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In-situ ecological interactions with a deployed tidal energy device; an observational pilot study

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ABSTRACT

At present, few studies exist that consider the relationship between species interactions and key environmental variables, with the added influence of offshore marine renewable energy technologies. Video footage and ADCP survey techniques were used, to examine the presence of fish and velocity flow rates within the vicinity of a deployed tidal energy device. Pilot trials were conducted across 15 day temporal periods, during the summer months of 2009 and 2010. Five random photographic stills were taken from the video footage at hourly intervals throughout each trial day to estimate species presence and abundance. Mean abundance then was compared between hour and day temporal scales and their relationship with velocity rate, for both years.

Pollack, *Pollachius pollachius* was observed aggregating in shoals temporarily round the deployed device, with larger abundance observed in 2009 than 2010. No other species were identified from the surveys. Pollack abundance was significantly associated to velocity rate for both trial years. Increased abundance was related to a reduction in velocity rate for both years, with shoals potentially using the device for temporary protection or feeding strategies. Responses to tidal velocity also differed between years, with 2009 abundances ranging from 0 to 1.2 m/s and 2010 abundances between 0.5 and 1.7 m/s. Overall this preliminary study outlined a potentially useful approach to investigate species responses with new anthropogenic activities in the marine environment.

1. Introduction

The scope for marine tidal energy development is increasing throughout the United Kingdom (UK); due to the government's future renewable energy contribution target aims (Bahaj, 2011; Devine-Wright, 2011). By 2020, the UK government aims for at least 30% of its electricity to be generated from renewable energy sources, with 10% potentially contributed by marine tidal energy development alone (DECC, 2009). At present, marine tidal energy development is centred on the operational activities of single test or commercial devices, which are deployed and trialled within offshore test sites. Within the UK, governmental and regulatory bodies request developers to submit consents and planning applications to approve such developments at the local, regional and national scale (EMEC, 2013). This regulatory process requires the developer to outline any potential environmental impacts and ecological interactions, through Environmental Impact Assessments (EIA) and Environmental Statements (ES).

In-depth knowledge of ecological interactions with marine tidal energy devices is still lacking (Boehlert and Gill, 2010; Gill, 2005; Neill et al., 2009; Shields et al., 2009). This is due to limited knowledge of these devices and field-based sampling difficulties within the sites selected for development (Shields et al., 2011). As a result, the available information primarily consists of qualitative ecological reviews or guidance documents. For example, few quantitative studies exist which examine how marine tidal energy devices influence fish species, in terms of presence, abundance or behavioural responses (Gill, 2005). Available information comprises of qualitative descriptions, which identify species displacement, collision risk, and the potential for devices to act as fish aggregation devices (FAD's). As such, the true ecological interaction may be missed, which may influence both regulator and developer's understanding of environmental impacts from marine tidal energy developments.

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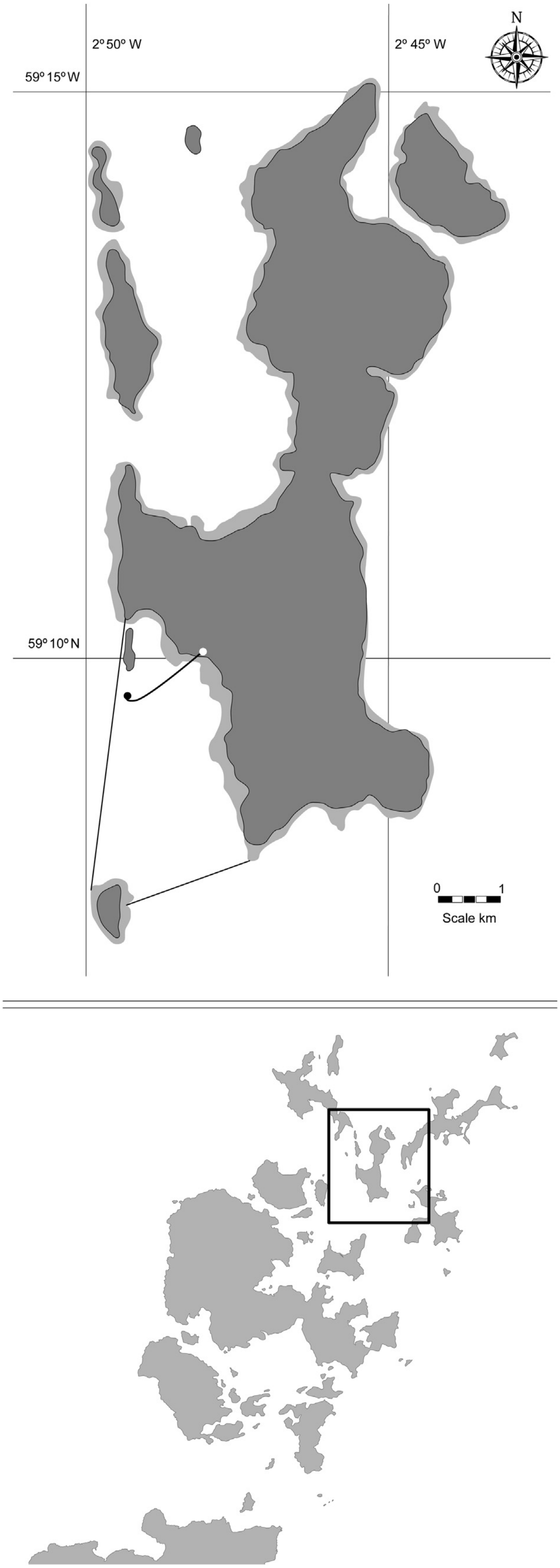

Fig. 1. Location of the EMEC tidal energy test site and OpenHydro Ltd deployed tidal device, situated off the South-West coast of the Isle of Eday, Orkney Isles. The black circle and joined line represents the position of the deployed OpenHydro Ltd test platform device and sub-sea cable route. The straight black lines represent the extent of the EMEC test facility (adapted from Aurora, 2005).

An advance in survey technology and experimental sampling designs can now provide a variety of methods to assess ecological interactions with this new marine anthropogenic activity (Ehrhold et al., 2006; Ierodiaconou et al., 2011; Judd, 2012). Video or photography camera systems, are extremely useful to record species observations, in terms of presence, abundance, behaviour, and habitat/species interactions (Albert et al., 2003; He, 2003; Lauth et al., 2004; Lorance and Trenkel, 2006; Reubens et al., 2011). Importantly, these techniques can measure ecological interactions at both the temporal and spatial scale, and are not limited in terms of sampling time or weather restrictions (Monk et al., 2011). Recently, video techniques have been used to evaluate ecological interactions from offshore wind and wave devices deployments (Langhamer et al., 2010; Reubens et al., 2011; Shields et al., 2011; Wilhelmsson et al., 2006).

