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# Key Biofouling Organisms in Tidal Habitats Targeted by the Offshore Renewable Energy Sector in the North Atlantic Include the Massive Barnacle *Chirona hameri*

**Andrew Want [1,2,*], Audrey Goubard [3], Solène Jonveaux [4,5], Donald Leaver [6] and Michael C. Bell [2]**

[1] Energy and Environment Institute, University of Hull, Hull HU6 7RX, UK
[2] International Centre for Island Technology, Heriot Watt University, Stromness KW16 3AN, UK
[3] European Institute for Marine Studies, University of Brest, 29238 Brest, France
[4] Department of Life Sciences, University of Nantes, 44035 Nantes, France; solene.jonveaux@hotmail.fr
[5] Department of Biology, University of Sherbrooke, Sherbrooke, QC J1K 2R1, Canada
[6] European Marine Energy Centre, Stromness KW16 3AW, UK; donald.leaver@emec.org.uk
* Correspondence: a.want@hull.ac.uk

**Abstract:** Marine habitats are being targeted for the extraction of offshore renewable energy (ORE) as part of the drive to decarbonise electricity generation. Unmanaged biofouling impacts ORE devices and infrastructure by elevating drag forces, increasing weight, and accelerating corrosion, leading to decreased performance and survivability, and extending costly periods of maintenance. ORE deployments in high tidal flow locations are providing opportunities to study the biofouling unique to these habitats. In this study, surveys of numerous devices and associated infrastructure deployed at the European Marine Energy Centre in Scotland identified high tidal flow fouling assemblages. Substrate orientation relative to tidal flow appears to affect the abundance of key fouling species, including the massive barnacle *Chirona hameri*. This species is shown to recruit to a wide range of artificial substrates, over a prolonged period from mid-spring to mid-summer, and in maximum current speeds from 0.4–4.0 m/s. For the first time, *C. hameri* is reported in near-surface depths, on uncoated components of a floating tidal device. The highly gregarious settlement behaviour and rapid growth exhibited by this species may have important implications for managing fouling in the ORE industry, especially in 'niche' areas. Anti-fouling strategies and maintenance scheduling applicable to ORE and other marine industries are discussed.

**Keywords:** marine renewable energy; marine growth; anti-fouling; barnacles; tidal currents; saddle oyster; sea anemone; soft coral

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## 1. Introduction

Deployments of offshore renewable energy (ORE) devices are expected to make a substantial contribution to meet global energy demands over the next several decades as part of objectives to decarbonise electricity generation [1,2]. In Scotland, a goal has been set to produce 50% of electricity from renewable technologies by 2030 [3], including ORE devices. It is estimated that the ORE capacity in Scottish waters totals 25% of the tidal, 10% of the wave, and 25% of the offshore wind resources in Europe [4,5].

### *1.1. Biofouling of Offshore Renewable Infrastructure*

A significant risk for industries working in the marine environment is biofouling—the settlement and growth of organisms on submerged structures [6]. Impacts of marine growth on shipping are well known and have been researched from hydrodynamic and economic perspectives [7,8], leading to the development of anti-fouling coatings [9]. Economic consequences of poorly managed biofouling result from a reduction in performance, costs incurred during removal or prevention of growth, and the need to replace corroded components. In the ORE sector, increased weight and drag from biofouling of tidal and wave devices may compromise functioning by affecting hydrodynamic performance of power delivery, and by increasing structural loading on the device or its moorings. As this sector develops, biofouling issues are being recognised that are specific to this industry, such as for moving parts unique to these technologies, i.e., rotating turbines [10,11], for the introduction of novel materials used in ways that have not been trialled before in marine environments [12], and for deployments taking place in habitats where structures have not been previously installed and studied (e.g., in strong tidal flow areas) [13]. There are also concerns about so-called 'niche' areas on devices and infrastructure where biofouling may flourish, and where removal or protection is more problematic [14,15]. Tidal habitats are challenging from an operational standpoint and typically feature highly abrasive and well-oxygenated conditions corrosive to anti-fouling coatings [10].

Owing to the early developmental stages of ORE devices and confidentiality concerns [16], limited published research exists on the interactions between tidal and wave devices and the biofouling communities. Published biofouling studies in this sector have included classification and quantification of fouling at tidal and wave test sites [13,17,18], on a wave device [19], and the assessment of fouling on buoys [17,20,21] and harbours used in the industry [17,21].

Differences in fouling communities are associated with a wide range of biological and physical factors including hydrodynamic conditions, substrate type, and depth [22–24]. Recent studies in Scotland have highlighted significant differences in fouling assemblages found between the relative shelter of harbours or marinas and extremely exposed ORE devices and infrastructure [17]. In aphotic, high-flow environments targeted for the deployment of tidal energy devices, earlier published studies have reported fouling assemblages dominated by the massive barnacle *Chirona hameri* [17] (Figure 1).


**Figure 1.** Major fouling organisms in high tidal flow environments in Scotland include saddle oysters (*Anomia ephippium*) (**upper left**), soft corals (*Alcyonium digitatum*) (**lower left**), barnacles (*Chirona hameri* (**centre**) and *Balanus balanus* (**upper right**)), and sea anemones (*Metridium dianthus*) (**lower right**). Scale bar 0–1 cm.

### 1.2. *Chirona hameri*

*Chirona hameri* (Ascanius 1767) is the largest barnacle found in the North Atlantic, with its maximum height and rostro-carinal length reported as 75 mm and 68 mm, respectively [25,26]. Owing to its large size, *C. hameri* has been used extensively in physiological studies, particularly concerning the arthropod nervous system and the properties of the cement used during larval settlement and its application to human dentistry [27–29]. The life history of this species, however, is not well understood. Earlier studies of the habitat requirements of *C. hameri* and its associated community have been limited to infrequent records obtained during dredging operations and sublittoral video surveys, and examination of retrieved deep-sea infrastructure [17,25,30–34].

Previous studies, in the Irish Sea, have reported that *C. hameri* carries fertilized eggs from January until March, with settlement of the cyprid larval stage occurring in April and May [35]. Settlement of larvae on the Georges Bank in the Northwest Atlantic appears to occur later and to be protracted from late April through to July [36]. Cyprids are highly gregarious, tending to settle in greater concentrations to substrates already inhabited by conspecifics, and settling over the parietal plates and even on the opercular valves of adults, in preference to adjacent bare surfaces [30,34,35]. There is no evidence of gonad development in first-year individuals in December, suggesting that reproductive activity does not begin until the second year of life [26].

*Chirona hameri* is a major component of structure-forming epifauna in high-flow conditions on deep-sea hard substrates in northern temperate to polar latitudes [26,31,32,36]. Distribution of this barnacle is limited to areas with strong tidal currents [17,26,31,32,34], reported as being at least 0.5 m/s [32], and in aphotic depths recorded down to 425 m [37] but most commonly in 40–100 m [25,30–33]. It has not been reported in near-surface depths. Its distribution extends from both sides of the North Atlantic east to the Barents and White Seas [31,38]. In the NE Atlantic, the southern edge of its range reaches the British Isles, where it has been recorded in the southern Irish Sea [26,35], the Celtic Sea [39], and in the North Sea down to the Wash [35] and off the northern coast of the Netherlands [40]; in the NW Atlantic, records occur from the mouth of the St. Lawrence south to Chesapeake Bay [26,41,42].

