Strategic Environmental Assessment of Wave Energy Technologies

SEAWave

Functional responses of benthic, demersal and pelagic fauna to ocean energy technology

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Report on the functional responses of benthic, mobile demersal and pelagic fauna to ocean energy technology

Combining SEA Wave project deliverables 4.1. “Report on the functional response of sessile and sedentary organisms to ocean energy technology” and 4.2. “Report on the functional response of mobile demersal and pelagic fauna to ocean energy technology”.

Note: At project inception the consortium intended to provide two reports, separating sessile and mobile organisms; however, as the project and data analysis have progressed, it became clear that findings should be combined in order to: i) provide a more comprehensive assessment of the ecological responses of these organism groups as a whole to ocean energy technology; ii) aid comparison between functional groups that are intrinsically interconnected; and iii) provide a fully integrated discussion of the challenges and opportunities for ecological sampling around ocean energy technologies, using different sampling methods.

1 Contents

2 INTRODUCTION

Marine renewable energy (MRE) is a means to reduce carbon emissions associated with energy production and combat climate change [1]. MRE has considerable potential for enhancing the diversity of energy sources, as well as for stimulating and diversifying the economy, and is expected to expand rapidly over the coming decades [1], [2]. MRE devices vary in their level of technological development; wave energy, derived through capturing kinetic energy of ocean waves through wave energy converters (WECs) is seen as a particularly underdeveloped area [3]. While the technological development of WECs is progressing fast, other non-technological barriers may hinder the development of the wave energy sector [4]. High among these are the risk and uncertainties regarding the ecological impacts of WEC arrays [4], [5]. Understanding the ecological impacts of WEC arrays, both negative and positive, is critical in order to de-risk the consenting process and enable faster, more sustainable uptake of wave energy globally [4].

2.1.1 Ecosystem interactions of marine renewable energy systems

Marine organisms can be attracted to marine artificial structures for multiple reasons, including protection from predators, energetic refuge from high tidal flows and turbulence, and to exploit food sources associated with hard structure, such as algal mats or epifauna [6], [7]. The aggregating effect of marine organisms around surface or subsurface structures has been described as the 'fish aggregation device' (FAD) effect [6], and where occurring on the sea-floor, as the 'artificial reef' effect [7]. Both these attraction and aggregating effects on marine fauna can also be created by the introduction of structures for marine renewable energy generation [8]. WEC designs are diverse, but many under development are either on the surface or just below, with connections to seabed anchor systems [3]. These devices and their associated floats, chains and seabed mooring structures have the potential to create artificial reef and FAD effects [8]. The cumulative effect may be significant in altering the local faunal assemblages, but there is a paucity of data regarding such effects [5], [8]. Understanding these effects is vital for predicting the ecological consequences of upscaling wave energy infrastructure.

2.1.2 Quantifying ecosystem interactions of MRE devices

Diverse survey methods have been employed to understand the impacts of artificial structures on marine communities. For sessile and sedentary fauna, towed underwater video systems (TUVS) or remotely-operated underwater vessels (ROVs) are mobile sampling technologies which offer a low impact method of sampling large areas, and have been used in a variety of settings, including quantifying the impact of different fisheries management measures on marine faunal assemblages, and characterising data-poor marine ecosystems [9]. For mobile demersal organisms which tend to avoid mobile sampling systems, baited remote underwater video systems (BRUVS) offer a robust sampling method which has been adopted globally [10], [11]. Data derived from mobile systems and BRUVS both enable the temporal and spatial comparison of key metrics such as species richness and abundance [12]. In addition, analyses of changes in the diversity of organisms belonging to different functional groups – functional analyses – are potentially critical to understanding changes in community composition over time, which can provide a more tangible representation of changes in community structure versus simple abundance or diversity metrics alone [13].

2.1.3 Objectives

During SEA Wave Tasks 3.1 and 3.2, data was collected around wave energy converters deployed at European Marine Energy Centre test sites in Orkney, UK, to enable an assessment of how these WECs and associated infrastructure may influence the abundance and diversity of sessile, sedentary, mobile demersal and pelagic marine fauna. This report explores the responses of sedentary and sessile species (SEAWave Task 4.1, using data collected during SEAWave Task 3.1), and demersal and pelagic fauna (Task 4.2, using data collected during SEAWave Task 3.2) to wave energy devices and associated infrastructure. Temporal and spatial trends in abundance and diversity metrics were quantified and compared in areas featuring WECs, with unimpacted reference areas in the same region, to determine whether there was evidence for an impact of WEC devices on marine faunal assemblages.

The report includes analyses of data collected in two regions, each including an EMEC test sites: western Orkney, including the EMEC Billia Croo test facility; and eastern Scapa Flow including the EMEC nursery site. In West Orkney, sampling design and analysis focused on assessing the impact of Wello’s Penguin device on marine faunal assemblages, using data collected over four years, initially though the CEFOW project, and latterly through SEAWave. At Scapa Flow, sampling and analysis was designed to assess the short-term impacts of Mocean’s Blue X device on assemblages, using data collected two months following the device’s deployment for testing in 2021.

3 METHODS

3.1 West Orkney: Study area, survey design and methodology

Surveys for Tasks 3.1 and 3.2 were conducted each summer from 2017-2021, encompassing the EMEC Billia Croo wave energy test site, as well as reference areas to the north and south (Figure 1). The survey design was based around the original intention for three Wello Penguin WECs to be deployed during the CEFOW and SEAWave project timeframe at the EMEC Billia Croo test site. Around each planned WEC, a circular zone of seabed with a 500m radius was divided into four quadrants (North, East, South and West), with sampling of sessile/sedentary and mobile demersal fauna occurring in the west, north and east quadrants. This design was replicated at three equivalent spatial zones within each of the north and south reference areas (Figure 1).

Although plans for the installation of two additional Wello WECs at Billia Croo did not materialise, and the original WEC at this site, Penguin 1, sank to the sea bed in March 2019, the original survey design remained consistent throughout the study years. This was in order to capture potential impacts of the sunken WEC on marine communities through artificial reef effects, which would be valuable data, if not necessarily representative of a functioning WEC.

3.1.1 West Orkney: sampling sessile and sedentary species (Task 3.1)

To sample sedentary and sessile species for Task 3.1, a towed underwater video system (TUV) was used [14]. Three TUV transects of 50m in length were conducted in each of the west, north and south quadrants in each sampling year. Start, end point and direction of each transect were determined by prevailing tide and wind conditions. Vessel position and transect length was monitored using a high resolution GPS system (Hypac); in the event that conditions took the survey vessel out of a quadrant during a transect, or towards an underwater hazard such as such WEC cables or other infrastructure, the transect was ceased, distance recorded, and restarted elsewhere within the quadrant.

3.1.2 West Orkney: sampling mobile demersal species (Task 3.2)

To sample mobile demersal species for Task 3.2, baited remote underwater video systems (BRUV) surveys were used. Each BRUV consisted of an aluminium frame, wide-angle lens housing and white light LED lighting system. An aluminium pole was attached to each BRUV to support bait (~100g of mackerel, fixed 1 m from lens); lead weights (30 kg) were fastened to the frame for deployment and stability. Panasonic HDC-SD60 and HDC-SD80 camcorders were used to gather video data [11].

Within each zone, three BRUV replicates of at least 45 minutes were conducted in each quadrant in a triangular formation, ~150m apart (Figure 1). At the end of each survey day, footage was reviewed to ensure deployments were successful, and unsuccessful deployments were repeated.