Numerous ecological studies also relate key environmental variables to ecological observations, such as sea surface temperature (Bosman et al., 2011; Hermant et al., 2010). Offshore sites allocated for tidal energy development are located within environments which exhibit strong hydrodynamic conditions, including increased water movements (Gill, 2005; Neill et al., 2009; Shields et al., 2011). Enhanced water movements are not only a fundamental environmental variable for tidal energy extraction, but are also known to strongly influence marine species' behaviour, presence and distribution (Hiscock, 1983; Shields et al., 2011). Therefore, the inclusion of this key environmental variable to determine species' response to tidal energy development activities is paramount (Shields et al., 2011). Technology such as Acoustic Doppler Current Profilers (ADCP) are commonly used to measure water movements and have been applied to a number of biological, geophysical and oceanographical studies in the past (Kostachuk et al., 2005; Reed et al., 2004; Wewetzer et al., 1999).

By integrating video photography techniques with ADCP tidal velocity measurements, fish interactions in response to deployed marine tidal energy devices and their relationship with key variables, may be identified. This could provide useful information for marine tidal energy regulators or developers, and also further knowledge on species ecological patterns (Langhamer et al., 2010; Shields et al., 2009). The overall aim for this study was therefore to (i) examine fish abundance responses to an operational marine tidal energy test device. Past studies also describe that fish species are known to alter temporally, and should be included in such studies (Macpherson, 1998; Stobart et al., 2007; Tessier et al., 2005; Wilhelmsson et al., 2006). Therefore this study also aims to (ii) assess fish abundance responses over temporal hour, day and year scales. The study finally aims to (iii) assess the relationship between fish abundance and tidal velocity rates. The study was developed as an experimental pilot trial, to provide initial information for ecological studies associated with marine tidal energy developments.

2. Materials and methods

2.1. Study area

The pilot study experimental trials were conducted within the European Marine Energy Centre (EMEC) offshore tidal energy test site, adjacent to the Isle of Eday, Orkney Isles (Fig. 1). The test site is situated within the Fall of Warness marine tidal race environment which is approximately 2 km (km) wide and 3.5 km long

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(Norris and Droniou, 2007). The stream has an average depth of 30–35 m, with tidal flow movements from both the north-west and south-east within a daily tidal cycle (Osalusi et al., 2009). The OpenHydro Ltd marine tidal energy device platform was installed during 2006, at the most northern part of the test site (59°09.448′ N, 02°49.561′ W). The device is a sub-tidal open turbine generator, consisting of a 6 m diameter turbine mounted on a twin mono-piled platform. The platform is placed into the seabed, producing a footprint approximately 10 m^2, approximately 700 m from the Eday coastline (OpenHydro Ltd, 2008). During the study, this test device was the only structure deployed within the EMEC test site.

The pilot study trials were conducted between the summer months of June and July in 2009 and 2010. These months were selected based on the ease of access to the device platform. Collecting the data from the platform is known to be highly difficult during other months, due to the unfavourable weather conditions and the potential risk of losing the data during collection. The trials were conducted across 15 day trial periods, with the 2009 trial beginning at the end of June and the 2010 trial beginning at the start of June. The 2010 trial lost nine days of video footage after day seven. This was due to a weak cable link between the recording device and the camera. The fault was identified during the survey and fixed straight away, with the survey extending for a further nine days to account for the missing data.

2.2. Video fish observation sampling method

The underwater footage was recorded using a video Triplex 8 Channel DVR, linked to a Submertec Camera System mounted to the outside of the OpenHydro Ltd platform device (Fig. 2). The camera system was mounted approximately 2 m from the face of the turbine allowing continuous recording of the entire 6 m turbine area. This system recorded continuously throughout the surveys and was switched off after the last survey day for both years. The video footage was collected manually after the full trial period each year and transferred to a compatible video computer Programmable Logic Controller (PLC) software system.

Five randomly chosen photographic still frames were extracted from the first 2 min of footage from each hour of the survey data, recording the hour, day and year of each image. The technique follows other timed animal behavioural methodologies that use photographic techniques to assess species abundances (Shucksmith et al., 2006). This gives an estimate of relative abundance, whilst reducing the chance of counting individual organism twice, which can occur during video assessments (Becker et al., 2010, 2011; Birt et al., 2012). Random photograph selection within the 2 min time period was determined by the second timeframe status, using a random number generation application in the R statistical software package (R Development Core Team., 2010). Due to the extremely long summer daylight hours at this latitude, the analysis was conducted across the 24 h clock cycle. However, during both survey years, some footage was excluded where weather conditions affected the quality of the photograph still, and where the field of view was obscured by the presence of marine algae debris.

Maximum fish abundance was first estimated within each sampled frame. Geometric mean fish abundance was then calculated across the five individual frames sampled within each hour, which included zero counts. Fish were identified visually from the photograph frames based on body shape, lateral line and mouth part descriptions where possible. Only individuals identified unequivocally to the species level were included within the analysis (Hayward and Ryland, 1995). The presence of other marine species such as marine mammal species was also recorded, if they occurred.