In early studies, samples were sourced by dredging reefs of the Horse mussel *Modiolus modiolus* encrusted with *C. hameri* in the Irish Sea [29,30,35,43]. This barnacle will settle and grow on various other substrata including shells of other mollusc species, such as the deep-water scallop *Placopecten magellanicus* on the Georges Bank [25] and the Red whelk *Neptunea antiqua* in the North Sea [34], coarse to massive rocky sediments [31,32,37], and artificial surfaces [17,33,34,44].

### 1.3. Associated Fauna

Fauna found in association with *C. hameri* vary with geographic location and include the serpulid worm *Filograna implexa* on glacial erratics deep in the Faroe-Shetland Channel [37] and on North Sea oil platforms [44]; the bryozoan *Eucratea loricata* and the rock-boring bivalve *Hiatella arctica* in the Russian Arctic [31]; and the saddle oyster *Heteranomia squamula* on the Georges Bank [36]. In addition to *C. hameri*, these sites typically share the presence of the sublittoral balanoids, *Balanus balanus* and *B. crenatus* [17,25,31,32], but generally exhibit low biodiversity [13,31,33], perhaps as a result of habitat instability owing to hydrodynamic stress [45,46].

### 1.4. Knowledge Gaps

Tidal turbine deployments are playing an important role in commercialisation of ORE technologies. Current deployments in Orkney waters and the Pentland Firth include individual 2 MW floating devices [47] and arrays of 1.5 MW submerged turbines [48]. With industrial-scale deployments of ORE devices underway, it is of paramount importance to better understand the impacts of biofouling and develop more effective management strategies fit for high tidal flow environments. Fouling from larger organisms, like *C. hameri*, may have profound consequences for the operation of structures in tidal habitats, and increased loadings resulting from heavy fouling may compromise the functioning of subsea mooring cables used on ORE devices and sensors [20,49,50]. The current studies are part of an ongoing strategy to provide timely evidence to the ORE sector regarding the characterisation of biofouling and for informing effective anti-fouling management strategies. These studies examined fouling assemblages on a variety of materials at test locations used by the European Marine Energy Centre (EMEC). The aims of this research were to identify key biofouling organisms in high tidal flow habitats (including invasive non-native species (INNS) which might use ORE structures as 'stepping-stones' to facilitate their spread), compare assemblages associated with other hydrodynamic conditions, explore the relationship between biofouling and substrate orientation relative to the direction of current, and gather life-stage data for the poorly understood foulant, *C. hameri*.

## 2. Materials and Methods

Studies of biofouling on ORE devices and infrastructure in high-flow tidal environments were conducted at three test sites operated by EMEC (Figure 2). The locations and general hydrodynamic conditions were the Fall of Warness (high tidal flow; moderate wave); Billia Croo (moderate tidal flow; high wave); and Scapa Flow (low tidal flow; moderate wave) (Table 1). In addition, limited opportunities for experimental data collection were available through deployment of settlement panels attached to subsea infrastructure.

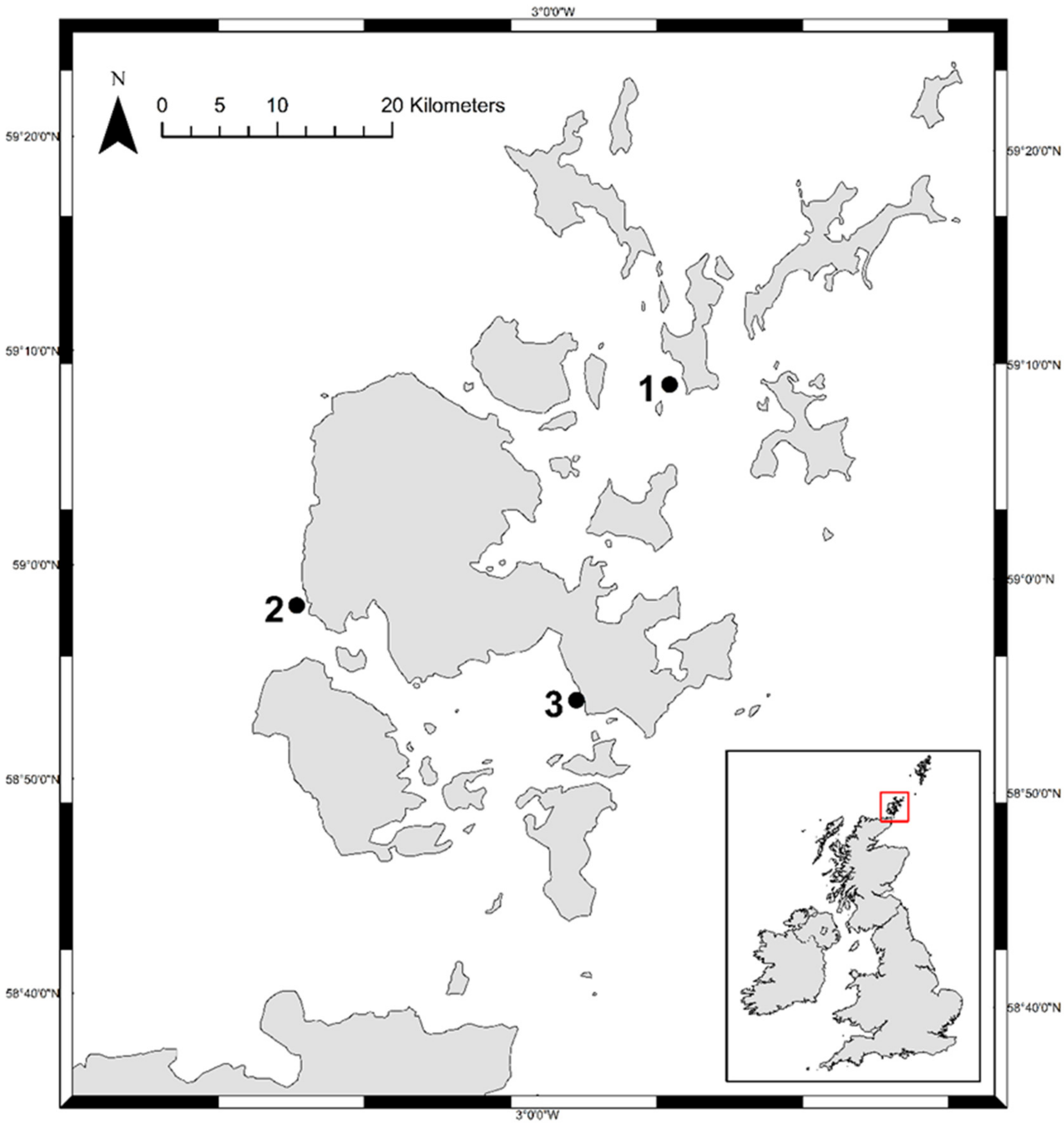


**Figure 2.** Map of sampling sites at the European Marine Energy Centre, Orkney. (1) Fall of Warness (59° 08.852′ N; 002° 48.101′ W) (2) Billia Croo (58° 58.795′ N; 003° 23.029′ W); and (3) Scapa Flow (58° 53.657′ N; 002° 57.128′ W). Inset: Orkney (red square) and the United Kingdom and Ireland.

