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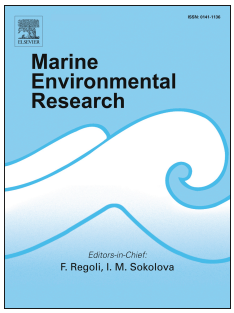

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Running head: Rigs-to-Reefs in the North Sea

Quantitative analysis of fish and invertebrate assemblage dynamics in association with a North Sea oil and gas installation complex

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ABSTRACT

Decommissioning of offshore infrastructure has become a major issue facing the global offshore energy industry. In the North Sea alone, the decommissioning liability is estimated at £40 billion by 2040. Current international policy requires removal of offshore infrastructure when their production life ends; however, this policy is being questioned as emerging data reveal the importance of these structures to fish and invertebrate populations. Indeed, some governments are developing 'rigs-to-reef' (RTR) policies in situations where offshore infrastructure is demonstrated to have important environmental benefits. Using Remotely Operated Vehicles (ROVs), this study quantified and analysed fish and invertebrate assemblage dynamics associated with an oil and gas (O&G) complex in the Dogger Bank Special Area of Conservation (SAC), in the North Sea, Germany. We found clear depth zonation of organisms: infralittoral communities (0-15 m), circalittoral assemblages (15-45 m) and epi-benthic communities (45-50 m), which implies that 'topping' or 'toppling' decommissioning strategies could eliminate communities that are unique to the upper zones. Sessile invertebrate assemblages were significantly different between structures, which appeared to be driven by both biotic and abiotic mechanisms. The O&G complex accommodated diverse and abundant motile invertebrate and fish assemblages within which the whelk *Buccinium undatum*, cod fish *Gadus morhua* and lumpsucker fish *Cyclopterus lumpus* used the infrastructure for different stages of reproduction. This observation of breeding implies that the structures may be *producing* more fish and invertebrates, as opposed to simply acting as sites of attraction (sensu the 'attraction vs production' debate). At present, there are no records of *C. lumpus* spawning at such depth and distance from the coast, and this is the first published evidence of this species using an offshore structure as a spawning site. Overall, this study provides important new insight into the role of offshore O&G structures as habitat for fish and invertebrates in the North Sea, thereby helping to inform decommissioning decisions.

Key words: Rigs-to-reefs, North Sea, Dogger Bank, ROV, decommissioning, invertebrate, fish, assemblage dynamics, oil and gas.

INTRODUCTION

The North Sea's Dogger Bank (DB) is a diverse and highly productive marine ecosystem (Callaway et al., 2002; Diesing et al., 2009; Hammond et al., 2002; Sell and Kröncke, 2013; Zijlstra, 1988; Zühlke et al., 2001) with significant economic value (Hattam et al., 2015), driven primarily by hydrocarbon and renewable energy industries. In 2015, the DB accommodated 79 offshore installations (OSPAR, 2015), many of which comprise an aging infrastructure requiring decommissioning, which is expected to increase exponentially within the coming decades (Jørgensen, 2012).

Sub-sea anthropogenic structures provide habitat heterogeneity in the form of hard, vertical substrata throughout the entire water column, compared to surrounding, often relatively featureless sedimentary benthos. O&G installations function as *de facto* artificial reef systems, often supporting diverse and abundant marine life such as anemones, hydroids, bryozoans, sponges, mussels, barnacles, soft and hard corals (Bergmark and Jørgensen, 2014; Forteath et al., 1982; Freeman, 1978; Guerin, 2009; Guerin et al., 2007; Larcom et al., 2014; Olsen and Valdemarsen, 1977; Valdemarsen, 1979), commercially-important fishes (Friedlander et al., 2014; Fujii et al., 2014; Guerin, 2009; Jørgensen et al., 2002; Løkkeborg et al., 2002; Olsen and Valdemarsen, 1977; Soldal et al., 2002; Valdemarsen, 1979) and top-level predators such as marine mammals (Arnould et al., 2015; Delefosse et al., 2017; Todd et al., 2009b; Todd et al., 2016; Triossi et al., 2013). In accordance with the Petroleum Act (1987), all North Sea active offshore O&G installations are surrounded by 500 m fishing and shipping exclusion zones, effectively acting as small-scale Marine Protected Areas (MPAs). Consequently, it has been proposed that obsolete installations could be decommissioned to form artificial reefs in an otherwise deteriorating environment (e.g. Bergmark and Jørgensen, 2014; Cripps and Aabel, 2002; Fowler et al., 2014; Jørgensen, 2012; Macreadie et al., 2011, 2012), a concept referred to collectively as 'Rigs-to-Reefs' (RTR).