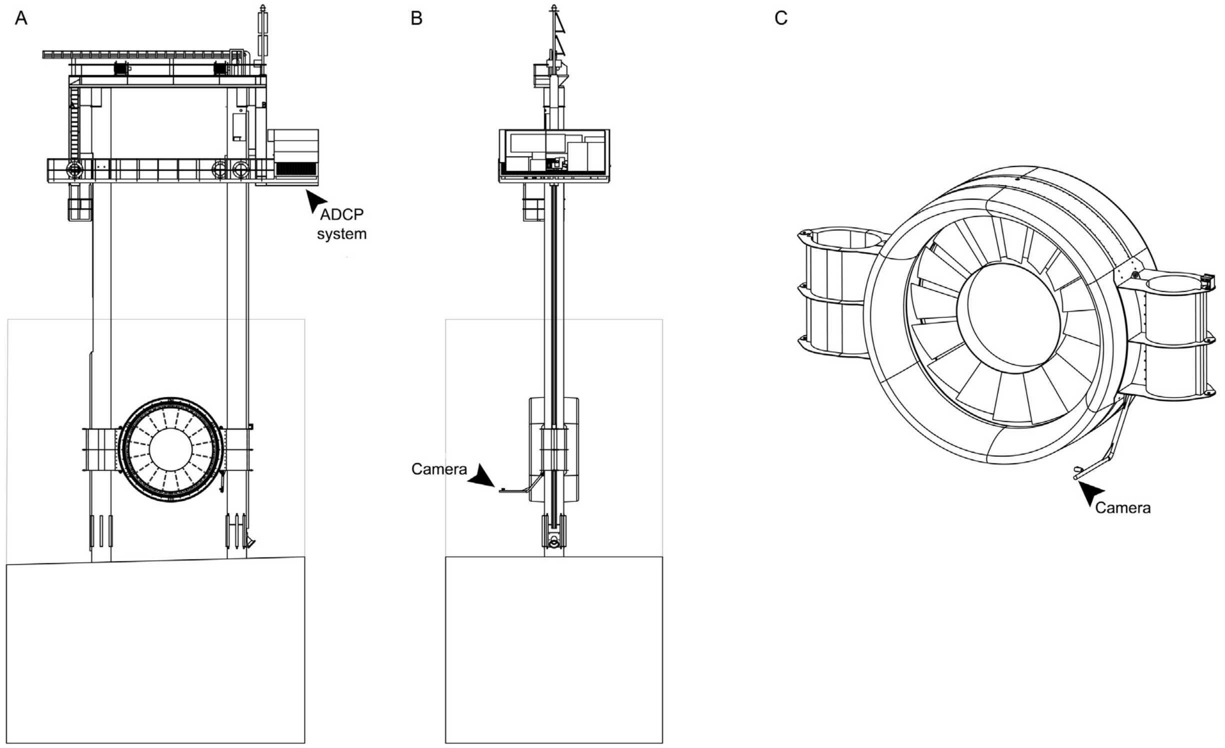

Fig. 2. Schematic diagrams of the front view (A), side view (B) and close view (C) of the attached camera and ADCP setup on the OpenHydro Ltd tidal device platform within the EMEC tidal energy test development site, Isle of Eday.

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2.3. ADCP velocity rate measurements

A Nortek Aquadopp two beam ADCP was deployed at the platform in order to measure the horizontal tidal current flow around the turbine and through the Fall of Warness over a 24 h cycle. The two beams were deployed either side of the platform to measure flow on flood (North) and ebb (South) tides. Data was streamed live to the PLC which is used for control and monitoring of the turbine. The tidal velocity data was sampled every 10 s and recorded onto a PC. The data was collected at the end of each annual trial and downloaded into a Microsoft Excel format for analysis, with velocity measured in metres per second (m/s). Hourly harmonic mean tidal velocity rates were then calculated across 10 s samples for both the North and South ADCP velocity measurements for each annual trial. In order to account for the change in direction in the tidal flow, the higher of the two hourly means from the North and South ADCP measurements were used in analyses.

2.4. Data analysis

Analyses were conducted with R statistical programming software (R Development Core Team., 2010). Integrated generalised linear models (GLM) with generalised additive models (GAM) were used, to examine ecological count data and also their relationship to environmental variables (Crawley, 2007).

A GLM was first used to investigate mean hourly fish abundance response with all explanatory variables and their interactions. The explanatory variables included the categorical temporal scales of hour (assigned to the 24 h clock), day and year, and the continuous explanatory variable, tidal velocity. This model showed significant interactions between the explanatory variables: tidal velocity and year ($F = 55.84$, $p < 0.001$, DF = 1 and 445); tidal velocity and hour ($F = 3.14$, $p < 0.001$, DF = 23 and 467) and, day and year ($F = 3.66$, $p < 0.001$, DF = 14 and 444). As such, the fish abundance response for each year was investigated separately, with the temporal scales hour and day. GAMs were then used to examine the relationship between fish abundance and tidal velocity rate for each year. This analysis was implemented using the R library function ‘mgcv’ (‘mgcv’ Cran package, from Wood, 2006). GAMs used the lowess non-parametric smoother to view the overall environmental—biotic relationship (Cleveland, 1981; Crawley, 2007). Models used the Poisson distribution of errors (family = Poisson, link function = log) and assessed in terms of homogeneity throughout visual inspection of the Q–Q plots (Crawley, 2007). The quasi-poisson error structure was used to deal with over-dispersion, where the residual deviance is greater than the residual degrees of freedom in the fitted model. This error structure frees the model from meeting strict assumptions of a specific distribution. The maximum likelihood and likelihood ratio tests cannot be used (Crawley, 2007). The significance of the explanatory variables within models were deduced by model deletion methods, using analysis of deviance with the F test. Variables were deemed significant based on the increase in deviance from their resulting removal ($\alpha = 0.05$) (Crawley, 2007).

3. Results

3.1. Video observations

The pilot study recorded the presence of fish during both 2009 and 2010 trials. Fish were identified to the Species taxonomic level, with all individuals identified as *Pollachius pollachius* (common name: Pollack). No other marine species (such as marine mammal species) were recorded during this study.

Table 1
Generalised linear model (GLM) F ratio and p value results for the temporal scales; year, hour and day of fish abundance for the 2009 and 2010 trials, Isle of Eday.

GLM	Explanatory variable	F ratio	p value	DF
Year		25.6	<0.001	521
2009	Hour	1.266	0.219	246
	Day	1.17	0.29	260
2010	Hour	2.81	<0.001	246
	Day	2.22	0.007	260

Across the total number of hours recorded ($n = 261$) in 2009, the total proportion of fish presence observed was 13%, with 8% in 2010. Generally, the 2009 trial estimated significantly larger fish abundance counts compared to the 2010, with a total sum of 664 individuals recorded in 2009 (Table 1.). The 2009 trial also recorded the largest range of abundance within each trial hour, ranging from 0 to 46 (mean count per hour = 44) (Fig. 3). The 2010 trial recorded a total sum of 121 individuals, with abundance ranging from 0 to 11 per hour (mean count per hour = 7). Across the trial days, fish abundance fluctuated for both years (Fig. 4). Fish abundance recorded during in 2009 showed no significant temporal relationships from the GLM results. However, the 2010 trial showed significant relationships between fish abundance and the temporal scales (Table 1.). During this trial year no counts were observed between the hours of 20:00–05.00, and the trial days 6–9 respectively.