### 2.1. Surveys

Detailed characterisations of fouling assemblages from full scale ORE test sites were acquired through opportunistic surveys of devices and infrastructure periodically retrieved for inspection, maintenance, and decommissioning from EMEC test sites, including a detailed study of a tether latch assembly recovered from Billia Croo and deployment of an integrated environmental monitoring pod (IEMP) at the Fall of Warness (Table 2). Fouling data from EMEC test sites was compared against previously published survey data [17] conducted on 'sheltered' sites, i.e., harbours and marinas, in Orkney Waters and the Pentland Firth.

All surveys were conducted based on rapid assessment methods [51]. Surveys aimed to record as comprehensive a list as possible of fouling species present at each site and to identify the most dominant foulants based on qualitative assessment of contribution to total fouling. Images of fouled devices and infrastructure were recorded using a digital SLR camera (Canon) and electronically labelled. When necessary, samples were collected for identification in the laboratory and preserved in 70% ethanol in seawater for long-term curation.

In a detailed case study, a tether latch assembly (TLA), comprised of high-density divinycell foam with a fiberglass shell [52], was recovered from the EMEC wave test site at Billia Croo in April 2018. The TLA formed part of the mooring system of a decommissioned wave device and had been deployed in 45 m of water, approximately 10 metres off the seabed, continuously over 6 years (Figure 3). At Billia Croo, an asynchronous tide, bearing approximately north–south, travels at 0.4 m/s and 0.2 m/s during the flood and ebb, respectively [53]. Throughout deployment, the TLA was static and orientated slightly obliquely to the direction of current flow. In addition to species identification and imaging, surveying the TLA provided a rare opportunity to collect detailed morphometric and abundance data for *C. hameri* and other associated fauna. Abundance of *Alcyonium digitatum*, *Anomia ephippium*, *Balanus balanus*, *C. hameri*, and *Metridium dianthus* (Figure 1) was based on density of individuals.

**Table 1.** Environmental and operational parameters provided by the European Marine Energy Centre test sites: $H_S$, mean significant wave height (metres); maximum current flow (metres/second); approximate water depth (metres); distance to closest shoreline; and distance to nearest port [53].

| Site | $H_S$ (m) | Current Flow (m/s) | Water Depth (m) | Distance to Shore (km) | Nearest Port (km) |
|---|---|---|---|---|---|
| Fall of Warness | 0.9 | 2.0–4.0 | 40 | 0.58 | 6.90 |
| Billia Croo | 3.0 | 0.2–0.4 | 45 | 1.27 | 7.54 |
| Scapa Flow | 0.5 | <0.2 | 25 | 0.71 | 10.05 |

**Table 2.** A survey inventory of ORE devices and infrastructure sampled in Orkney from 2015–2019 noting the most dominant fouling organism and presence of *Chirona hameri*. Site: FW = Fall of Warness; BC = Billia Croo; SF = Scapa Flow; Depth: refers to the submerged depth of the substrate rather than bathymetric depth; 'Surface' refers to floating structure with maximum depth of approximately 1 m; Structure: TEC = tidal energy converter; WRB = Waverider buoy; ADCP = acoustic Doppler current profiler; IEMP = integrated environmental monitoring pod; WEC = wave energy converter; Date: month/year; Substrate: HDPE = high-density polyethylene; Dominant foulant was based on qualitative assessment of contribution to total fouling; *C. ham* = *Chirona hameri*; * = tether latch assembly.

| Site | Depth | Structure | Date | Substrate | Dominant Foulant | *C. ham* |
|---|---|---|---|---|---|---|
| FW | 40 | TEC moorings | 01/15 | Concrete | *Chirona hameri* | + |
| FW | 40 | IEMP | 10/15 | HDPE | *Chirona hameri* | + |
| FW | 40 | IEMP | 09/17 | HDPE | *Chirona hameri* | + |

**Table 2.** *Cont.*

| Site | Depth | Structure | Date | Substrate | Dominant Foulant | *C. ham* |
|---|---|---|---|---|---|---|
| FW | 40 | ADCP frame | 12/17 | HDPE/steel | *Chirona hameri* | + |
| FW | 3 | TEC subunit | 10/18 | Steel | *Ciona intestinalis* | + |
| FW | 40 | TEC subunit | 05/19 | Steel | *Chirona hameri* | + |
| FW | 40 | TEC moorings | 09/19 | Steel | *Chirona hameri* | + |
| BC | Surface | WRB | 06/15 | Steel | *Alaria esculenta* | - |
| BC | Surface | WRB | 02/18 | Steel | *Ectopleura larynx* | - |
| BC | Surface | WRB | 02/18 | Steel | *Hincksia hincksia* | - |
| BC | 35 | WEC moorings * | 03/18 | Fiberglass | *Metridium dianthus* | + |
| BC | 45 | WEC cable end | 04/18 | Steel | *Chirona hameri* | + |
| BC | Surface | WRB | 10/18 | Steel | *Semibalanus balanoides* | - |
| BC | Surface | WRB | 09/19 | Steel | *Semibalanus balanoides* | - |
| BC | Surface | WRB | 09/19 | Steel | *Ectopleura larynx* | - |
| SF | Surface | WRB | 05/15 | Steel | *Amphisbetia operculata* | - |
| SF | Surface | WRB | 02/18 | Steel | *Petalonia fascia* | - |
| SF | 25 | WEC | 06/18 | Steel | *Balanus crenatus* | - |
| SF | 25 | WEC moorings | 08/18 | Mixed | *Balanus crenatus* | - |
| SF | 25 | ADCP frame | 09/18 | HDPE/steel | *Spirobranchus triqueter* | - |
| SF | Surface | WRB | 10/18 | Steel | *Chordaria flagelliformis* | - |
| SF | Surface | WRB | 09/19 | Steel | *Semibalanus balanoides* | - |

Volume of *C. hameri* individuals (n = 699) on the TLA was determined by measuring length along the rostro-carinal axis and maximum parietal plate height for *C. hameri* (n = 699) from all vertical surfaces of the structure, and using the following formula:

$$V = \pi r^2 h$$

where $r$ is radius (approximated as half the rostro-carinal length) and $h$ is height. Volume has been found to be a more accurate measure of barnacle size than rostro-carinal length alone, owing to density-based distortion of individual barnacles at certain locations [54]. Measurements could not be obtained from the top and bottom surfaces of the structure owing to removal of biofouling and accessibility issues during transport and storage. Volume values were normalised by cube root transformation to produce a linearly scaled representation of size [55]. Histograms of size classes were produced based on these transformed data.