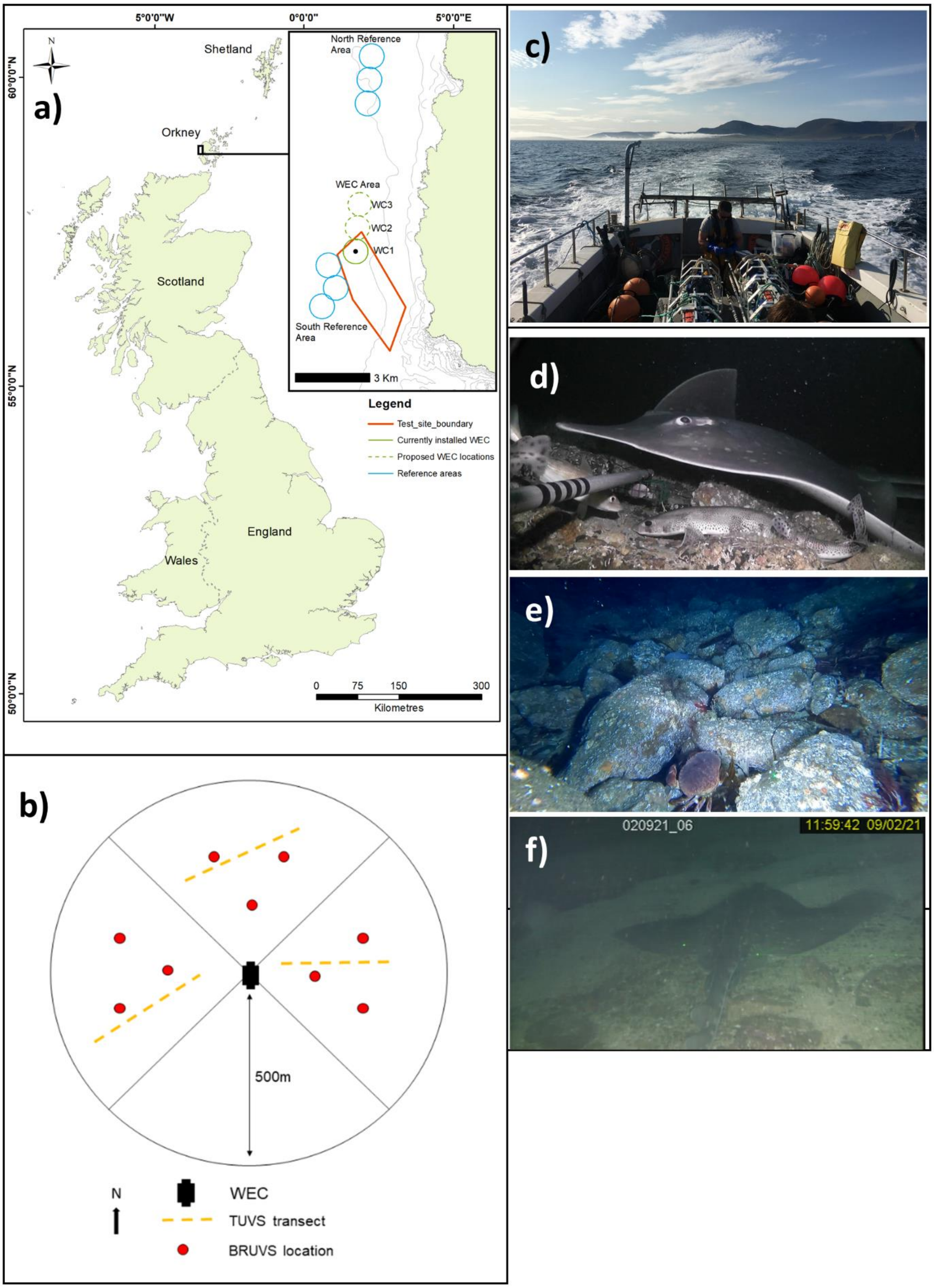

Figure 1: Survey design and data collection at Billia Croo and reference areas off the west coast of mainland Orkney; a) map of study area and experimental design; b) schematic showing sampling locations within experimental zones; c) preparing for BRUVs surveys on *MV Challenger;* d) image from BRUVS video from South Reference area of flapper skate *Dipturus batis,* Atlantic cod *Gadhus morhua* and spotted catshark; e) towed video image of brown crab *Cancer pagarus* amongst boulders in the North Reference Area; f) towed video image of male flapper skate *Dipturus batis.*

3.2 Scapa Flow: Study areas, survey design and methodology

In addition to long-term monitoring at Billia Croo, surveys for tasks 3.1 and 3.2 were also conducted at the EMEC Scapa Flow test site in August 2021. The Mocean Blue X, a half-scale floating WEC (length: 19.3m, max width: 4.2m), was deployed at this site for summer testing in June 2021 (Figure 2). The device was moored via subsurface buoys to two 50 tonne concrete clump weights positioned directly to the north and south, respectively (Figure 2). A section of ground chain connected the subsurface buoys to the clump weights. Surveys at this site focused on quantifying short term local impacts of this device and its mooring system on faunal diversity and abundance.

3.2.1 Scapa Flow: sampling sessile and sedentary species (Task 3.1)

A remotely-operated underwater vessel (ROV) (VideoRay Pro 5) was used to sample sessile and sedentary marine species in Scapa Flow, enabling the seabed directly proximate to the Mocean WEC and associated infrastructure to be sampled, which would not have been possible using TUV. Eight survey transects of 100m were conducted; two 'clump' transects, along the length of each ground chain to the north and south clump weights, respectively; two 'under' transects beginning directly beneath each subsurface buoy and heading under the footprint of device; two 'away' transects beginning directly beneath each subsurface buoy and heading away (west) from the device; and two 'control' transects beginning at reference sites 300m to the northeast and southwest respectively (Figure 2). All transects were completed on one day in August 2021.

3.2.2 Scapa Flow: sampling mobile demersal species (Task 3.2)

To sample mobile demersal species in Scapa Flow, BRUVs were deployed for 45 minutes at six near-device locations (~50m from device clump weights) and six far control locations (~300m from clump weights) (Figure 2). Each deployment were replicated on three different days.

3.2.3 Scapa Flow: sampling pelagic species (Task 3.2)

In Scapa Flow, the ability to deploy equipment in close proximity to the WEC, enabled a further assessment of potential FAD effects at the Mocean Blue X by using unbaited midwater cameras. On each of three survey days in August, Pelagicams [15] were deployed at four near locations and two far reference locations, for a minimum deployment of 45 minutes at a depth of 7m. For the 'near' locations, the aim was to obtain footage of the water column as close as possible to the device, and ideally with the device or associated infrastructure in view (Figure 2b). 'Far' Pelagicam reference locations were at equivalent locations to far BRUV locations, i.e. ~200m from the device clump weights.

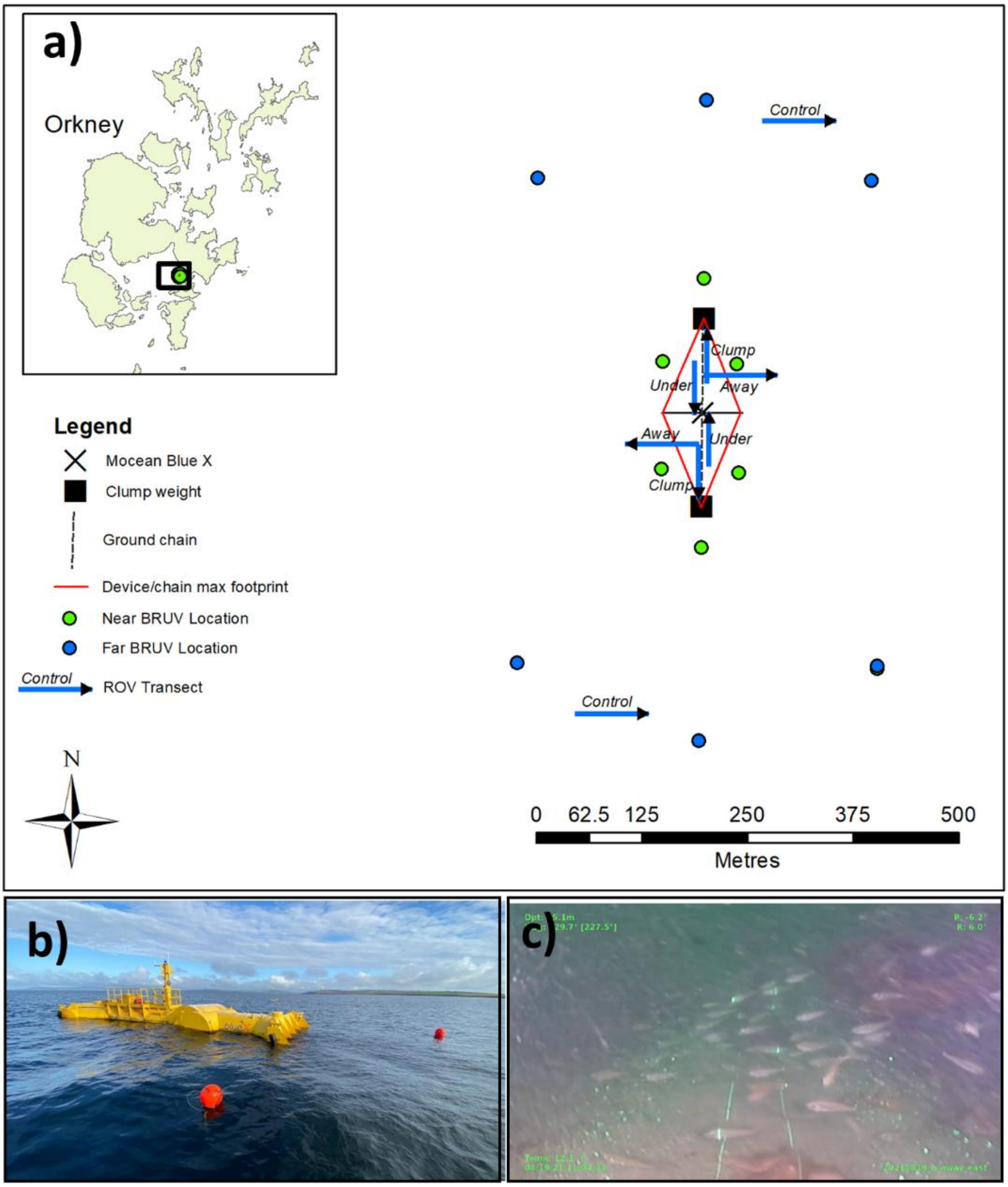

Figure 2: Survey design and data collection around the Mocean Blue X Wave energy converter in Scapa Flow, Orkney; a) map of study area and survey design including position of Mocean Blue X and mooring system, and locations of baited remote underwater video deployments and remotely-operated underwater vessel transects; b) two Pelagicams deployed near to the Mocean Blue X; and c) frame from ROV transect showing poor cod *Trisopterus minutus* adjacent to mooring ground chain (visible in upper right corner) of Mocean Blue X.