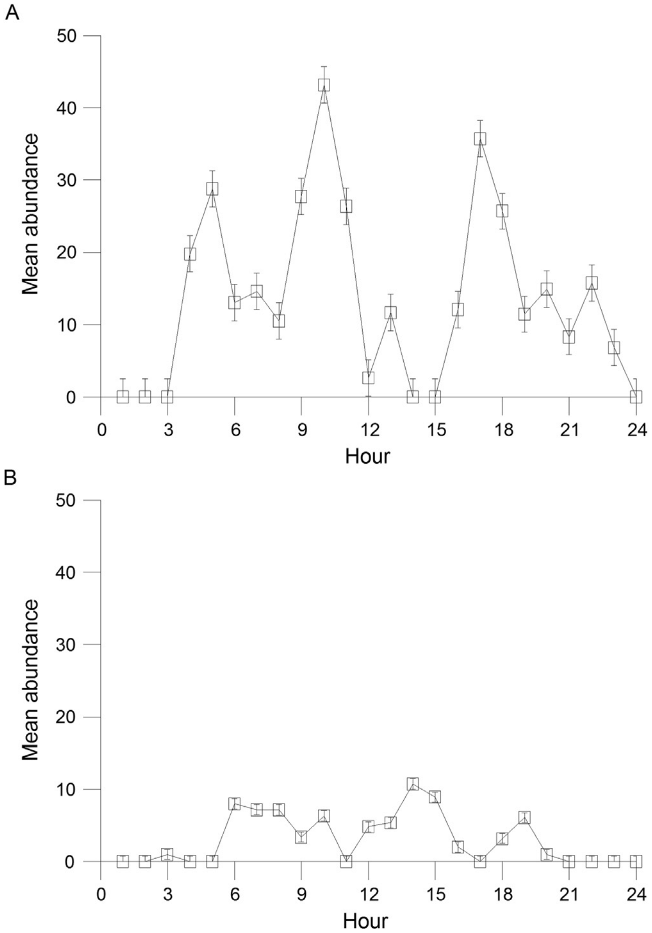

Fig. 3. Mean fish abundance recorded per hour during the 2009 (A) and 2010 (B) video survey trials (±1 S.E.M), Isle of Eday.

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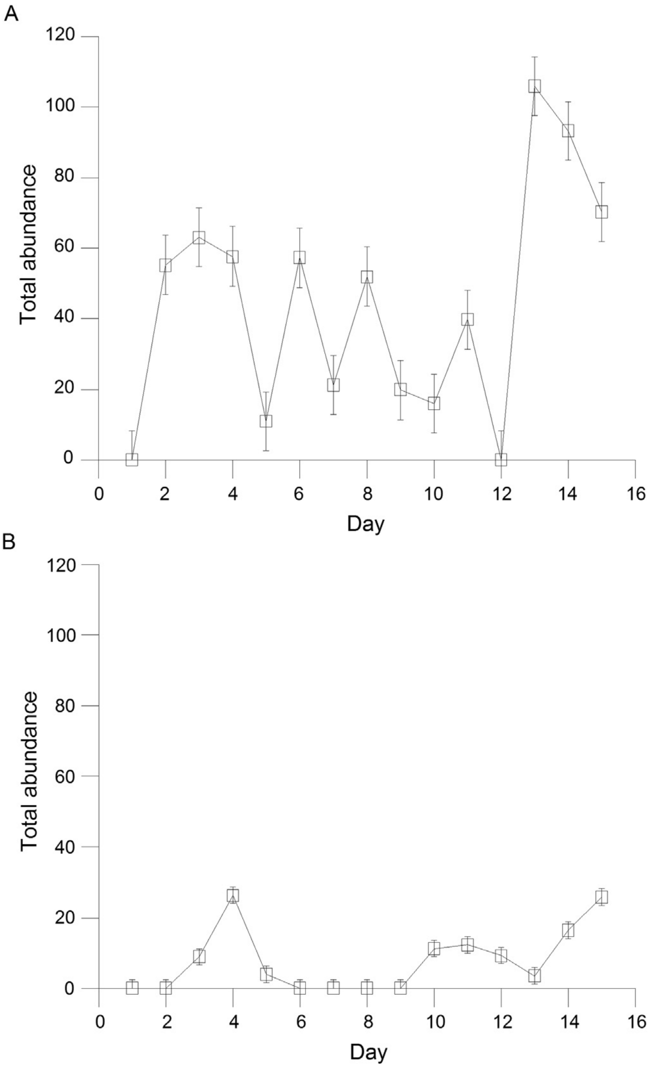

Fig. 4. Total fish abundance recorded per trial day during the 2009 (A) and 2010 (B) video survey trials (±1 S.E.M), Isle of Eday.

3.2. *ADCP velocity rate trials*

The ADCP tidal velocity rate trials identified a larger velocity rate range in 2010 than 2009. During 2009, velocity rates ranged from 0.260 to 2.780 m/s, with the highest velocity rate observed in day 9 and the lowest rate in day 14 (Fig. 5). The largest range of velocity rates occurred in days 8 and 9, and the lowest range in days 2 and 13. The 2010 trial showed velocity rate to range from 0.180 to 3.05 m/s, with the highest velocity rate observed in day 10 and the lowest in day 15. The largest velocity rate range occurred during days 9 and 11, with the lowest range in days 2 and 7. This pattern generally mirrored the two separate time periods across the overall survey.

3.3. *Fish abundance responses to tidal velocity*

The GAM models for both years outline a significant relationship with fish abundance and velocity rates ($GAM^{2009VELOCITY}$: $F = 40.96$, $p < 0.001$, $n = 261$, $DF = 4.42$; $GAM^{2010VELOCITY}$: $F = 4.806$, $p \leq 0.001$, $n = 261$, $DF = 3.51$), with abundance declining as velocity rates increased. However, the pattern of this relationship differed for both years (Fig. 6). During 2009, fish abundance rapidly declined as velocity rate increased. Fish abundance was observed to occur largely between velocity rates of 0–1.0 m/s, with few observations of fish presence after 1.3 m/s. During 2010, fish presence predominately occurred between 0.5 and 1.7 m/s and then declined after 1.8 m/s.