### 2.2. Data Analysis

Fouling assemblage composition was statistically analysed using species occurrence data and Primer v6 software [56]. Resemblance of species presence–absence composition between survey samples was quantified using Bray–Curtis similarities [57]. Groupings of samples with similar species were identified using non-metric multi-dimensional scaling (MDS) ($\alpha$ = 0.1) and data plots were used to represent similarities in two dimensions. Analysis of similarity (ANOSIM) function was used to investigate how epibenthic fouling assemblages compared among deployment locations. Locations were grouped by habitat based on dominant hydrodynamic conditions (tidal; wave; sheltered) and deployed depth of surveyed substrates (shallow, i.e., surface to approximately 3 m; deep, >20 m). Similarity percentage analysis (SIMPER) was used to identify which species contributed most to differences among these groupings [58].


**Figure 3.** Biofouling of the tether latch assembly (TLA) mooring system of a wave-energy converting device. Scale bar 0–20 cm (image: EMEC).

## 3. Results

### *3.1. Chirona hameri Dominates Biofouling Assemblages in Tidal Habitats*

The main fouling species and the presence of *C. hameri* on ORE devices and infrastructure surveyed during these studies are summarised in Table 2. *C. hameri* was only found at full-scale test sites at the Fall of Warness and in deep water at Billia Croo, the latter featuring maximum current speeds of up to 0.4 m/s. At these sites, *C. hameri* successfully recruited onto steel, HDPE, fiberglass, and concrete surfaces. When present, *C. hameri* dominated fouling on most structures. Dominant fouling on other ORE structures, subject to lower current speeds, was mostly associated with hydroids, macroalgae, and other barnacle species. No invasive non-native species (INNS) were detected at either of the full-scale test sites.

Analysis of similarity confirmed that there was a statistically significant difference in assemblage composition among deployment habitat groupings (global $r = 0.75$; $p = 0.001$) (Table 3). Cluster analysis identified three discrete groups comprised of fouling assemblages on (a) only shallow, high-wave-exposed substrates; (b) tidal and deep-deployed high-wave substrates; and (c) harbour and marina substrates (Figure 4). The 2D stress of the MDS plot was 0.12, indicating a good level of support for the observed groups [58]. It should be noted that the fouling assemblage on one Waverider buoy clustered with the latter group.

This buoy was deployed at the relatively shallow and sheltered scale wave test site at Scapa Flow; closer examination of the survey revealed that the fouling assemblage on this buoy featured several species typically forming a major component of fouling on harbour and marina substrates.

**Table 3.** One-way analysis of similarities (ANOSIM) showing the R statistic (significance level) comparing biofouling assemblages surveyed from test sites operated by the European Marine Energy Centre and harbours and marinas in Orkney waters and the Pentland Firth. 'Tidal' and 'Wave' refer to dominant hydrodynamic conditions; 'Deep' and Shallow' refer to the submerged depth of the substrate rather than bathymetric depth, with 'Deep' defined as >20 m, and 'Shallow' as surface to approximately 3 m. Harbour and marina survey data previously reported in Want et al. [17]. Global R = 0.746; $p$ = 0.001. Significant dissimilarities ($p \leq 0.05$) are indicated in bold type.

| | Tidal Deep | Tidal Shallow | Wave Deep | Wave Shallow | Harbour |
|---|---|---|---|---|---|
| **Tidal Shallow** | 0.48 (0.133) | | | | |
| **Wave Deep** | 0.57 (**0.029**) | 0.21 (0.300) | | | |
| **Wave Shallow** | 0.85 (**0.008**) | 0.69 (**0.048**) | 0.33 (0.125) | | |
| **Harbour** | 1.00 (**0.006**) | 0.95 (**0.022**) | 1.00 (**0.006**) | 0.81 (**0.002**) | |
| **Marina** | 1.00 (0.067) | 0.75 (0.333) | 1.00 (0.100) | 0.47 (0.143) | 0.22 (0.133) |

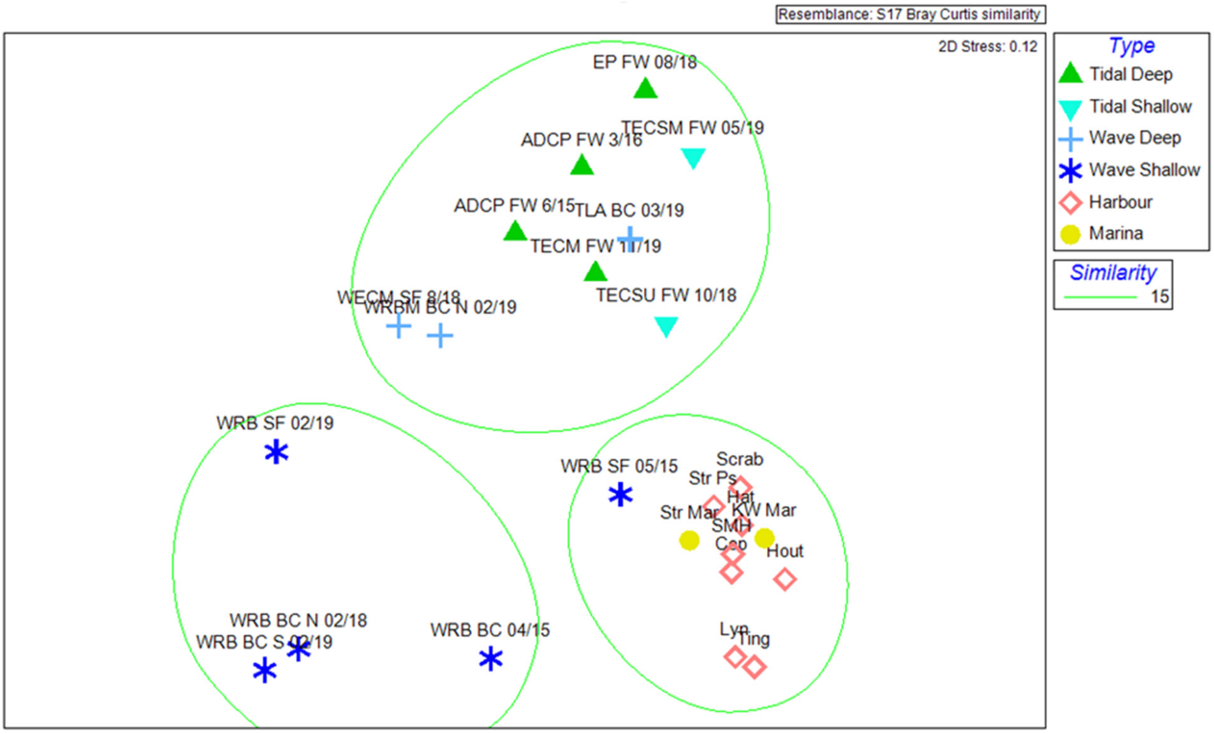


**Figure 4.** Multidimensional scaling plot using biofouling assemblage data associated with various deployment habitats. Ellipses represent groups identified by average-linkage cluster analysis based on Bray–Curtis similarities. 'Tidal' and 'Wave' refer to dominant hydrodynamic conditions; 'deep' and 'shallow' refer to the submerged depth of the substrate rather than bathymetric depth, with 'deep' defined as >20 m, and 'shallow' as surface to approximately 3 m. Harbour and marina survey data previously reported in Want et al. [17].