In 1982, a RTR decommissioning strategy was implemented successfully in the Gulf of Mexico (Jørgensen, 2009), but debate is ongoing regarding introduction of a similar programme in the North Sea (see Baine, 2002; Bergmark and Jørgensen, 2014; Cripps and Aabel, 2002; Fujii et al., 2014; Jørgensen, 2012; Picken et al., 2000; Sayer and Baine, 2002; Soldal et al., 2002). Since 1998, dumping (deliberate disposal of waste or other matter), and/or leaving wholly or partly in place, of disused offshore installations is prohibited in the North Sea within the Oslo and Paris Convention (OSPAR) maritime area under auspices of Decision 98/3 on the Disposal of Disused Offshore Installations. Currently, all disused installations are removed completely during decommissioning with the exception of some concrete-based installations and steel structures weighing over ten thousand tonnes, which can be considered for derogation (OSPAR, 1998). Subsequent reviews of OSPAR guidelines have unanimously upheld the ban on RTR on the basis that there has been insufficient technical and scientific advances to justify changes in derogation criteria (Dacre and Edwards, 2013); however, offshore installation removal incurs significant costs and models show that removal can be more detrimental to the environment than leaving statures in place (Nicolette et al., 2013). Moreover, a recent global survey found that 94.7% of environmental experts agreed that a more flexible case-by-case approach to decommissioning could benefit the North Sea environment (Fowler et al., 2018).

There is a clear need for rallied scientific research into offshore installation-associated flora and fauna to assess suitability of a potential RTR programme in the North Sea (Fowler et al., 2014; Jørgensen, 2012; Macreadie et al., 2012; Murray et al., 2018), especially in three key areas: 1) depth zonation of floral and faunal communities in different geographical locations (Baine, 2002; Fowler et al., 2014; Guerin et al., 2007; Thorpe, 2012); 2) assemblage dynamics in relation to structural design across vertical and horizontal profiles (Baine, 2001; Macreadie et al., 2011); and, 3) ecological dependency, and impact of installation / removal on surrounding ecosystems and industries (Baine, 2002; Baine and Side, 2003; Bergmark and Jørgensen, 2014; Bohnsack, 1989; Fowler et al., 2014; Fujii et al., 2014; Guerin, 2009; Sayer et al., 2005). This study addresses the first two issues through the investigation of invertebrate and fish assemblages associated with an offshore installation complex in a bid to contribute to a wider evaluation of the utility of RTR as a future strategy for offshore installation decommissioning in the North Sea. We hypothesised that floral and faunal assemblages (abundance, diversity) will vary with the water depth spanned by O&G installations, and that assemblages with vary among installations. This information is

important for making installation-specific decommissioning decisions (e.g. in the case of vertical zonation, this may inform whether 'topping' or 'toppling' are appropriate; Macreadie et al. 2011).

METHODS

Site description

Figure 1 shows location of the offshore natural gas production platform (Installation A) and jack-up drilling rig (Installation B) complex in the Northeast German Sector of the DB.