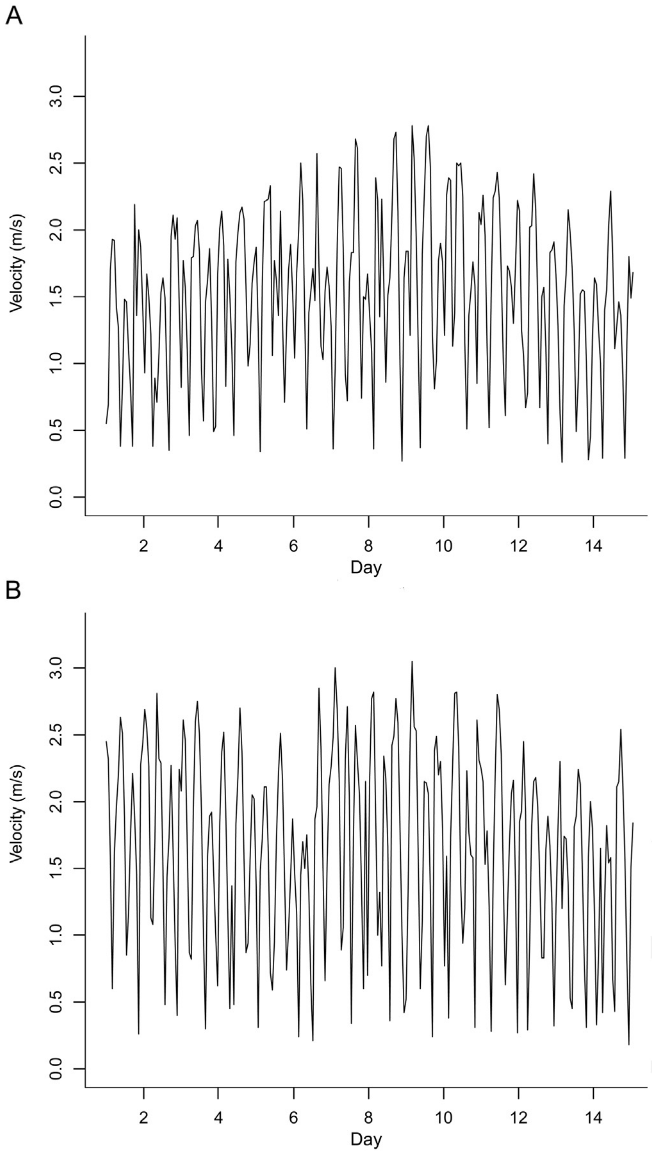

Fig. 5. ADCP velocity rates across the total survey days for (A) 2009 and (B) 2010, Isle of Eday. Velocity is measured as metres per seconds (m/s).

4. Discussion

4.1. *Video observations*

The experimental pilot study recorded the presence of *P. pollachius* surrounding the deployed marine tidal energy device. This gadoid fish species is found throughout the British Isles, including the Orkney Isles (Henderson and Bird, 2010; Sarno et al., 1994). It is regarded as a non-commercial species, and as such, limited information (i.e. regional landing stock data) exists (ICES, 2012a; ICES, 2012b). During the study no other marine species were recorded, including other fish species, marine mammals or

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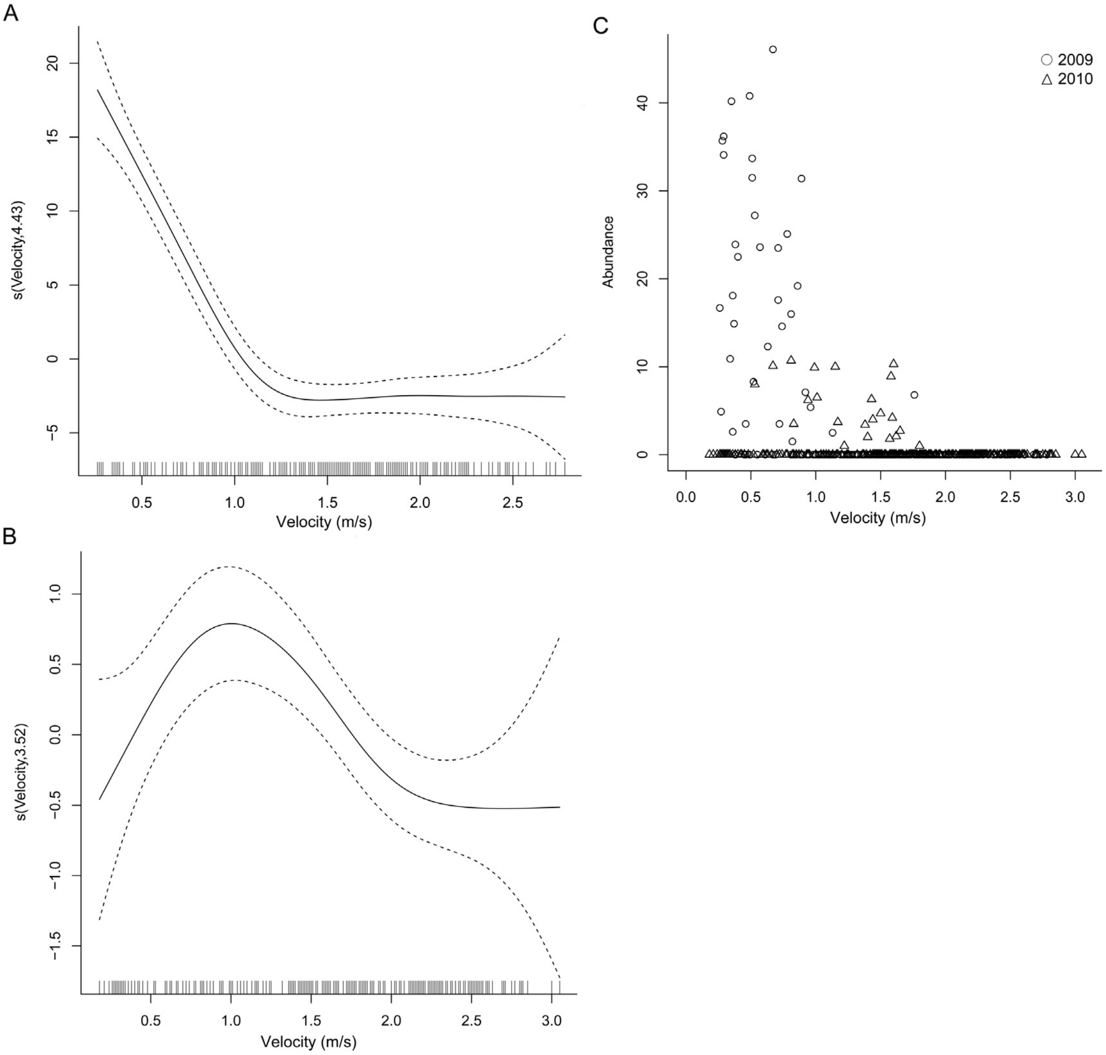

Fig. 6. Generalised additive models (GAM) of the relationship between *Pollachius pollachius* abundance and the measured velocity rates for 2009 (A) and 2010 (B), and the individual abundance counts recorded across velocity rate for both years (C), Isle of Eday. For (A) and (B), dashed lines represent the 95% confidence intervals. For (C) circles represent the 2009 survey trial, with triangles representing the 2010 survey trial abundance counts. Velocity is measured as metres per seconds (m/s).

diving seabirds. This information will aid regulatory bodies and developers understand the potential environmental impacts from marine tidal energy developments.