3.3 Data processing

3.3.1 Video analysis: TUV and ROV data

An overall Site x Species matrix ([S]) was created by combining abundance information from two separate video analysis methods. Firstly, all inconspicuous or infrequent fauna were counted from watching the entire transect video at normal speed, enumerating all individuals that passed through the 'gate' between the two laser scaling points (Figures 1, 2). Secondly, frame grabs were extracted from the video (Cybertronix frame extractor) and a digital 0.25 m^2 quadrate overlaid. Frames were selected and analysed if they met certain criteria of habitat (occurrence of hard substrate), focus of camera (substrate and any taxa within focus) laser placement (lasers are within boundaries of the digital quadrate that make the area of the digital quadrate 0.25 m^2) and visibility (the substrate and any taxa are discernible and identifiable). Thirty frames per transect was shown to give equivalent results to assessing the entire transect, while saving significant amounts of time [16]. All species were identified to the highest possible taxonomic resolution.

3.3.2 Video analysis: baited camera and Pelagicam data

All mobile fauna were identified to the highest taxonomic resolution possible, and counted. Relative abundance of each taxon was recorded as the greatest MaxN value during the 30 minutes analysed. MaxN is considered a conservative estimate of relative abundance of mobile species attracted to the bait, which decreases the chance of an individual being repeatedly recorded [10]. Pelagicam footage was watched at normal speed and all species and their abundances recorded following the same methodology as BRUVs.

3.3.3 Univariate Metric Calculation

To assess the differences, a selection of univariate metrics were calculated. A combination of taxonomic and functional based metrics were selected. Species Richness was the number of different species present per site, Total Abundance was the total abundance of all species present, Simpsons Index is a diversity metric that considers species richness and total abundance, and functional richness calculates the proportion of the total possible functional space filled by the current community.

3.4 Statistical analyses and modelling: West Orkney

Statistical analyses and modelling for Tasks 4.1 and 4.2 were conducted on data collected at West Orkney between 2017 and 2020. Due to the low number of surveys completed in 2019 due to poor weather conditions, this year was excluded from analyses.

3.4.1 Univariate analysis

To assess the hypothesis that there were differing responses over time between Billia Croo (WEC) and reference areas to the north (RN) and south (RS), Generalised Linear Mixed Effects Models (GLMMs) were used. Models were fit using the r packages 'glmmADMB' and 'lme4' [17], [18]. Response metrics were assessed as a function of Year (continuous: 0-4) and Area (categorical: WEC, RS and RN) with Zone (categorical: 1:3) as a random factor.

Within the Billia Croo wave energy test site, two of three zones that were originally intended to feature wave energy devices were empty throughout the study period. These zones could thus act as unimpacted control sites and enable a more fine-scale assessment, by comparing ecological responses of the area immediately surrounding Wello's Penguin device (WC1), with the two unimpacted zones to the north (WC2 and WC3) (Figure 1). General Linear Models

(GLMs) were used to assess the change in response variables as a function of Year (continuous: 0-4) and WEC zone (WC1, WC2 and WC3).

Univariate modelling for tasks 4.1 and 4.2 was conducted separately on data collected using TUVs (4.1) and BRUVs (4.2). For both tasks, the response variables tested were: species richness, Simpson's biodiversity index, functional richness and total abundance. A poisson distribution was used for the count variables (species richness and total abundance from BRUVs), a gamma distribution for the non-negative continuous variable (total abundance from TUVs) and a beta distribution was used for all proportional data between 0 and 1 (Simpson's Index and functional richness). A marginal transformation was applied to all proportional data to fit the assumptions of the Beta distribution following Smithson and Verkeulen (2006) to account for the presence of zeros and ones in the data. Model selection was carried out by step-wise deletion of terms and pairwise comparison of models by AICc. The most parsimonious models were applied and the highest order interactions evaluated. Sample vs fitted residuals, quartile-quartile and autocorrelation of temporally sequential samples were assessed visually, to fit assumptions of the models used. Stated values are GLMM model estimate means per video ± 95% confidence.

3.4.2 Multivariate analyses

Permutational multivariate analysis of variance (PERMANOVA) [7,8] was used to test differences between years and areas for all taxa recorded with TUVs and BRUVs. Year and area were fixed factors (Year, 3 levels: 2017, 2018 and 2020; Area, 3 levels: WC, RS and RN). Analyses were carried out on the basis of a Bray–Curtis dissimilarity matrix calculated from fourth root transformed abundance data. The statistical significance of the variance components was tested using 9999 permutations under a reduced model [21]. PERMANOVA was selected as it is robust to unbalanced designs [16]. Visualisation of multivariate data was carried out by a non-metric multidimensional scaling (MDS) ordination.

3.5 Statistical analyses and modelling: Scapa Flow

Statistical analyses and modelling for Tasks 4.1 and 4.2 were conducted on data collected in Scapa Flow in August 2021. Analyses focused on BRUV data, comparing abundance and species richness between locations near and far to the device (Figure 2). Additionally, abundance of Atlantic cod *Gadhus morhua* was also compared between near and far sites, to gain an understanding of the short term impacts of the device on aggregation of commercially important species. Only eight ROV transects were carried out at the site due to challenging conditions and safety considerations; data from these transects were not assessed formally but diversity metrics (species richness and total abundance) were calculated and compared between transects conducted at near and far locations relative to the device. Although Pelagicam videos at the Mocean device at control sites were collected and processed, there were no pelagic species recorded on these videos and thus no statistical analyses were conducted.

To assess the hypothesis that there were differing responses between near and far locations, Generalised Linear Mixed Effects Models were used. Models were fit using the r package 'lme4' [18]. Response metrics were assessed as a function of Treatment (categorical: near and far) with Direction (categorical: North, North-East, North-West, South, South-East and South-West) as a random factor. Replication was achieved through temporal repetition of survey design over 3 days. The response variables tested were: Relative Abundance of Atlantic cod *Gadus morhua*, Number of Taxa and Total Abundance from BRUVs. A poisson distribution was used for all response variables. Sample vs fitted residuals, quartile-

quartile and autocorrelation of temporally sequential samples were assessed visually, to fit assumptions of the models used.

4 RESULTS

4.1 Surveys and data: West Orkney

Towed camera and BRUV surveys were conducted at Billlia Croo and reference areas during four study years (Table 1). In 2019, poor weather conditions reduced the number of surveys that could be completed, particularly at the reference areas.

Table 1: Summary of sedentary and sessile (towed) and mobile demersal (BRUVs) camera deployments at Billlia Croo (WEC area), north reference area (RN) and south reference area (RS) by year.

Survey Site	Year	Number of BRUVs surveys	Number of towed surveys	Survey period
Billia Croo	2017	27	29	25 Aug -02 Sep
	2018	27	27	27 Aug – 04 Sep
	2019	17	19	21 Aug-02 Sep
	2020	30	27	20 Aug -31 Aug
North Reference	2017	26	27	25 Aug -02 Sep
	2018	24	26	27 Aug – 04 Sep
	2019	0	19	21 Aug-02 Sep
	2020	27	27	20 Aug -31 Aug
South Reference	2017	27	27	25 Aug -02 Sep
	2018	27	27	27 Aug – 04 Sep
	2019	5	22	21 Aug-02 Sep
	2020	27	27	20 Aug -31 Aug

4.2 Sedentary and sessile species across survey areas (Task 4.1)

The best-fitting GLMMs of diversity metrics for sedentary and sessile organisms indicated some significant differences between survey areas, with the north reference area having significantly higher species richness relative to the WEC area and south reference area and significantly higher total abundance and functional richness relative to the WEC area (Table 2 and Figure 3). A significant difference in total abundance was present across survey years, and there were also significant interactions between survey year and area, although the direction of this interaction differed between metrics; the increase in species richness and total abundance and the decrease in Simpson's index were significantly greater in the WEC area relative to the north reference area.