Pairwise testing between deployment habitats confirmed that the biofouling assemblages were most dissimilar between hydrodynamically exposed locations vs. sheltered harbours and marinas, although these were not statistically significant in all comparisons (Table 3). The greatest similarities were between tidal shallow vs. wave deep, and harbours vs. marinas, although these were not statistically significant.

SIMPER analysis identified species that most characterised fouling assemblages among the habitats studied. Deep tidal habitats were characterised by communities consisting mainly of *C. hameri*, the saddle oyster, *A. ephippium*, and the colonial tunicate *Botryllus schlosseri*. Shallow tidal assemblages featured *C. hameri*, *A. ephippium*, another subtidal barnacle *B. balanus*, the plumose anemone *M. dianthus*, and the blue mussel *Mytilus edulis*. Deep wave habitats were characterised by *A. ephippium*, *B. balanus*, and the calcareous polychaete *Spirobranchus triqueter*. Shallow wave habitat surveys highlighted the contributions of the tube-making amphipod *Jassa falcata*, the chlorophyte *Ulva lactuca*, and the hydroid *Ectopleura larynx*. Harbour and marina assemblages indicated greater variety in key species but were most represented by the macroalgae *Fucus vesiculosus*, the intertidal barnacle *Semibalanus balanoides*, and *U. lactuca*.

### *3.2. The Tether Latch Biofouling Assemblage Was Dominated by Five Organisms with Varying Abundances on Differently Orientated Vertical Faces*

Comprehensive study of biofouling on the TLA identified 14 animal species (Table 4). The abundance of five major fouling species, including *C. hameri*, is shown in Figure 5. The abundance of these organisms varied markedly among the vertical faces orientated differently towards the direction of current flow. The abundance of *C. hameri* was greatest on the side predominantly facing the higher flow velocities of the flood tide. In contrast, *A. ephippium* and *M. dianthus* were found in greater abundance on the sides of the structure not facing the direction of ebb or flood. *A. digitatum* and *B. balanus* were found in much lower abundances and were homogeneously distributed with regard to orientation to the flow.

**Table 4.** Fouling organisms recorded from the tether latch assembly.

| Species | Type | Species | Type |
|---|---|---|---|
| *Alcyonium digitatum* | Dead man's fingers | *Electra pilosa* | An encrusting bryozoan |
| *Amphisbetia operculata* | A hydroid | *Metridium dianthus* | Plumose anemone |
| *Anomia epihippium* | Saddle oyster | *Mytilus edulis* | Common mussel |
| *Balanus balanus* | An acorn barnacle | *Omalosecosa ramulosa* | An encrusting bryozoan |
| *Caryophyllia smithii* | Devonshire cup coral | *Ophiothrix fragilis* | Common brittlestar |
| *Cellepora pumicosa* | An encrusting bryozoan | *Spirobranchus triqueter* | Tube worm |
| *Chirona hameri* | An acorn barnacle | *Scruparia chelata* | An encrusting bryozoan |

A histogram of individual barnacle size shows a bimodal pattern featuring a smaller peak of relatively small *C. hameri* and a larger peak of more massive individuals (Figure 6). Without additional evidence, it is not possible to assign ages to individual barnacles or size classes but the size of the individuals in the smaller peak is consistent with many observations of known juvenile *C. hameri.*

Histograms of individual barnacle volumes from different sides of the TLA reveal a contrast in size distribution associated with substrate orientation (Figure 7). When compared with the overall population on this structure, far fewer *C. hameri* recruited to the 'stern', facing the slower 'ebb' tide. On this surface, there were proportionally a greater number of smaller barnacles and fewer larger barnacles. In contrast, far more barnacles recruited to the 'bow', facing the faster 'flood' tide; the majority of these belonged to the larger size class where rapid growth may be linked with larval and nutrient supply, and timing of settlement.

### *3.3. Novel Observations of Chirona hameri*

Surveys following short-term deployments of acoustic Doppler current profilers (ADCPs) in September–October indicate that *C. hameri* settlement had ceased by late summer; dominant fouling at this time was instead characterised by newly attached *A. ephippium*. Evidence from ORE deployments at various periods of the year confirmed protracted settlement of *C. hameri* larvae beginning in the end of April and continuing into July.

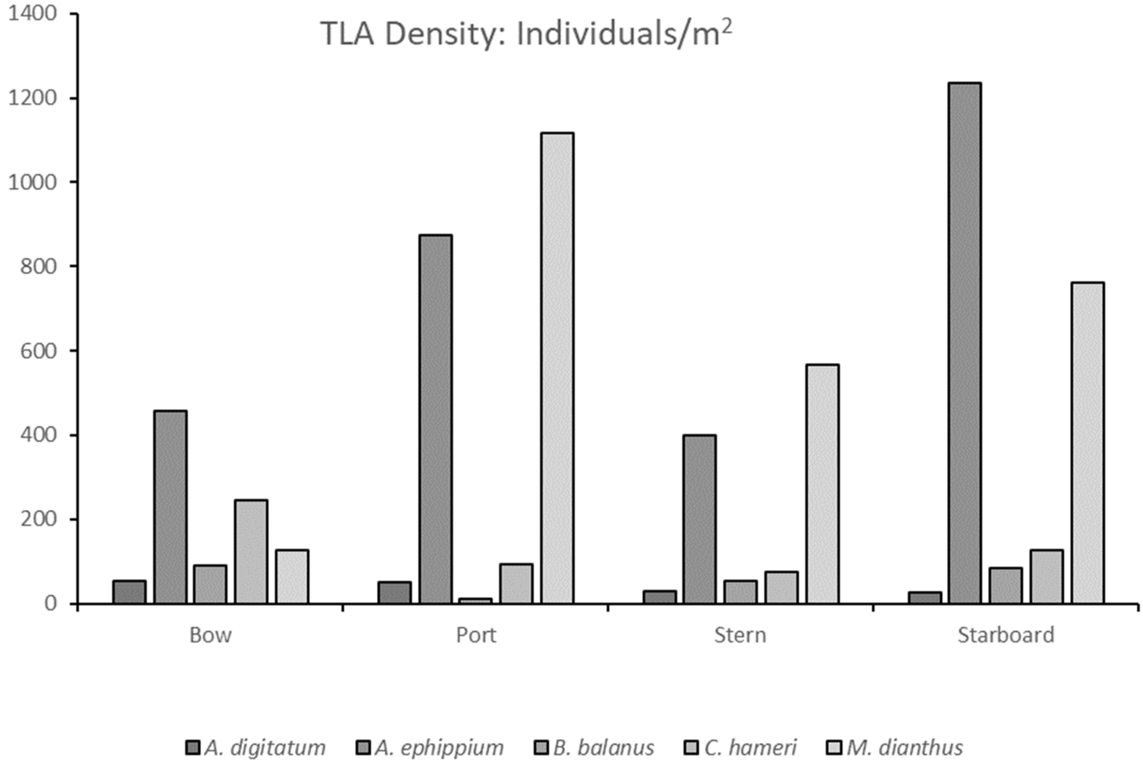


**Figure 5.** Density of key fouling species on the TLA (individual/m$^2$). The roughly cuboidal TLA was orientated slightly obliquely to tidal flow. Each vertical face has been labelled according to orientation relative to the flood tide. Bow refers to the side predominantly facing the faster flood tide; stern refers to the side predominantly facing the slower ebb tide.

