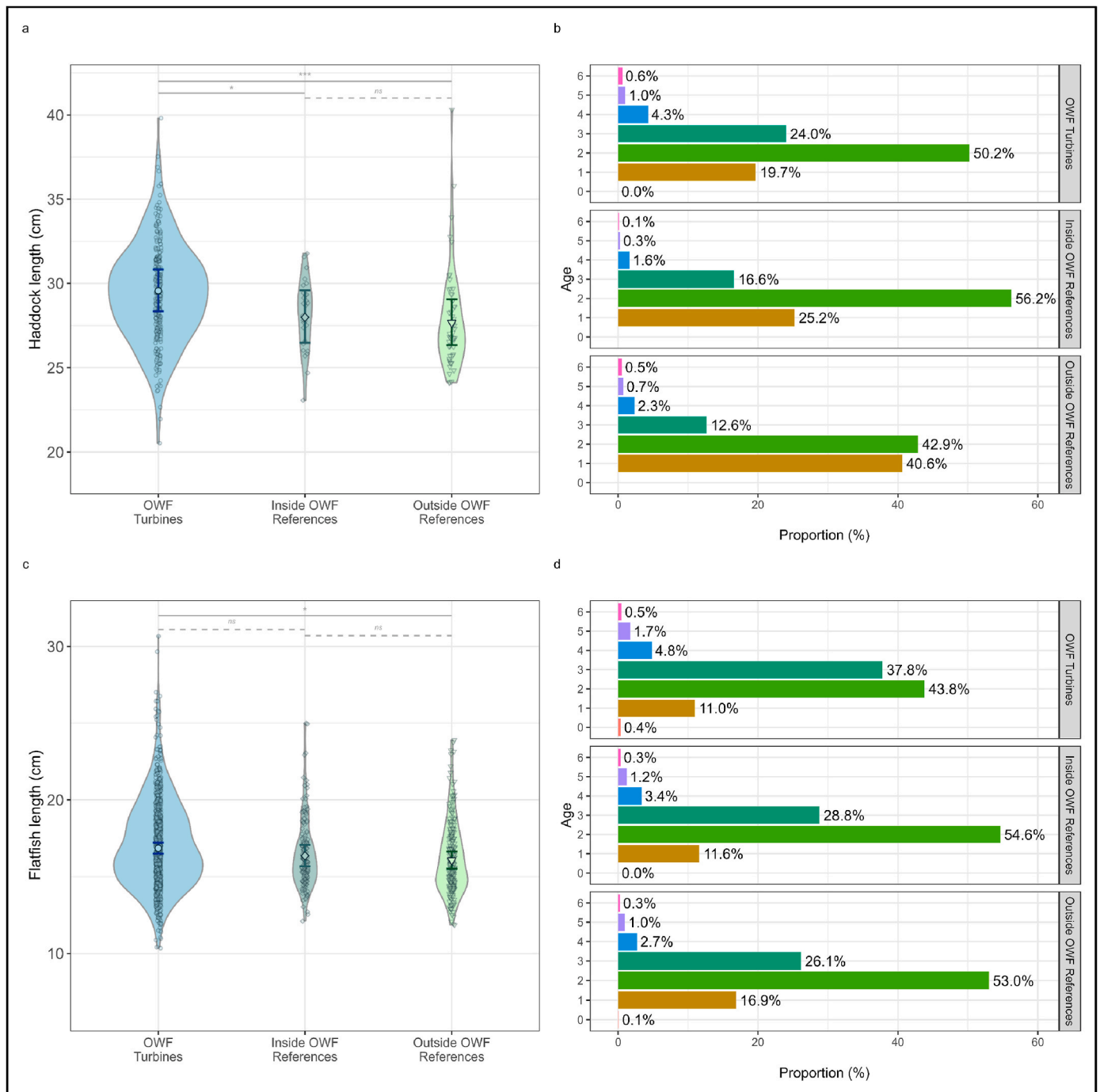
Fig. 5. Violin and point plots for **(a)** haddock and **(c)** flatfish length data from survey sites within and outside the Moray Firth wind farms, with model predictions (± confidence intervals). Solid grey bars indicate the paired comparison that are significantly different and dashed grey lines where they are not. Significance labels: *ns* = not significant, * = p = value < 0.05, ** = p = value < 0.01 & *** = p = value < 0.001. Estimated percentage age classes of haddock **(b)** and flatfish **(d)** for each sample group using species age-length-key calculated from ICES DATRAS data.

4.2. Fish aggregation

Haddock are known to occur in a range of benthic habitats (Brodziak, 2005; Cuff et al., 2023; González-Irusta and Wright, 2016; van der Kooij et al., 2011), but not generally associated with hard substrate like some gadoids (Elliott et al., 2017a, 2017b; Gomes et al., 2024), so are not considered a good example for assessing the predicted higher abundance around hard substrate structures. Similarly, dab prefer soft sediment habitat (Eggleton et al., 2018; Kaiser et al., 2004; Sell and Kröncke, 2013), therefore not expected to be greatly affected by the foundations.