Table 2: Best-fitting Generalised Linear Mixed Effect model outputs for Univariate response metrics relating to sedentary and sessile organisms (Richness, Total Abundance, Simpson's Index and Functional Richness) derived from towed video, as functions of Year and Area with Zone as a random factor. Year, Reference North, Reference South and Wave Energy Converter are abbreviated to Yr, RN, RS and WC.

Metric	Terms	Estimate	Std. Error	Statistic	p value
Richness					
	(Intercept)	2.4000	0.2450	9.800	**<0.0001*** **
	Yr	0.0193	0.0261	0.738	0.46
	RN vs RS	-0.8100	0.3530	-2.290	**0.022***
	RN vs WC	-3.2800	0.4350	-7.540	**<0.0001*** **
	RN vs RS x Yr	0.0151	0.0438	0.344	0.73
	RN vs WC x Yr	0.3050	0.0917	3.320	**<0.0001*** **
Total Abundance					
	(Intercept)	6.1700	0.7720	8.000	**<0.0001*** **
	Yr	-0.4840	0.2420	-2.000	**0.045***
	RN vs RS	-1.2900	1.0500	-1.230	0.22
	RN vs WC	-7.4800	1.0800	-6.930	**<0.0001*** **
	RN vs RS x Yr	-0.0888	0.3180	-0.279	0.78
	RN vs WC x Yr	0.7720	0.3300	2.340	**0.019***
Simpson					
	(Intercept)	0.1900	0.3160	0.602	0.55
	Yr	-0.0326	0.1190	-0.274	0.78
	RN vs RS	-0.4990	0.4440	-1.130	0.26
	RN vs WC	0.3140	0.4380	0.716	0.47
	RN vs RS x Yr	0.0882	0.1680	0.526	0.6
	RN vs WC x Yr	-0.3570	0.1640	-2.180	**0.029***
Functional Richness					
	(Intercept)	-1.4500	0.1580	-9.170	**<0.0001*** **
	RN vs RS	-0.4160	0.2390	-1.740	0.082
	RN vs WC	-1.4100	0.4550	-3.100	**0.0019****

Bold values denote significant p values (<0.05) and asterisks define level of significance: p<0.0001 = '<0.0001***'; p< 0.001 = '***'; p < 0.01 = '**' ; p<0.05 = '*'

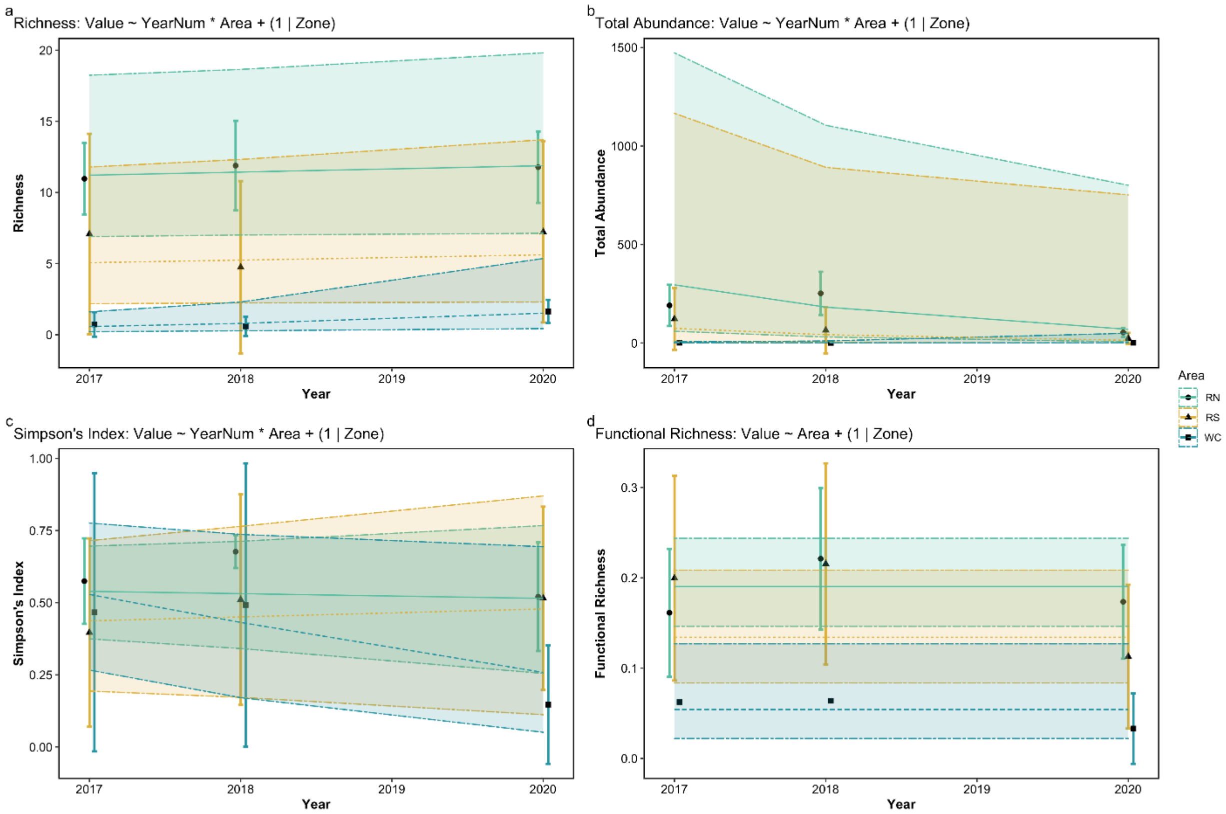

Figure 3: Temporal change in diversity metrics (Species Richness (a), Total Abundance (b), Simpson's Biodiversity Index (c) and Functional Richness (d)) derived from Towed Videos from Wave Energy Converter (WC: blue), Reference North (RN: green) and Reference South (RS: yellow) locations. Lines show model estimates with shading and dotted lines indicate 95% confidence intervals. Symbols with error bars show raw mean values and 95% confidence intervals.

Assemblage composition across areas significantly changed over time (Table 3). The WC site was more similar to the RS than the RN but RS became more similar to RN between 2018 and 2020 (Figure 4).

Table 3: PERMANOVA output for the Assemblage Composition as a function of Year and Area with Zone as a random factor. Year, Area and Zone are abbreviated to Yr, Ar and Z respectively.

Terms	df	SS	Statistic	p value
Ar	2	246,000	23.70	**0.0017****
Yr	2	26,900	7.70	**<0.0001*****
Z(Ar)	6	31,200	5.46	**<0.0001*****
ArxYr	4	22,500	3.22	**<0.0001*****
YrxZ(Ar)	12	21,000	1.83	**<0.0001*****
Res	217	207,000		

Bold values denote significant p values (<0.05) and asterisks define level of significance: p<0.0001 = '<0.0001***'; p< 0.001 = '***'; p < 0.01 = '**' ; p<0.05 = '*'

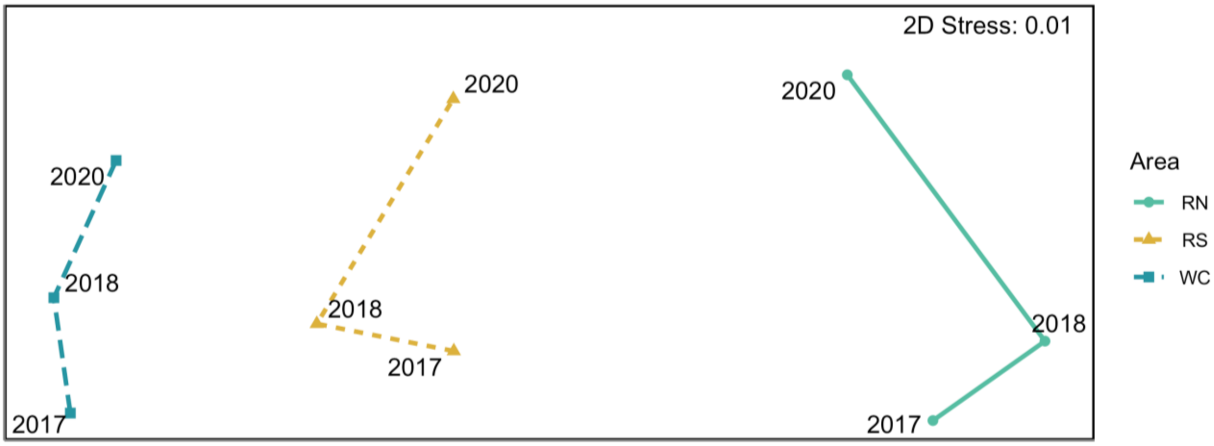

Figure 4: MDS ordination showing the differences of assemblage composition over three Years between the three Areas (Rn: green circles, RS: yellow triangles and WC: blue squares). Lines show yearly progression from 2017 to 2018 to 2020.