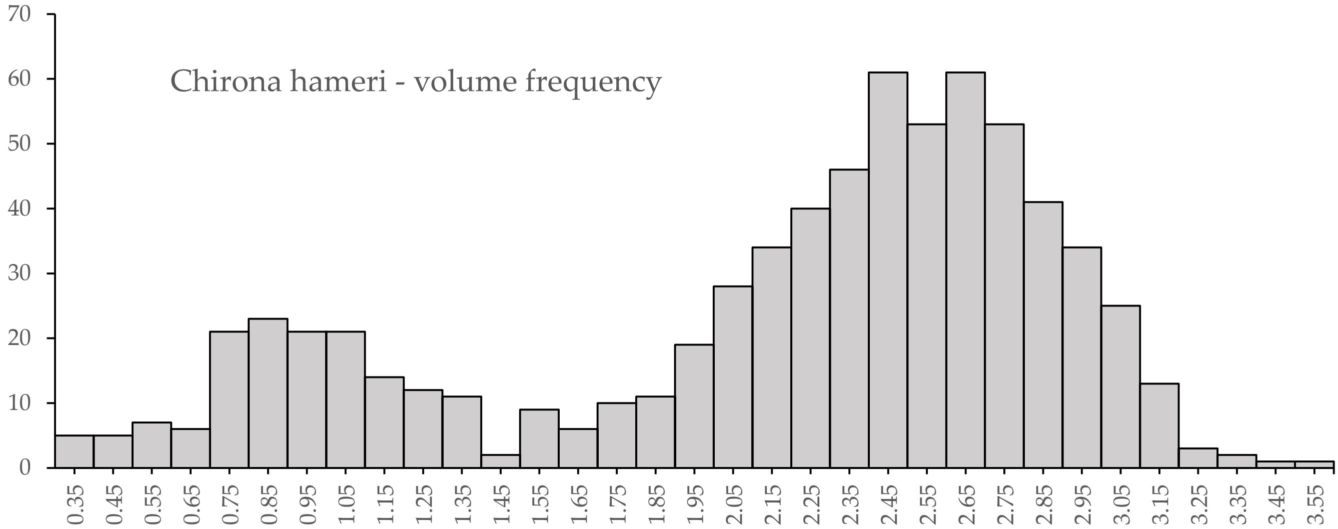


**Figure 6.** Histogram based on cube-root transformed volume (n = 699) of individual *C. hameri* size on the tether latch assembly deployed at Billia Croo, Orkney.

The current studies confirm earlier observations of the highly gregarious nature of *C. Hameri* [30,35]; settlement of younger barnacles atop older individuals, typically with survival of both age classes, was commonly observed, as well as dense juvenile recruitment onto remaining conspecific base plates and adjacent surfaces treated with the fouling-release coating, Hempel X7 (Figure 8).

A surprising observation in October 2018 was the presence of *C. hameri* on a tidal energy converter (TEC) subunit on a floating device deployed at the Fall of Warness—the subunit being submerged to approximately 3 m in depth—evidenced by large adults found on an uncoated stainless-steel surface orientated into the tidal stream. A cohort of juvenile *C. hameri* was also found on surfaces of this structure coated with Hempel X7 but their small size and ease of slipping off suggest that shear stress overcomes adhesion forces when anti-fouling coatings are applied, and the organism is lost while relatively small [59].

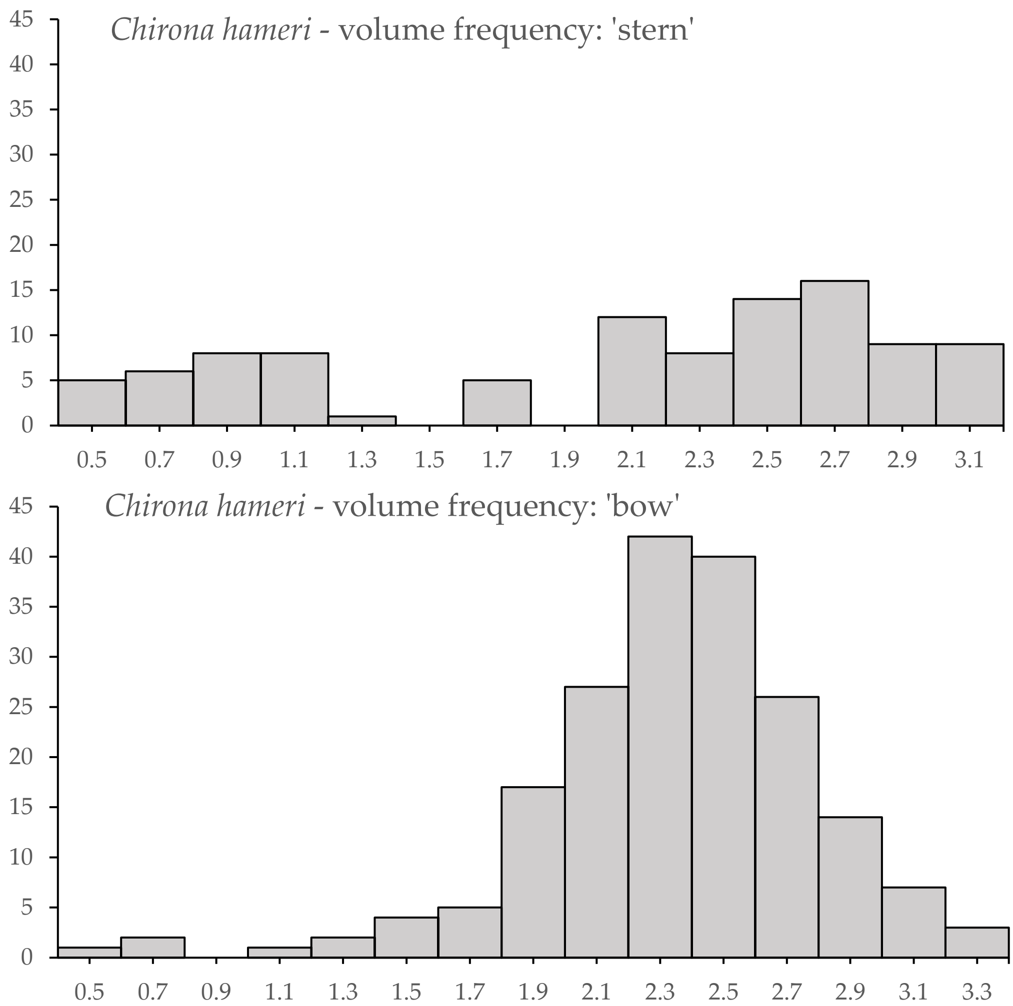


**Figure 7.** Histograms of subsets of individual *C. hameri* size based on cube-root transformed volume from opposite surfaces of the TLA. Top: 'stern' (n = 101) refers to the side predominantly facing the slower ebb tide (0.2 m/s); bottom: 'bow' (n = 191) refers to the side predominantly facing the faster flood tide (0.4 m/s).