Thus, the evidence of aggregation for both species around turbine foundations in Beatrice wind farm suggests this is not a direct effect of habitat preference but possibly an indirect benefit of the hard substrate environment providing feeding opportunities. This would align with evidence from previous diet studies in other wind farms that found a difference in prey composition for gadoids (Atlantic cod, poor cod & pouting) and flatfish (plaice, dab and flounder) close to monopile turbine foundations compared to reference locations (Buyse et al., 2023a; Derweduwen et al., 2012, 2017; Reubens et al., 2011, 2013c; Wilber et al., 2022). Stomach content and stable isotope studies revealed

demersal species were feeding on hard substrate *amphipoda* and *crustacea* that occur on the foundations, compared to soft sediment infaunal prey species found in individuals caught at reference locations (Buyse et al., 2023a; Derweduwen et al., 2017; Reubens et al., 2011, 2013c). Food intake estimates for plaice and dab, and stomach fullness index calculated for pouting were also higher for individuals sampled closer to turbines compared to locations further away (Buyse et al., 2023a; Derweduwen et al., 2017), indicating these introduced artificial habitats are providing increased food availability for demersal species (Buyse et al., 2023b; Reubens et al., 2013c). The larger haddock, and to a lesser degree dab, observed around turbines in both wind farms may also be related to food availability, which could have contributed to enhanced body condition and growth (Buyse et al., 2023a; Reubens et al., 2013c; Rueda et al., 2015). Plaice and pouting caught close to turbines in Belgium waters in the southern North Sea were also found to be larger, suggested to be due to higher quality prey items providing more energy for metabolism and growth (Buyse et al., 2023a; Reubens et al., 2013c). An increased growth rate would also influence the age estimates based on the age-length-key in this study and may explain or contribute to the differences in age structure and proportions found between the turbine and reference sites in the Moray Firth.

The shelter offered by jacket turbine foundations is another possible explanation for aggregation close to them. The frame of the jacket (Fig. 2c and d) provides more open space and opportunities for sheltering within the pipe structure, compared to solid monopile foundations with scour protection. For species with close association with reef or hard substrate habitats the jackets could be an attractive environment, however, there is no evidence in the literature that adult haddock or dab use structures as shelter (e.g. for protection or reproduction) and both are linked with mobile benthic habitats, suggesting it is an unlikely driver of the aggregation found in this study.

4.3. Biomass and production

Biomass estimates integrate the various factors that contribute to changes in fish abundance and size, into a metric with direct relevance to energy fluxes in species assemblages and ecosystem functioning (Mora et al., 2011). The Beatrice wind farm turbine foundations had on average ~2.9 times more haddock and ~2.5 times more flatfish biomass close to them compared to reference sites, and Moray East turbines had ~2 times more haddock biomass. Such repeated concentration of biomass around foundations across single or multiple wind farms will alter the feeding topography for higher predators, such as marine mammals (Fernandez-Betelu et al., 2022; Russell et al., 2014). These changes in prey location, availability and quality could be important for survival, reproduction and ultimately population dynamics, especially for marine mammals with high daily energy demands (i.e. porpoises; Booth, 2020; Booth et al., 2023). Whether the foundations are producing new fish biomass or redistributing the existing quantity is also important to understand the overall effect on ecosystem function and services (Isaksson et al., 2023; Raoux et al., 2017). Biomass data calculated in the present study cannot distinguish between these alternatives due to lack of temporal sampling and the baited technique used, however, evidence from studies around offshore platforms show that jacket foundations offer complex habitat that make them highly productive for some demersal fish species (Birt et al., 2024; Claisse et al., 2014). There is indirect evidence from studies at wind farms that indicate the aggregating effect could lead to higher production through increased reproduction (Gimpel et al., 2023) and feeding opportunities (Buyse et al., 2022, 2023a; Mavraki et al., 2021; Reubens et al., 2013c) for demersal species, but direct evidence through quantitative estimates is still needed to confirm the inference. A program of work using underwater camera technology that includes the site replication, seasonal sampling and reference areas to gather the core abundance and length data required to calculate quantitative estimates of fish production (for details of production calculation methods see: Birt et al., 2024; Claisse

et al., 2014; Connolly et al., 2024; zu Ermgassen et al., 2016) would be logistically challenging and expensive to conduct in temperate offshore environments (Bicknell et al., 2019). Production estimates also require data not available from camera observations, such as total mortality (sum of natural and fishing mortality) and species fidelity metrics (Birt et al., 2024), so may require complimentary survey methods (e.g. fish tagging and acoustic telemetry tracking) or rely on the literature. Producing these estimates is not an insignificant task but would be necessary to provide direct evidence for wind farms.