4.3 Sedentary and sessile species within Billia Croo area (Task 4.1)

The best-fitting GLMs of diversity metrics for sedentary and sessile organisms between WEC zones within the Billia Croo area included a significant increase in species richness and a decrease in Simpson's Index across the survey years (Table 4, Figure 5). However, none of the best-fitting models for diversity metrics include zone as a covariate, therefore providing little support for an effect of the sunken WEC on local sedentary and sessile biodiversity metrics observable on towed video.

Table 4: Best-fitting Generalised Linear model outputs for Univariate response metrics (Richness, Total Abundance, Simpson's Index) derived from towed underwater video system as functions of Year and Zone. Year is abbreviated to Yr.

Metric	Terms	Estimate	Std. Error	Statistic	p value
Richness					
	(Intercept)	-0.857	0.2720	-3.15	**0.0016****
	Yr	0.325	0.0878	3.70	**<0.0001*****
Total Abundance					
	(Intercept)	0.629	0.2170	2.90	**0.0048****
Simpson					
	(Intercept)	0.326	0.3160	1.03	0.3
	Yr	-0.251	0.1180	-2.12	**0.034***

Bold values denote significant p values (<0.05) and asterisks define level of significance: p<0.0001 = '<0.0001***'; p< 0.001 = '***'; p < 0.01 = '**' ; p<0.05 = '*'

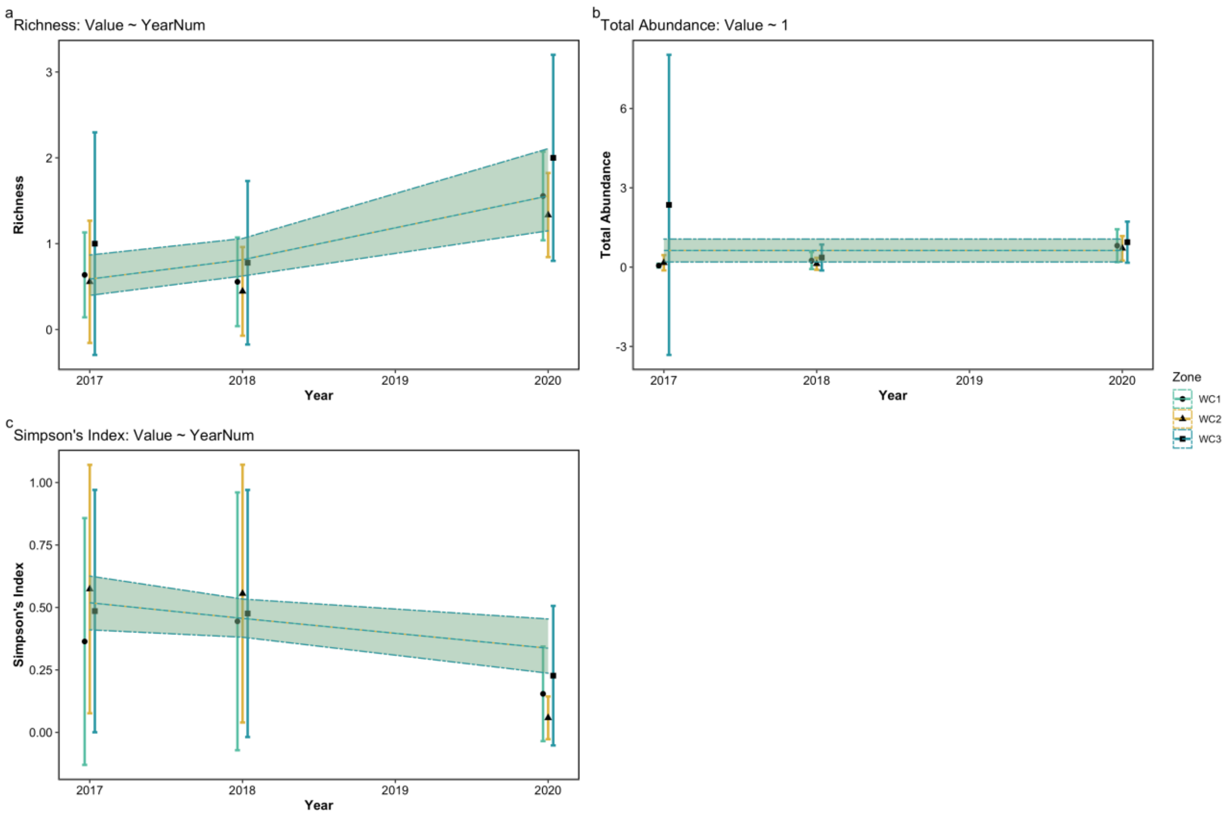

Figure 5: Temporal change in Diversity Metrics (Richness (a), Total Abundance (b), Simpsons Index (c) derived from TUVs data from Wave Energy Converter zones (WC1: green, WC2: yellow and WC3: blue). Lines show model estimates with shading and dotted lines indication 95% confidence intervals. Symbols with error bars show raw mean values and 95% confidence intervals.

4.4 Mobile demersal species across survey areas (Task 4.2)

The best-fitting GLMMs of diversity metrics for mobile demersal organisms indicated some significant differences between survey areas, with the north reference area having significantly higher species richness and functional richness relative to the WEC and south reference areas (Table 5 and Figure 6). A significant decrease in Simpson's index and functional richness was also present across survey years, as well as a significant interaction between survey year and area for total abundance.

Table 5: Best-fitting Generalised Linear Mixed Effect model outputs for Univariate response metrics (Richness, Total Abundance, Simpson's Index and Functional Richness) derived from Baited Remote Underwater Videos as functions of Year and Area with Zone as a random factor. Year, Reference North, Reference South and Wave Energy Converter areas are abbreviated to Yr, RN, RS and WC.

Metric	Terms	Estimate	Std. Error	Statistic	p value
Richness					
	(Intercept)	1.86000	0.0568	32.8000	**<0.0001*** **
	RN vs RS	-0.34000	0.0844	-4.0300	**<0.0001*** **
	RN vs WC	-0.30900	0.0845	-3.6500	**<0.0001*** **
Total Abundance					
	(Intercept)	2.87000	0.1350	21.3000	**<0.0001*** **
	Yr	0.00134	0.0292	0.0461	0.96

Metric	Terms	Estimate	Std. Error	Statistic	p value
	RN vs RS	-0.15100	0.1920	-0.7840	0.43
	RN vs WC	-0.12800	0.1900	-0.6750	0.5
	RN vs RS x Yr	-0.12700	0.0402	-3.1500	**0.0016****
	RN vs WC x Yr	-0.05160	0.0386	-1.3400	0.18
Simpson					
	(Intercept)	0.47400	0.1320	3.5800	**<0.0001*****
	Yr	-0.15700	0.0487	-3.2300	**0.0012****
Functional Richness					
	(Intercept)	-3.08000	0.1290	-23.9000	**<0.0001*****
	Yr	-0.09400	0.0434	-2.1700	**0.03***
	RN vs RS	-0.35700	0.1220	-2.9200	**0.0035****
	RN vs WC	-0.74900	0.1320	-5.6900	**<0.0001*****

Bold values denote significant p values (<0.05) and asterisks define level of significance: p<0.0001 = '<0.0001***'; p< 0.001 = '***'; p < 0.01 = '**' ; p<0.05 = '*'