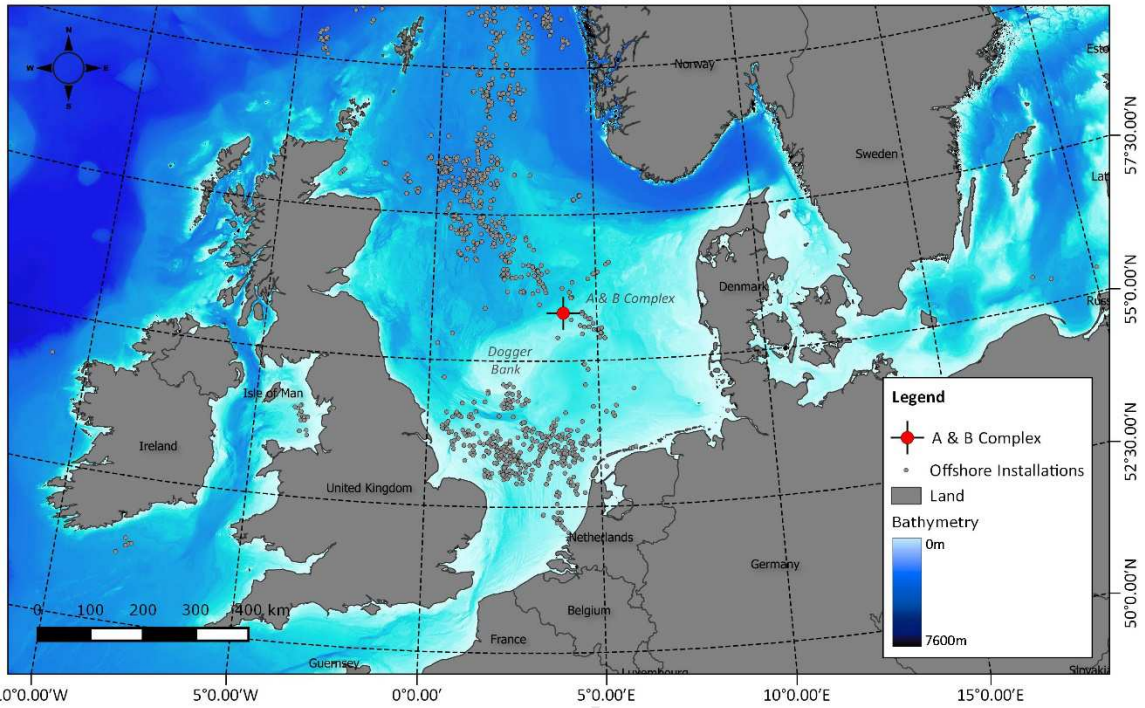

Figure 1. Map of the North East Atlantic showing location of the offshore production platform (Installation A) and jack-up drilling-rig (Installation B) complex in relation to bathymetry and other offshore O&G installations.

Installation A has been *in situ* since July 1999, located in field sector A6-B4 (55°47'28.895''N 003°59'39.584''E) in an average water depth of 48.45 m, on a seabed composed of soft clay, sand, gravel and sporadic artificially placed rock (used to cover pipelines and the base of pylons to reduce localised sediment erosion and resultant 'free span' which may threatened the structural integrity of such infrastructure). Installation B was con-joined to the south of Installation A in February 2014 in a depth of 48.50 m.

Videographic sampling and timing

Footage was provided by installation operators and survey contractors and collected using inspection-class Remotely Operated Vehicles (ROVs), including a sub-Atlantic Mohican One and SAAB Seaeye Falcon, during routine maintenance surveys. ROV partnerships between O&G industry and scientists are the foundation of programs like SERPENT (www.serpent.com), and have fuelled major scientific advances in ocean observation (Gates et al., 2017; Hudson et al., 2005; Jones, 2009b; Macreadie et al., 2018). Surveys comprised a spudcan inspection of Installation B (40 - 50 m) on 06/04/2014 and General Visual Inspection (GVI) of Installation A (0 - 50 m) between 02/12/14 and 04/12/14. At Installation B, footage was only available between 40 and 50 m due to the nature of the spudcan survey.

Sessile fouling assemblages

To quantify fouling organism percentage cover, footage from each installation was divided into ten depth bands at 5 m intervals (Figure 2), adapted from Guerin et al. (2007). At each depth band, six still images were extracted from footage using a random stratified technique, as per Whomersley and Picken (2003). Distance between the ROV and installation fluctuates (Eleftheriou, 2013)

altering area covered by extracted stills, therefore, care was taken to extract stills of similar proximity (0.5-1.0 m).