*Chirona hameri* individuals showed age- and density-dependent morphological differences, a trait shared with better studied balanoids [60,61]. While juvenile *C. hameri* tend to exhibit a relatively low-profile conical shape, as individuals develop into adults, the parietal plates tend to either retain the general juvenile morphology but proportionally extend vertically into a steeper conical shape, or grow more vertically, creating a cylindrical form with a distinct 'tulip' appearance surrounding the operculum, which was previously used to describe this species [26,30]. The density of barnacles suggests that cylindrical growth patterns in *C. hameri* are a response to space resource competition in more 'crowded', optimal locations, similar to 'hummocking' seen in other barnacle species [60,62].


**Figure 8.** *Chirona hameri* individuals are highly gregarious, commonly settling on conspecifics (**left**) and the remnants of basal plates (**right**). Scale bar 0–5 cm.

## 4. Discussion

Biofouling surveys of ORE devices and infrastructure conducted in the current study identified key organisms that characterise the assemblages found at tidal and wave test sites, on several substrates used by the industry. This study found heterogenous recruitment onto different faces of deployed infrastructure in tidal environments, suggesting that orientation to flow may be a key factor influencing recruitment [63]. Fouling by the barnacle *Chirona hameri* is of particular concern owing to its dominant role in high-flow assemblages in the North Atlantic and its rapid growth to large size. The settlement of *C. hameri* is heaviest in mid-spring but continues into mid-summer. This species may be of particular concern to the ORE industry owing to its highly gregarious behaviour with dense settlement onto basal plates that remain following cleaning operations. For the first time, *C. hameri* is reported in near-surface depths owing to an unusual combination of high tidal currents and shallow deployment of a suitable artificial substrate. The consequences for the functioning of renewable energy devices and mooring structures, resulting from increased drag and loadings, are particularly relevant to developers and test centres working in tidal sites. Evidence provided in the current studies goes some way to addressing important knowledge gaps in the life cycle and settlement behaviours of organisms that may help inform anti-fouling strategies [17,64].

### *4.1. Fouling Assemblages in High Tidal Flow Environments*

Surveys of ORE deployments in high tidal flow, aphotic habitats in Orkney waters have revealed animal-dominated assemblages with low biodiversity, compared with more sheltered habitats [13]. It should be noted, however, that introduced hard substrates may function to increase overall biodiversity in a given location [65,66]. While several INNS have been recorded in sheltered Orkney waters [67], including the tunicate *Styela clava* in Scapa Flow [68], no INNS have been observed at full-scale tidal or wave test sites operated by the EMEC.

As a general statement, in moderate current speeds (such as at Billia Croo), fouling assemblages comprise a mixture of soft-bodied animals, such as *A. digitatum*, *M. dianthus*, and several species of hydroids, and hard-bodied encrusting animals, including barnacles, bryozoans, and saddle oysters (e.g., *A. ephippium*). As current speeds increase (such as at the Fall of Warness), soft-bodied organisms are less likely to be found (except in limited spaces of relative shelter, including 'niche' areas), presumably because of direct hydrodynamic stress or indirectly through current-driven abrasion [69–71]. Many of these encrusting species (i.e., bryozoan colonies and saddle oysters) are of small size and low profile, with relatively minor hydrodynamic and loading impacts expected (although component corrosion may be an ongoing issue with unmanaged biofouling). From a hydrodynamic standpoint, when compared with other fouling organisms in this environment, high profile, rigid barnacle shells create far greater impacts on drag [11,72–74].

### *4.2. Hydrodynamic Forces and Orientation Preferences*

Results from the TLA mooring system deployed at the EMEC wave test site at Billia Croo show that *C. hameri* is capable of successful recruitment in more moderate maximum tidal speeds of 0.4 m/s compared with previous reports of 0.5 m/s [32]. It should be noted that at this location, significant wave height has recently been recorded as high as 19 m [53]; extreme wave exposure may have important hydrodynamic consequences for the benthic community, even in relatively deep waters [70], and this may influence biofouling communities. *C. hameri* is consistently abundant on structures deployed at the EMEC tidal test site at the Fall of Warness where tidal flow rates of up to 4.0 m/s have been recorded [53]. In addition to the importance of larval supply from adjacent hard substrates, localised abundance suggests that challenges for survival in high current flow habitats may release *C. hameri* from competition for space resources with other fouling organisms. This does raise the question of whether there exists an upper limit of tidal velocity, above which *C. hameri* is not found. This is not known but might result from the inability of larvae to attach and complete metamorphosis, or for growing barnacles to remain attached [72,75]. This may be important when deploying devices and infrastructure into locations with tidal flows exceeding 4 m/s. The goose barnacle *Conchoderma virgatum* has been recorded attaching to vessel hulls travelling at 6.9 m/s [76]

A consistent finding in these studies is that recruitment of fouling organisms is not homogeneous among surfaces differently orientated to tidal currents. Evidence collected in these studies showed higher recruitment of *C. hameri* to surfaces facing the direction of highest flow (Figure 7). *A. ephippium* and *M. dianthus* were less abundant on surfaces dominated by *C. hameri* but more abundant and dominating on perpendicular vertical surfaces. Orientation may play an important role in creating optimal surfaces for settlement and successful growth [62]; barnacle growth is positively associated with areas of greater productivity [74]. While substrate orientation relative to the sun plays a dominate role in determining shallow-water assemblages [77–79], this is not expected to be the case in deeper, aphotic habitats. Other variables that are expected to affect habitat preferences for individual species include nutrient level, oxygenation, temperature, salinity, and the contributing hydrodynamic influence of wave climate [80–82].

The current studies suggest that surfaces orientated towards lower tidal velocities may feature less conspecific competition for space resources in *C. hameri*, thus facilitating cyprid settlement onto available space (Figure 7). However, while there may be a relative shift favouring juvenile *C. hameri* on less optimal surfaces, fewer individuals are able to sufficiently exploit these locations to attain larger size. In contrast, surfaces orientated towards higher tidal velocities appear to be more optimal for this species and are dominated by large individuals, densely packed and limiting available free space for juvenile conspecifics and other fouling species. Heterogeneous recruitment of *C. hameri* to subsea infrastructure, showing apparent optimal and suboptimal orientations, has also been observed on cable-end connectors used to couple tidal and wave devices to subsea electrical cables and on settlement panels attached to an IEMP in 2015 and 2017 [83]. Consistent with observations on the TLA, the surface most orientated to the direction of highest tidal velocity featured the greatest abundance and cover of *C. hameri*. Caution should be applied to these findings owing to the limitations of largely opportunistic surveys.

### *4.3. Settlement Behaviour and Growth*

The current study showed that in the NE Atlantic, *C. hameri* recruitment to artificial structures occurs from mid-spring to mid-summer, with a dominant period of settlement occurring early in the season followed by a protracted period with a much lower rate of recruitment. *C. hameri* fouled infrastructure comprised of steel, HDPE, fiberglass, and concrete, indicating low substrate specificity (Table 2).