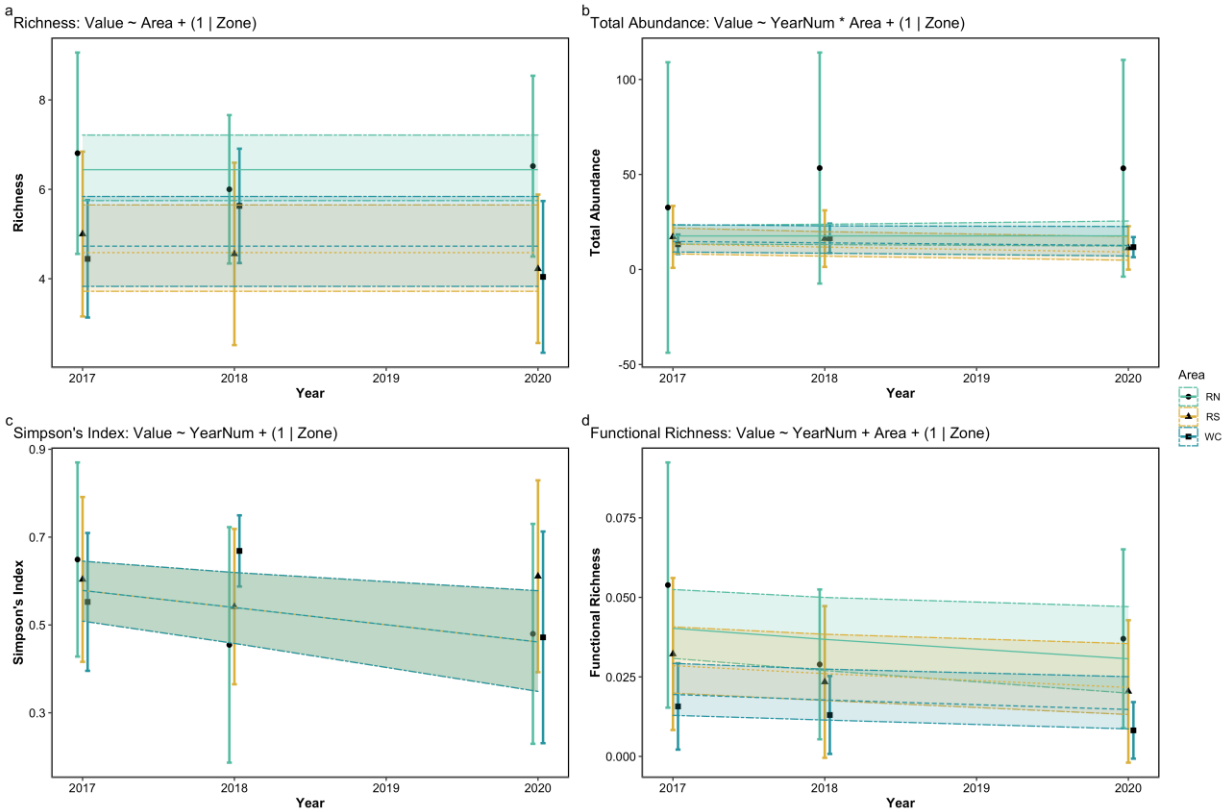

Figure 6: Temporal change in Diversity Metrics (Richness (a), Total Abundance (b), Simpsons Index (c) and Functional Richness (d)) derived from Baited Remote Underwater Videos from Wave Energy Converter (WC: blue) Reference North (RN: green) and Reference South (RS: yellow) areas. Lines show model estimates with shading and dotted lines indicating 95% confidence intervals. Symbols with error bars show raw mean values and 95% confidence intervals.

Assemblage composition across areas significantly changed over time (Table 6). However, this was most apparent in RN, where there were clear yearly changes to composition. WC assemblage composition showed very little yearly change and was most distinct from RN and RS (Figure 7).

Table 6: PERMANOVA output for the assemblage composition as a function of Year and Area with Zone as a random factor. Year, Area and Zone are abbreviated to Yr, Ar and Z respectively.

Terms	df	SS	Statistic	p value
Ar	2	159,000	23.000	**0.003****
Yr	2	13,600	8.470	**<0.0001*****
Z(Ar)	6	20,700	3.660	**<0.0001*****
ArxYr	4	18,300	5.680	**<0.0001*****
YrxZ(Ar)	12	9,660	0.854	0.79
Res	209	197,000		

Bold values denote significant p values (<0.05) and asterisks define level of significance: p<0.0001 = '<0.0001***'; p< 0.001 = '***'; p < 0.01 = '**' ; p<0.05 = '*'

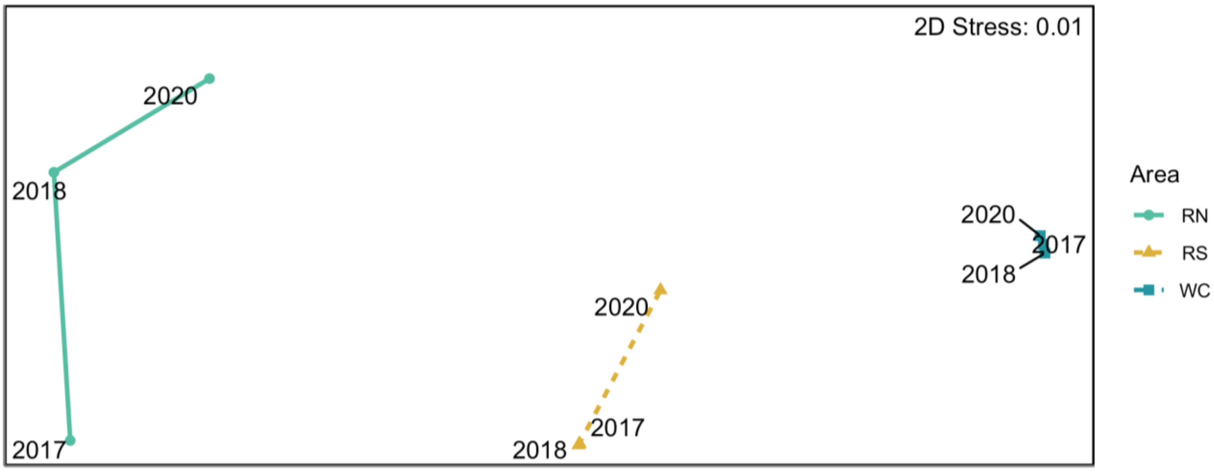

Figure 7: MDS ordination showing the differences of assemblage composition over three Years between Billia Croo wave energy test sites (WC), and north and south reference areas (RN, RS) (RN: green circles, RS: yellow triangles and WC: blue squares). Lines show yearly progression from 2017 to 2018 to 2020.

4.5 Mobile demersal species within Billia Croo area (Task 4.2)

The best-fitting GLMs of diversity metrics for mobile demersal organisms between WEC zones within the Billia Croo area suggested that WC1 had significantly higher total abundance relative to WC3, although this may have been driven primarily by high mean abundance values recorded in 2018, while mean abundance values for 2020 at WC1 were lower than the unimpacted zones (Table 7, Figure 8). No significant difference was present between zones was observed for species richness, Simpson's Index or Functional richness, while a significant interaction between year and zone was included in the best fitting model of Simpson's index; according to this model, changes over time (increase) in Simpson's Index at WC1 was significantly different to that observed at WC3 (decrease) (Table 7, Figure 8).

Table 7: Best-fitting Generalised Linear model outputs for Univariate response metrics (Richness, Total Abundance, Simpson's Index and Functional Richness) derived from BRUVS data as functions of Year and Zone. Year and Wave Energy Converter (1, 2 and 3) are abbreviated to Yr, WC1, WC2 and WC3.

Metric	Terms	Estimate	Std. Error	Statistic	p value
Richness					
	(Intercept)	1.550	0.0521	29.900	**<0.0001*****

Metric	Terms	Estimate	Std. Error	Statistic	p value
Total Abundance					
	(Intercept)	2.710	0.0526	51.600	**<0.0001*** **
	WC1 vs WC2	-0.028	0.0727	-0.385	0.7
	WC1 vs WC3	-0.226	0.0764	-2.950	**0.0032** **
Simpson					
	(Intercept)	0.257	0.3480	0.739	0.46
	Yr	0.130	0.1450	0.893	0.37
	WC1 vs WC2	0.379	0.4810	0.787	0.43
	WC1 vs WC3	0.735	0.4840	1.520	0.13
	WC1 vs WC2 x Yr	-0.356	0.1920	-1.860	0.063
	WC1 vs WC3 x Yr	-0.644	0.1950	-3.300	**<0.0001*** **
Functional Richness					
	(Intercept)	-4.050	0.1860	-21.800	**<0.0001*** **
	Yr	-0.143	0.0792	-1.810	0.071

Bold values denote significant p values (<0.05) and asterisks define level of significance: p<0.0001 = '<0.0001***'; p< 0.001 = '***'; p < 0.01 = '**' ; p<0.05 = '*'