The results identified that for both years, fish predominately occurred in groups, with few observations of solitary individuals. Grouping, shoaling and aggregation activities are a common behavioural trait in fish species, particularly in *P. pollachius*, by providing individuals with the potential for increased feeding, spawning and predator avoidance (Cohen et al., 1990; Froese and Pauly, 2007; Rangeley and Kramer, 1995; Rowley, 2008; Seppälä et al., 2008). *P. pollachius* are a predatory species, and feed by using natural or anthropogenic structures to strike out at passing prey (Froese and Pauly, 2007; Pizzolon et al., 2008). As such, the device could offer this species a new site for feeding or refuge from predators. This follows other studies which suggest that such offshore structures can act as artificial reefs or fish aggregation devices (Langhamer et al., 2010; Wilhelmsson et al., 2006). During both years, fish presence was relatively small, in comparison to the total recorded video footage. *P. pollachius* is known to remain within the vicinity of local waters, suggesting that the observed aggregations could potentially be the same group, repeatedly returning to the device (Cohen et al., 1990; Sarno et al., 1994). However, it was not possible to identify if this was the case, but does suggest the need for future fish tagging experiments.

The results also showed significant temporal variations and interactions with fish abundance. Fish populations are known to fluctuate naturally, with daily behavioural cycles influenced by biological and environmental cues including; light, water depth, water direction or prey/predator movements (Cargnelli et al., 1999; Sarno et al., 1994; Seppälä et al., 2008). Annual variations are also often linked to other annual variables including sea surface temperature changes and also the population structure of the fish aggregation i.e. juvenile nursery aggregations or grouped adult spawning events (Cargnelli et al., 1999; Le Fur and Simon, 2009; Selleslagh and Amara, 2008). Importantly, it outlines the significance of including temporal scales and other related variables (i.e. diel effects) in assessments required to examine species interactions with marine energy developments (EMEC, 2013).

4.2. Tidal velocity fish response

The increased velocity rates and temporal variations observed are comparable to past independent ADCP surveys, with the local environment known for substantially strong and varied tidal flow

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conditions (Norris and Droniou, 2007). This is due to the land masses of the Isle of Eday and Muckle Green Holm within the area creating a natural narrow channel constricting the tidal flow, which leads to the observed increased velocity rates (Norris and Droniou, 2007). In-depth surveys within these types of environments are exceedingly uncommon, due to the complexity of the physical seabed characteristics and the degree of variation of these strong hydrodynamic conditions restricting survey effort (Bailly du Bois et al., 2012). As such, velocity rate information derived from key texts including Chart Datum only provides an initial, basic viewpoint of the system. Therefore, these results also further aid key information on the nature of these environments, in terms of velocity profile descriptions.

The GAM models portrayed comparative relationships between fish abundance and velocity rates surrounding the deployed tidal device for both annual trials. Significantly fewer *P. pollachius* were observed at high velocity flow rates, with increased abundance counts related to low tidal velocity rates. The larger velocity rates observed may drive *P. pollachius* away from the device to other local regions and structures, for protection or better feeding conditions (Selleslagh and Amara, 2008). As tidal velocity declines, shoals may then be more inclined to move away from these areas and aggregate round the device. The ADCP surveys for both years identified subtle tidal velocity curves, which could be the result of periodic neap and spring tidal pattern conditions. Further comparisons to periodic tidal pattern currents such as spring and neap cycle scenarios or other tidal current patterns (such as ebb or flood cycles) could therefore advance the understanding of fish abundance responses to the device. During the 2010 trial, fish observations were seen to occur at larger velocity rates than the populations observed in the 2009 trial. Shoals are known to aggregate over different spatial scales, influenced by the complexity of physical structures, habitat patchiness and the natural behaviour of the species or population involved (Le Fur and Simon, 2009). *P. pollachius* also portray opportunistic trait tendencies and are found in a variety of pelagic, benthopelagic and estuarine environments and often regarded as marine migrant opportunists (Henderson and Bird, 2010; Li et al., 2010). Overall, fish abundance responses surrounding the tidal device could be described as temporary opportunistic aggregations, responding to local abiotic factors, such as tidal velocity conditions.

4.3. Combined survey methods: caveats and future approaches

The combined use of video/still photography and ADCP sampling techniques are useful for such offshore, extreme hydrodynamic environments (Krag et al., 2009; Monk et al., 2011; Reed et al., 2004; Wewetzer et al., 1999). In the context of the study aims, the study provided preliminary ecological quantitative information, which can assist regulatory bodies and developers begin to define ecological interactions with marine tidal energy developments. However, further experimental testing of the study's method design is recommended, for scientific rigour and in-depth analysis of ecological responses with tidal energy devices (Diesing et al., 2009; Hermant et al., 2010; Osalusi et al., 2009). For example, a proportion of unexplained variation and interaction was identified between the abundance and tidal velocity rates for both annual trials (☐ (from analysis of deviance) 2009 = 35%, ☐ 2010 = 86%), with the 2010 trial outlining considerable unexplained variation. This is the likely result of other direct or indirect biotic and abiotic factors. In addition, the 2010 survey trial also lost a number of video survey days which could therefore attribute to the high unexplained variation value, which is further shown by the wider spread of the confidence intervals and the level of interaction in the GLM and GAM results.

Overall, this pilot study could be enhanced by the addition of replication units (number of cameras, control sites, deployed tidal energy devices), the inclusion of other key variables (i.e. light/diel, sea temperature and meteorological information) and also implementing additional methods (electronic fish tagging techniques) (Selleslagh and Amara, 2008). In addition, a wider-scaled collaborative research is recommended, to examine fish interactions with other types of offshore developments, such as wind energy devices and oil and gas platforms (Dempster et al., 2010). For example, this could include examining fish interactions with different development life stages (deployment, operational and decommissioning cycles), development structural complexity (structure shape and size) and their location within the marine environment (adjacent habitat types). This approach would be extremely beneficial for developers, regulators, ecologists and the scientific community, to examine the true patterns of ecological responses with new offshore anthropogenic activities. This is inherently important given the potential large scale of such developments in the future (Albert et al., 2003; EMEC, 2013).

4.4. Conclusions

The pilot study outlined *P. pollachius* to aggregate temporally surrounding the deployed marine tidal energy device during the 2009 and 2010 trials. Fish aggregations fluctuated considerably across hour and day temporal scales, with temporal interactions found in 2010. Tidal velocity was identified to influence the presence of fish aggregations, with increasing tidal velocities seen to clearly reduce the number of observations. Fish aggregations were not observed above 1.3 m/s in 2009 trials and 1.8 m/s in 2010 respectively. Overall this experimental approach identified preliminary responses of local species interactions with this marine tidal energy device. However, further method testing, replicate samples and assessment of this pilot study is recommended to aid future environmental impact assessments for tidal energy developers and regulators.