The cyprid larvae of *Chirona hameri* are highly gregarious [30,34,35] and this may have profound implications for the ORE industry (Figure 8). In the well-studied littoral barnacle *Semibalanus balanoides*, settlement depends on the density of conspecifics, where increased density will tend to favour increased settlement [84,85]. This relationship may provide a marine example of the Allee effect, more commonly seen in 'closed' terrestrial populations [86]. Greater settlement density is expected to increase the post-settlement mortality of juveniles as growing conspecifics compete for limited space [87–89]. This may explain the differences between densities and size classes of *C. hameri* recruitment to contrasting surface orientations relative to current flow, where proportionally few juveniles survive on more optimal adult-dominated surfaces. Similar population differences were observed in the stalked barnacle *Pollicipes polymerus* between apparently optimal and suboptimal locations in California [90]. As free space begins to fill, distance between settling spat will decrease [61]. Hence, in strongly gregarious species such as *C. hameri*, it might be expected that during low recruitment periods, settlement may be denser on smaller patches of available surface amid remnant adults, and less dense on much larger cleared areas without adult conspecifics. Regarding anti-fouling strategies, extended deployment of devices or incomplete cleaning operations, where either individual barnacles or basal plates remain, may result in subsequent periods of denser larval settlement. Poorly managed fouling by *C. hameri* may therefore rapidly progress, resulting in non-linear increases in hydrodynamic and loading impacts.

When compared with other barnacles, cyprids of *C. hameri* are very large, averaging 1.45 mm [35]. Following metamorphosis, the low profile, conical form of juvenile *C. hameri* is morphologically typical of other similarly sized organisms managing extreme drag forces (e.g., limpets), while the higher-profile, steeper-sided form exhibited by adults will experience increased acceleration reaction forces which may create an upper growth limit [71,72,91]. *C. hameri* exhibit bimodal size distribution at population level (Figure 6), where the first peak represents the latest annual cohort (i.e., 'juveniles' aged approx. 8–11 months) and the second peak represents an amalgamation of all +1 year 'adult' cohorts. This indicates that *C. hameri* grows fast, and the massive size of this barnacle—and, importantly, the potential impact on the functioning of ORE devices and infrastructure—is attained by the individual's second year. With settlement beginning as early as April, this strongly suggests that no reproductive activity occurs in the first year, confirming earlier observations by Moore [30]. Rapid growth in this species may be possible due to its lighter shell, when compared against the smaller but more solid *B. balanus* [92]. Other species of large barnacles displaying similar rapid growth patterns include the commercially harvested *Austromegabalanus psittacus* [93] and *Megabalanus azoricus* [94]. Large larval size and rapid growth rate may be adaptive responses to improve the survival of organisms [95] in high-flow conditions by providing greater adhesion strength. Prioritising nutritional resources towards growth rather than reproductive outputs may be an adaptive response necessary to survive in specialist ecological niches [96]. Settlement onto shell fragments [25,29,30,43] and aggressive gregariousness (e.g., onto conspecific opercula) [35] may be further evidence of survival strategies used by *C. hameri*.

While all previous records, including extensive studies in the current research, have only described *C. hameri* in depths exceeding 30 metres, its presence on an uncoated part of a floating TEC subunit provides evidence that, when a suitable substrate is available in high current velocities, fouling from *C. hameri* is not limited to deeper, aphotic substrates. This may have particularly important implications for floating ORE devices deploying in tidal sites and for the maintenance of anti-fouling coatings. Surface deployments in these conditions may create new habitats for successful recruitment of other deeper-water organisms.

### 4.4. Importance to the Offshore Renewable Energy Sector

Biofouling of ORE devices and infrastructure impedes performance and survivability, corroded components are costly to access and replace, and the downtime necessary for maintenance and cleaning comes with a substantial economic impact. Power and thrust performance reductions of 20% have been estimated for axial-flow turbine blades fouled by barnacles [10]. Stringer and Polagye [11] describe significant declines in cross-flow turbine performance with increased height of fouling, modelled on *Balanus crenatus*, a barnacle with a maximum height of approximately 15 mm [26]; *C. hameri* may grow to five times this height.

Conservative estimates suggest that reducing device access by one visit per year may save GBP 25 K per unit [53]. Scaled up to a moderately sized array of 10 devices, over a 25-year operational lifetime, this translates to potential savings of over GBP 6 million. Improved device efficiency and maintenance will also provide substantial benefits in reducing annual carbon emissions; realistic estimates of 3% improvement in energy capture achieved through properly managed fouling on 1.5 MW tidal devices currently installed in the Pentland Firth is estimated to save 41 tonnes per device [48], fuel savings achieved by reducing one maintenance operation saves a further 16 tonnes [53], and greater harvesting of energy creates greater returns on investments.

Anti-fouling coatings can be effective against barnacle settlement [9,59,97]. While in situ performance of coatings in high current speeds has not been rigorously studied, high current speeds will tend to reduce coating efficiency through increased rates of anti-foulant dissolution [98]; coatings may be further compromised by sediment abrasion [10]. However, high-percentage coverage of *C. hameri* and *B. balanus* on cable-end connectors deployed directly on the seabed at the Fall of Warness provides evidence that sediment abrasion may not be a problem for the survival of large barnacle species.

## 5. Conclusions

The current study has identified key fouling organisms and the critical role that the massive barnacle *C. hameri* plays in biofouling in tidal habitats used by the ORE sector. *C. hameri* dominates the fouling assemblage in higher-flow conditions, on a variety of artificial substrates. Knowledge gaps exist about the seasonality of reproduction and settlement of *C. hameri* and other major fouling organisms, knowledge that may be particularly valuable in informing anti-fouling strategies. There are potentially substantive steps to reduce cost of ownership for the ORE industry by improved management of fouling on devices, mooring systems, subsea cables, and other infrastructure. Similar issues may affect the use of cages and moorings in other marine industries, such as aquaculture [99].

Identification of problem foulants in specific habitats and geographic regions is providing timely information important to the developing ORE industry. Additional data germane to substrate, depth, and hydrodynamic profiles of these habitats can provide guidance to the sector to better manage biofouling. Operations and maintenance can be scheduled to avoid periods of time when the main fouling occurs or to allow key foulants to be most effectively removed [17,64]. In the case of *C. hameri* in tidal habitats of the North Atlantic, owing to the prolonged settlement period beginning in mid-spring, device and infrastructure maintenance should be considered for late in the summer. At this time, removal of newly metamorphosed *C. hameri* will be relatively easy (e.g., through power washing), no further settlement of the species would be expected for 8–9 months, and the weather window for operations at sea remains favourable. If resources permit, an earlier cleaning, following major settlement of biofouling in the spring, would enhance the efficacy of this strategy. The current studies also highlighted the strongly gregarious nature of *C. hameri* settlement, providing an extra incentive for removing fouling at these locations and in niche areas of devices and other infrastructure.

Experimental studies may help quantify the impacts of *C. hameri* and other fouling species on drag and loading forces in different hydrodynamic conditions and substrate orientations. Such studies might also help in our understanding of the role of tidal velocity (and potentially wave climate) in settlement and recruitment processes of key biofoulants. Experiments designed to capture successional data throughout the year may lead to better guidance on seasonal management of biofouling [13,100,101]. Working closely with developers and test centres in these challenging environments is essential in addressing remaining knowledge gaps.

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