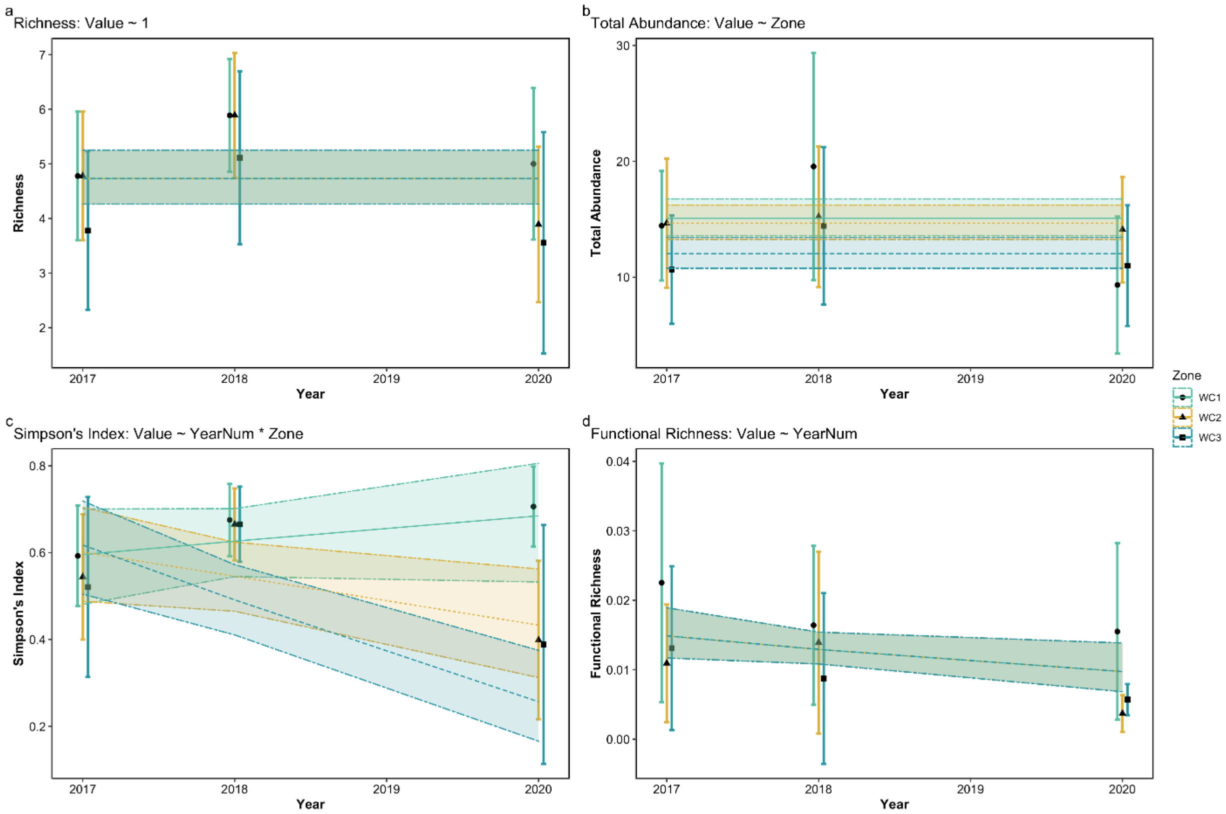

Figure 8: Temporal change in Diversity Metrics (Richness (a), Total Abundance (b), Simpsons Index (c) and Functional Richness (d)) derived from Baited Remote Underwater Video systems from Wave Energy Converter sites (WC1: green, WC2: yellow and WC3: blue). Lines show model estimates with shading and dotted lines indicating 95% confidence intervals. Symbols with error bars show raw mean values and 95% confidence intervals.

4.6 Surveys and data: Scapa Flow

As part of SEA Wave tasks 3.1 and 3.2, BRUVs, Pelagicam and ROV Surveys at the EMEC test site in Scapa Flow were conducted over three days in August 2021.

4.7 Scapa Flow: Mobile demersal species (Task 4.2)

GLMMs indicated a significantly higher abundance of Atlantic cod at sites near to the Mocean device relative to far control sites (Table 8, Figure 9). No significant difference in species richness or total abundance was observed between near and far sites. (Table 8, Figure 9).

Table 8: Generalised Linear Mixed Effect model outputs for response metrics (relative abundance of *Gadhus morhua*, species richness and total abundance) derived from BRUVs as a function of Treatment (close, far) with Direction as a random factor.

Metric	Terms	Estimate	Std. Error	Statistic	p value
Gadus morhua abundance					
	(Intercept)	2.080	0.0925	22.500	**<0.0001*** **
	Close vs Far	-0.382	0.1300	-2.930	**0.0034** **
Species richness					
	(Intercept)	1.660	0.1030	16.200	**<0.0001*** **
	Close vs Far	0.110	0.1410	0.775	0.44
Total abundance					
	(Intercept)	3.340	0.0455	73.500	**<0.0001*** **
	Close vs Far	-0.038	0.0632	-0.600	0.55

Bold values denote significant p values (<0.05) and asterisks define level of significance: p<0.0001 = '<0.0001***'; p< 0.001 = '***'; p < 0.01 = '**' ; p<0.05 = '*'

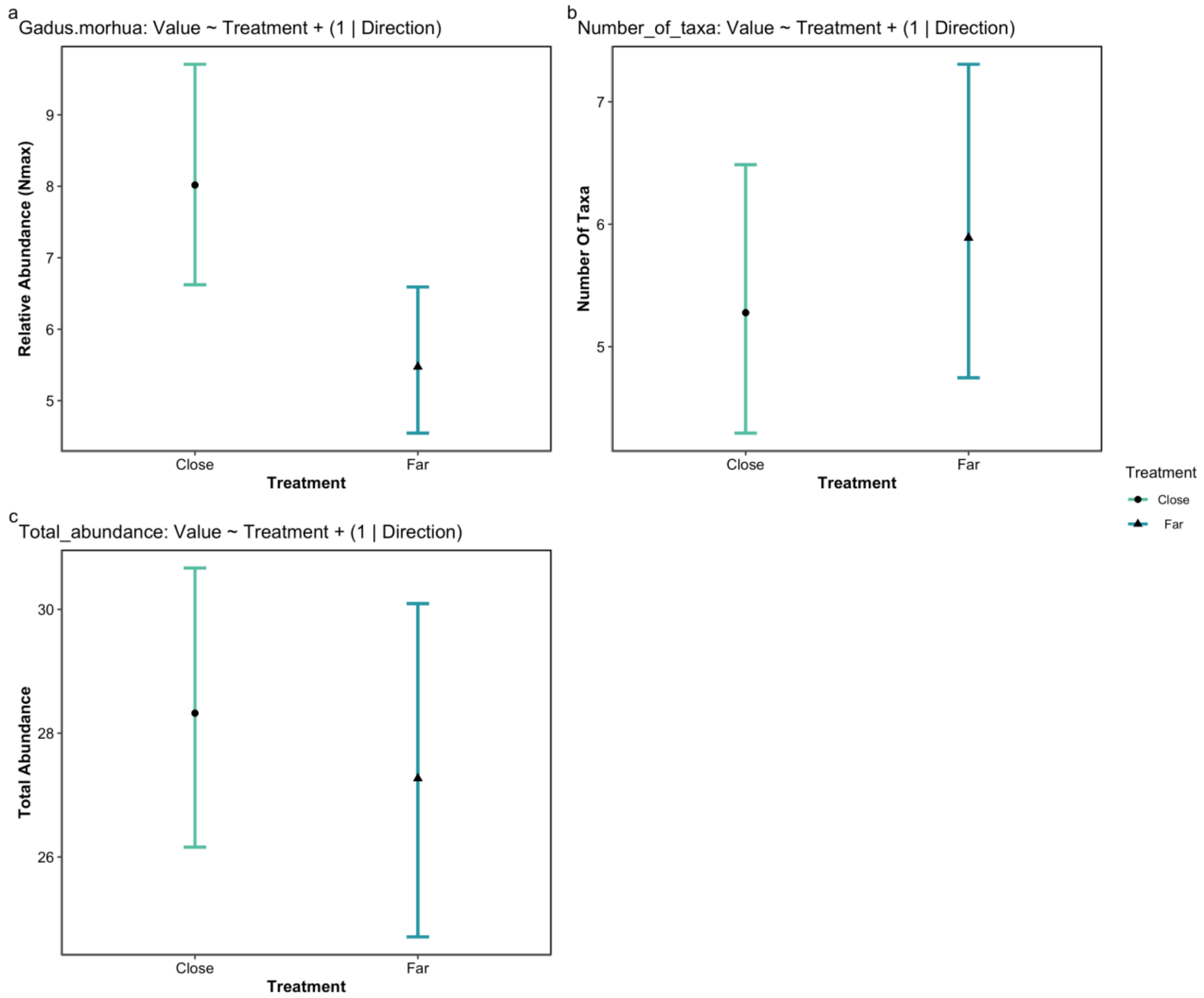

Figure 9: Spatial change in relative abundance of Atlantic cod *Gadhus morhua* (a), species richness (b) and total abundance (c) between locations close and far to the Moean Blue X deployed in Scapa Flow, derived from BRUV data. Symbols with error bars show raw mean values and 95% confidence intervals.

4.8 Scapa flow ROV surveys (Task 4.1)

Species richness and total abundance was generally lower for ROV transects conducted along the ground chain of the Mocean Blue X device ('Clump', Figure 10) relative to transects completed under the device ('under) and at near ('away') and far ('control') sites. However, some species, including poor cod *Trisopterus minutus* (Figure 2c) and brown crab *Cancer pagarus* were notably only present within transects conducted along the ground chain, with observed behaviour of these species indicating their use of the ground chain as a refuge.