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References

Albert, O.T., Harbitz, A., Høines, A.S., 2003. Greenland halibut observed by video in front of survey trawl: behaviour escapement, and spatial pattern. J. Sea. Res. 50, 117–127.

Aurora, 2005. EMEC Tidal Test Facility Fall of Warness Eday, Orkney. Environmental Statement. Aurora Environmental Ltd, Orkney, p. 176.

Bahaj, A.S., 2011. Generating electricity from the oceans. Ren. Sus. En. Rev. 15, 3399–3416.

Bailly du Bois, P., Dumas, F., Solier, L., Voiseux, C., 2012. In-situ database toolbox for short-term dispersion model validation in macro-tidal seas, application for 2D-model. Con. Shelf. Res. 36, 63–82.

Becker, A., Cowley, P.D., Whitfield, A.K., 2010. Use of remote underwater video to record littoral habitat use by fish within a temporarily closed South African estuary. J. Exp. Mar. Bio. Eco. 391, 161–168.

Please cite this article in press as: Broadhurst, M., et al., In-situ ecological interactions with a deployed tidal energy device; an observational pilot study, Ocean & Coastal Management (2014), http://dx.doi.org/10.1016/j.ocecoaman.2014.06.008

Becker, A., Cowley, P.D., Whitfield, A.K., Järnegren, J., Naesje, T.F., 2011. Diel fish movements in the littoral zone of a temporarily closed South African estuary. J. Exp. Mar. Bio. Eco 406, 63–70.

Birt, M.J., Harvey, E.S., Langlois, T.J., 2012. Within and between day variability in temperate reef fish assemblages: learned response to baited video. J. Exp. Mar. Bio. Eco 416–417, 92–100.

Boehlert, G.W., Gill, A.B., 2010. Environmental and ecological effects of ocean renewable energy development. A current synthesis. Oceanology 23, 68–81.

Bosman, S.H., Methvena, D.A., Courtenay, S.C., Hanson, J.M., 2011. Fish assemblages in a north Atlantic coastal ecosystem: spatial patterns and environmental correlates. Estuar. Coast. Shelf Sci. 92, 232–245.

Cargnelli, L.M., Griesbach, S.J., Packer, D.B., Berrien, P.L., Johnson, D.L., Morse, W.W., 1999. Essential Fish Habitat Source Document: Pollock, *Pollachius Virens*, Life History and Habitat Characteristics. Tech. Rep. NMFS-NE-131. NOAA, US, p. 30.

Cleveland, W.S., 1981. LOWESS: a program for smoothing scatterplots by robust locally weighted regression. T Ame. Stat. 35, 54.

Cohen, D.M., Inada, T., Iwamoto, T., Scialabba, N., 1990. FAO Species Catalogue. In: Gadiform Fishes of the World (Order Gadiformes). An Annotated and Illustrated Catalogue of Cods, Hakes, Grenadiers and Other Gadiform Fishes Known to Date. Fish. Synop. Rep, vol. 10. FAO, Rome, p. 125, 442p.

Crawley, M.J., 2007. The R Book. John Wiley & Sons Ltd, Chichester.

DECC, 2009. The UK Renewable Energy Strategy. Department for Energy and Climate Change, UK, p. 235. Report CM7686.

Dempster, T., Sanchez-Jerez, P., Uglem, I., Bjørn, P.-A., 2010. Species-specific patterns of aggregation of wild fish around fish farms. Estuar. Coast. Shelf Sci. 86, 271–275.

Devine-Wright, P., 2011. Enhancing local distinctiveness fosters acceptance of tidal energy: a UK case study. Ener. Pol. 39, 83–93.

Diesing, M., Coggan, R., Vanstaen, K., 2009. Widespread rock reef occurrence in the central English Channel and the implications for predictive habitat mapping. Estuar. Coast. Shelf Sci. 83, 647–658.

Ehrhold, A., Hamon, D., Guillaumont, B., 2006. The REBENT monitoring network, a spatially integrated, acoustic approach to surveying nearshore macrobenthic habitats: application to the Bay of Concarneau (South Brittany, France). ICES. J. Mar. Sci. 63, 1604–1615.

EMEC, 2013. Guidance for Developers at EMEC Grid Connected Sites: Supporting Environmental Documentation. Report No: GUIDE009-02-02 20130402. European Marine Energy Centre Ltd, Orkney Isles.

Froese, R., Pauly, D., 2007. Fishbase Homepage on a Global Information System on Fishes [On-line] URL:
http://www.fishbase.org (accessed 20.02.12.).

Gill, A.B., 2005. Offshore renewable energy: ecological implications of generating electricity in the coastal zone. J. App. Eco. 42, 605–615.

Hayward, P.J., Ryland, J.S. (Eds.), 1995. Handbook of the Marine Fauna of North-West Europe. Oxford University Press, Oxford.

He, P., 2003. Swimming behaviour of winter flounder (*Pleuronectes americanus*) on natural fishing grounds as observed by an underwater video camera. Fish Res. 60, 507–514.

Henderson, P.A., Bird, D.J., 2010. Fish and macro-crustacean communities and their dynamics in the Severn Estuary. Mar. Poll. Bull. 61, 100–114.

Hermant, M., Lobry, J., Bonhommeau, S., Poulard, J.-C., Le Pape, O., 2010. Impact of warming on abundance and occurrence of flatfish populations in the Bay of Biscay (France). J. Sea Res. 64, 45–53.

Hiscock, K., 1983. Water movement. In: Earll, R., Erwin, D.G. (Eds.), Sublittoral Ecology. The Ecology of the Shallow Sublittoral Benthos. Oxford University Press, Oxford, pp. 58–97.

ICES, 2012a. Report of the ICES Advisory Committee 2012. ICES Advice, 2012. Book 5. International Council for the Exploration of the Sea.

ICES, 2012b. ICES assessed stocks. Summary Report of New Advice Published in June and October, 2012. International Council for the Exploration of the Sea.

Ierodiaconou, D., Monk, J., Rattray, A., Laurenson, L., Versace, V.L., 2011. Comparison of automated classification techniques for predicting benthic biological communities using hydroacoustics and video observations. Cont. Shelf Res. 31, S28–S38.

Judd, A., 2012. Guidelines for Data Acquisition to Support Marine Environmental Assessments for Offshore Renewable Energy Projects. Cefas Contract Report ME5403 – Module 15. (Cefas, Lowestoft).