4.4. Wind farm characteristics

This study found the effect of turbine foundations on demersal fish abundance and biomass varied across sites, even when in proximity to each other and subject to similar seabed and tidal environments (Fig. 1b). Beatrice turbine foundations had higher abundance and biomass for haddock and flatfish, whereas only higher haddock metrics were found at the Moray East turbine foundations compared to reference sites. The effect size of these significant comparisons was also larger for the Beatrice turbines. Time since construction and jacket foundation design (Fig. 2c and d) are two factors that could help explain these disparities (Coolen et al., 2022; Leonhard et al., 2011). The earliest Beatrice turbine foundations were built in 2017, whereas the Moray East were completed in 2020, making them at least 2 years older. The Beatrice jackets have 4 legs, compared to 3 at Moray East, providing a more complex subsea structure. These confounding variables mean it is not possible to disentangle the relative contribution of each factor to the differences found at Beatrice, but it is likely that both have an influence (Degraer et al., 2020; Langhamer, 2012). Shelter for mobile species will be available immediately after construction of the foundations, but colonization, growth and proliferation of sessile and epi-benthic organisms that provide habitat and food takes time to occur, and subsequently influence fish behaviour (Degraer et al., 2023; Pondella et al., 2022). The Beatrice foundations have had more time for these communities and habitats to progress and create an attractive environment for haddock and flatfish. In addition, increased complexity (rugosity and void spaces) is known to create higher fish species richness, density and biomass around artificial reefs across a large geographic range, with positive relationships to production (Pondella et al., 2022). The extra complexity 4-legged jacket foundations offer may act in a similar manner, enhancing the effect more than the less complex Moray East foundations. Age and complexity are not mutually exclusive and will act together in creating the subsea environment (Pondella et al., 2022). Depending on their contribution to forming the foundation's subsea communities, the Beatrice foundations could maintain a more attractive environment for haddock and dab if complexity is the main driver, alternatively, the Moray East sites could become similar if time for community development is more important. The seabed piled jackets assessed in this study are one of the three main foundation types currently in operation globally, alongside monopiles and gravity-based structures (Degraer et al., 2023; Krone et al., 2017). The amount of hard substrate introduced, and spatial footprint of the foundations, depends on the design and type of scour protection (e.g. boulders, rock mattresses etc.) but all have a 'reefing' effect that can attract fish to varying degrees (Degraer et al., 2023; Krone et al., 2017). The challenge is to detail how variable these effects are, and how they scale up and interact across single or network of sites, with single or mixed foundation types. Whether the effects observed around fixed foundation wind farms transfer well to floating wind turbine structures is debatable, but given they will have subsea moorings attached to the seabed interactions with demersal fish communities will occur, albeit to a lesser degree and mostly in deeper water environments (Danovaro et al., 2024; Edwards et al., 2024). The large floating structures are more likely to influence pelagic (shoaling) species by acting as Fish Aggregation Devices (FADs) to concentrate fish underneath and in proximity (Castro et al., 2002; Dempster and Taquet, 2004), which could alter the biomass distribution

for this component of the local fish assemblage (Lopez et al., 2017).

4.5. Marine policy

Offshore wind farm developments have already surpassed most previous large scale introductions of artificial structures (Paolo et al., 2024), and will continue to expand to meet targets on global reduction of CO_2 emissions (Akram et al., 2023; Lee et al., 2021). There is a push to transition from government policies of NNL of biodiversity and ecosystem services to a Marine Net Gain (MNG) approach, which not just mitigates the impact of building wind farms but generates a positive impact from their construction (Edwards-Jones et al., 2024). Developing these principles into policy that can be effectively implemented is not an insignificant task, and the various stakeholders involved can have a range of opinions on what should be prioritized and/or actioned (e.g. UK: Edwards-Jones et al., 2024). Helping to restore coastal and offshore fish populations that have been depleted through overfishing or habitat destruction, as known in the North Sea (Couce et al., 2020), is seen as a positive effect and desirable action (Edwards-Jones et al., 2024). In this study, and others around wind farms, turbine foundations have been found to have higher abundance and biomass of demersal fish species, suggesting the presence of these structures can play a role in helping toward positive gains. However, as previously discussed, production of new fish biomass has not been directly tested so the actual impact (positive or negative) on the fish populations is unclear and should be a focus for future research.

CRediT authorship contribution statement

Anthony W.J. Bicknell: Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Samuel Gierhart:** Formal analysis, Data curation. **Matthew J. Witt:** Writing – review & editing, Methodology, Investigation, Funding acquisition, Conceptualization.

Data statement

Data available via figshare repository: 10.6084/m9. figshare.26948122

Ethics statement

All study activities were conducted in compliance with the University of Exeter's ethics and Health and Safety policies.

Funding

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Anthony Bicknell reports financial support was provided by The Crown Estate. Samuel Gierhart reports financial support was provided by The Crown Estate. Matthew Witt reports financial support was provided by The Crown Estate. If there are other authors, they 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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marenvres.2025.106977.

Data availability

Data will be made available on request.

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