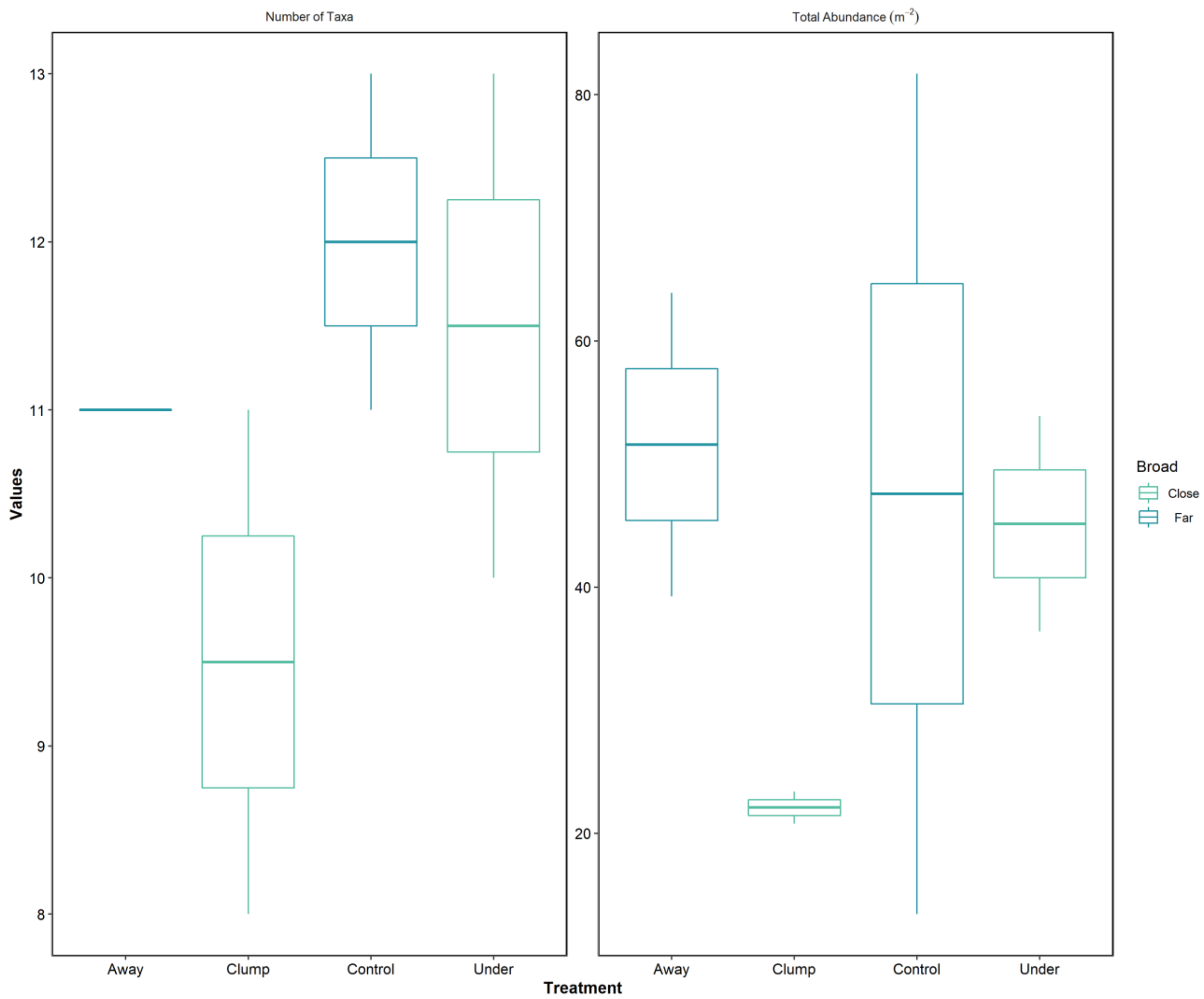

Figure 10: Boxplot showing spatial change in species richness (a), and total abundance (b) between locations close and far to the Mocean Blue X deployed in Scapa Flow, derived from ROV transects. Boxes show interquartile range, whiskers show 95% range and the centre line shows the median of the data per transect.

4.9 Pelagic fauna (Pelagicam) survey results

During 18 45-minute pelagicam deployments across three days of surveying, no pelagic fauna were observed on Pelagicams positioned close to the Mocean Blue X (*n* surveys = 12), nor at far controls (*n* = 6).

5 DISCUSSION

5.1.1 West Orkney

Wave energy devices and arrays have the potential to alter marine communities in their vicinity through FAD and reef effects, which can occur when structures are introduced to the marine environment [6], [7], [22], [23]. Marine renewable energy, including wave energy, is likely to see a substantial increase over the next two decades [24]. However, the nature of the effects of wave energy devices on communities of sedentary/sessile, mobile demersal and pelagic organisms are poorly understood.

In West Orkney, there were significant differences in diversity and abundance of both sessile and mobile demersal organisms between Billia Croo and reference areas, indicative of the markedly different habitats present in the Billia Croo WEC area (predominantly sandy substrate) versus the reference areas (reference north: predominantly rocky reef, and reference south: rocky reef/sand). Rocky reefs are known to contain a higher species diversity and abundance compared to sandy substrate [25], so these findings would be expected. An increase in species richness for sedentary and sessile fauna did occur at Billia Croo relative to reference areas; however, comparisons between zones within Billia Croo revealed that this increase was observed in each zone, rather than specifically around the sunken WEC, suggesting this increase may have resulted from natural variability rather than an effect of the sunken WEC. Similarly for mobile demersal fauna, the north reference area had significantly higher species richness and functional richness, relative to the WEC area and south reference area. Natural variation was also present for mobile demersal fauna, in the form of a significant decrease in Simpson's index and functional richness across survey years. Modelling provided little evidence for a device effect on diversity or abundance metrics between areas. Within the Billia Croo area, there was evidence that total abundance was higher within the zone with the sunken WEC versus unimpacted Zone 2, potentially consistent with an artificial reef effect occurring for mobile demersal species. However, this difference was not significant between the WEC and unimpacted Zone 3, and the difference may have been driven by one particularly abundant year (2018), with the later years showing a decreased abundance at the WEC zone versus unimpacted zones.

Overall, there was little support for an effect of the Wello's Penguin WEC on diversity or abundance of sedentary/sessile or mobile demersal organisms, relative to reference from broad-scale area comparisons, or fine-scale zone comparisons. The results nonetheless provide a valuable baseline for further assessment of WEC devices at the EMEC Billia Croo test site, particularly if multiple devices are deployed, as well as the decommissioning of Wello's Penguin. Sampling with adequate proximity to the device, particularly after it sunk, was challenging – as results from Scapa Flow indicate (see below), effects can potentially be localised (Section 5.1.3), and working with developers to sample effectively within close proximity to the device should be a priority for future studies.

5.1.2 Scapa flow

In Scapa Flow data from BRUVS surveys around the Mocean Blue X WEC suggested that mobile demersal fauna overall were not significantly different in abundance or diversity between near and far sampling sites. However, cod, *Gadhus morhua* were significantly greater in abundance at near sites versus far sites, potentially suggesting an aggregation effect of the Mocean Blue X for certain key species of commercial importance. Images from ROV surveys, did not strongly indicate a difference in abundance of sedentary and sessile organisms between transects conducted at different distances from the device, but ROV footage did show schools of small fish aggregating around the device ground chain, indicative of the chain being used as a refuge, which may explain the higher abundance of juvenile cod at sites near to the device. Juvenile cod are known to occupy a broad range of inshore habitats during their early life phases [26], but in habitat selection experiments have shown preferences for complex substrate types over simple sediments in the presence of predators [27]. The results suggest that the Mocean Blue X device may have provided refuge habitat, with impacts on fish abundance occurring over a relatively short timescale – in this case within 2 months of device deployment. The removal of the device away from its Scapa Flow location during the autumn of 2021 will prevent further investigation of its ecological impacts at this site, but the results are a promising avenue which should be explored further, potentially using other devices on test deployments at the EMEC Scapa Flow test site. The results from Scapa Flow highlight the importance of sampling with adequate proximity to devices to detect their effects; for comparison, in Scapa Flow, 'near' sites were within 50m of device infrastructure, while 'near' sites at Billia Croo were similar proximity as 'far' sites in Scapa flow due to operational constraints and conditions at the Billia Croo site.

Wave energy converters have the potential to aggregate pelagic animals through FAD effects [10,18], but no pelagic animals were observed at on midwater cameras deployed at the Mocean Blue X site. Video footage suggested that proximity to the device was adequate to observe FAD effects if present, because the device was visible on the majority of 'near' surveys. The lack of pelagic fauna may be due to the short device deployment prior to sampling, or low abundance of pelagic fauna in the area or at the selected sampling depth – further research, encompassing longer device deployment durations is required to understand FAD effects of wave energy converters.

5.1.3 Summary

The surveys of conducted as part of SEA Wave tasks 3.1 and 3.2 were designed to enable a comprehensive assessment of the impacts of wave energy devices on marine faunal composition around wave energy test sites in Orkney. Alterations to device deployment schedules by developers and damage to devices during the course of the project precluded planned assessments of operational WECs, or array-level effects. However, the results reveal important insights into single device effects, and the data collected provide an extremely valuable baseline for future surveys.

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