Kostachuk, R., Best, J., Villard, P., Peakall, J., Franklin, M., 2005. Measuring flow velocity and sediment transport with an acoustic Doppler current profiler. Geo 68, 25–37.

Krag, L.A., Madsen, N., Karlsen, J.D., 2009. A study of fish behavior in the extension of a demersal trawl using a multi-compartmental separator frame and SIT camera system. Fish Res. 98, 62–66.

Langhamer, O., Haikonen, K., Sundberg, J., 2010. Wave power-sustainable energy or environmentally costly? A review with special emphasis on linear wave energy converters. Ren. Sus. Ener. Rev. 14, 1329–1335.

Lauth, R., Wakefield, W., Smith, K., 2004. Estimating the density of thornyheads, *Sebastolobus* spp., using a towed video camera sled. Fish Res. 70, 39–48.

Le Fur, J., Simon, P., 2009. A new hypothesis concerning the nature of small pelagic fish clusters: an individual-based modelling study of *Sardinella aurita* dynamics off West Africa. Eco. Mod. 220, 1291–1304.

Li, W., Han, R., Chen, Q., Qu, S., Cheng, Z., 2010. Individual-based modelling of fish population dynamics in the river downstream under flow regulation. Eco. Inf. 5, 115–123.

Lorance, P., Trenkel, V.M., 2006. Variability in natural behaviour, and observed reactions to an ROV, by mid-slope fish species. J. Exp. Mar. Bio. Eco. 332, 106–119.

Macpherson, E., 1998. Ontogenetic shifts in habitat use and aggregation in juvenile sparid fishes. J. Exp. Mar. Bio. Eco. 220, 127–150.

Monk, J., Ierodiaconou, D., Bellgrove, A., Harvey, E., Laurenson, L., 2011. Remotely sensed hydroacoustics and observation data for predicting fish habitat suitability. Cont. Shelf Res. 31, S17–S27.

Neill, S.P., Litt, E.J., Couch, S.J., Davies, A.G., 2009. The impact of tidal stream turbines on large-scale sediment dynamics. Ren. Ener. 34, 2803–2812.

Norris, J.V., Droniou, E., 2007. Update on EMEC activities, resource description, and characterisation of wave-induced velocities in a tidal flow. In: Proceedings of the 7th European Wave and Tidal Energy Conference, Portugal, p. 3.

OpenHydro Ltd, 2008. Environmental Scoping Document. Alderney Subsea Tidal Array. OpenHydro Ltd, Ireland, p. 35.

Osalusi, E., Side, J., Harris, R., 2009. Structure of turbulent flow in EMEC's tidal energy test site. Int. Com. Heat. Mass Trans. 36, 422–431.

Pizzolon, M., Cenci, E., Mazzoldi, C., 2008. The onset of fish colonization in a coastal defence structure (Chioggia, Northern Adriatic Sea). Estuar. Coast. Shelf Sci. 78, 166–178.

Rangeley, R.W., Kramer, D.L., 1995. Tidal effects on habitat selection and aggregation by juvenile Pollock, *Pollachius virens* in the rocky intertidal zone. Mar. Eco. Pro. Ser. 126, 19–29.

R Development Core Team, 2010. R: a Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Reed, R.E., Glasgow, H.B., Burkholder, J.M., Brownie, C., 2004. Seasonal physical-chemical structure and acoustic Doppler current profiler flow patterns over multiple years in a shallow, stratified estuary, with implications for lateral variability. Estuar. Coast. Shelf Sci. 60, 549–566.

Reubens, J.T., Degraer, S., Vincx, M., 2011. Aggregation and feeding behavior of pouting (*Trisopterus luscus*) at wind turbines in the Belgium part of the North Sea. Fish. Res. 108, 223–227.

Rowley, S., 2008. *Pollachius pollachius*. Pollack homepage. Marine Life Information Network: Biology and Sensitivity Key Information [On-line] URL:
http://www.marlin.ac.uk/speciesinformation.php?speciesID=4155 (accessed 08.03.12.).

Sarno, B., Glass, C.W., Smith, G.W., 1994. Differences in diet and behaviour of sympatric Saithe and Pollack in a Scottish sea loch. J. Fish. Bio. 45, 1–11.

Selleslagh, J., Amara, R., 2008. Environmental factors structuring fish composition and assemblages in a small macrotidal estuary (eastern English Channel). Estuar. Coast Shelf Sci. 79, 507–517.

Seppälä, O., Karvonen, A., Valtonen, E.T., 2008. Shoaling behavior of fish under parasitism and predation risk. Anim. Behav. 75, 145–150.

Shields, M.A., Dillon, L.J., Woolf, D.K., Ford, A.T., 2009. Strategic priorities for assessing ecological impacts of marine renewable energy devices in the Pentland Firth (Scotland, UK). Mar. Pol. 33, 635–642.

Shields, M.A., Woolf, D.K., Grist, E.P.M., Kerr, S.A., Jackson, A.C., Harris, R.E., Bell, M.C., Beharie, R., Want, A., Osalusi, E., Gibb, S.W., Side, J., 2011. Marine renewable energy: the ecological implications of altering the hydrodynamics of the marine environment. Ocean. Coast. Man. 54, 2–9.

Shucksmith, R., Hinz, H., Bergmann, M., Kaiser, M.J., 2006. Evaluation of habitat use by adult plaice (*Pleuronectes platessa* L.) using underwater video survey techniques. J. Sea. Res. 56, 317–328.

Stobart, B., García-Charton, J.A., Espejo, C., Rochel, E., Goñi, R., Reñones, O., Herrero, A., Crec'hriou, R., Polti, S., Marcos, C., Planes, S., Pérez-Ruzafa, A., 2007. A baited underwater video technique to assess shallow-water Mediterranean fish assemblages: methodological evaluation. J. Exp. Mar. Bio. Eco. 345, 158–174.

Tessier, E., Chabanet, P., Pothin, K., Soria, M., Lasserre, G., 2005. Visual census of tropical fish aggregations on artificial reefs: slate versus video recording techniques. J. Exp. Mar. Bio. Eco. 315, 17–30.

Wewetzer, S.F.K., Duck, R.W., Anderson, J.M., 1999. Acoustic Doppler current profiler measurements in coastal estuarine environments: examples from the Tay Estuary, Scotland. Geo 29, 21–30.

Wilhelmsson, D., Malm, T., Öham, M.C., 2006. The influence of offshore windpower on demersal fish. ICES J. Mar. Sci. 63, 775–784.

Wood, S.N., 2006. Generalized Additive Models: an Introduction with R. Chapman and Hall/CRC, USA.

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