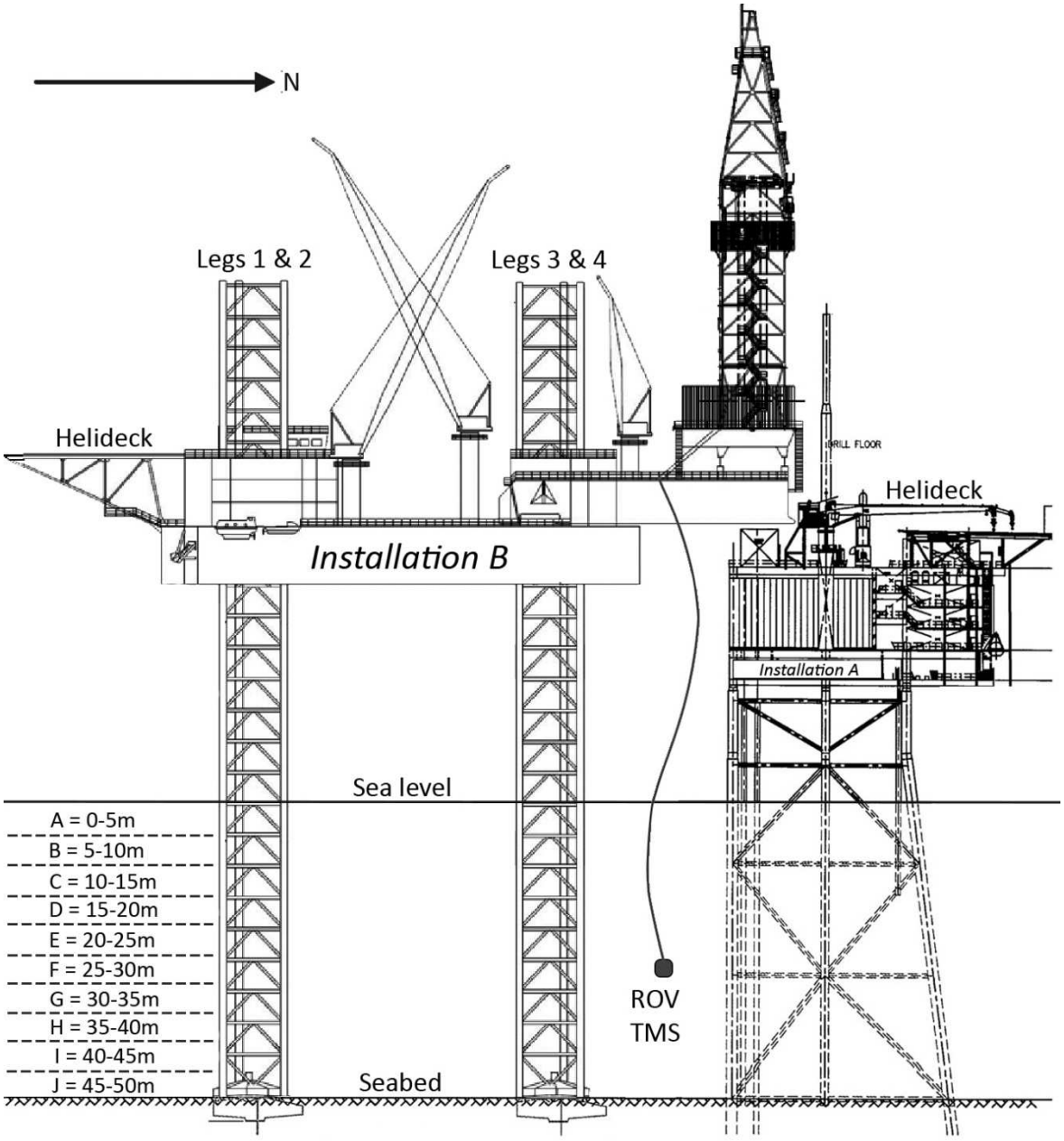

Figure 2. Structural diagram of the offshore natural gas production platform (Installation A) and jack-up drilling rig (Installation B) complex in relation to depth bands and Remotely Operated Vehicle (ROV) Tether Management System (TMS).

Given known difficulties of *ex situ* subsea species identification (Andaloro et al., 2013; Eleftheriou, 2013; Jones, 2009a; Söffker et al., 2011), sessile invertebrates were assigned to fouling categories (Table S1). Category percentage cover was then calculated using Digital Interactive Colour Segmentation (DICS).

Digital interactive colour segmentation

Stills were inserted into Adobe Photoshop CS6 Extended, and fouling categories delineated manually by assigning specific colours to each category using the 'paint brush' and 'magic wand' tools, modified from Bernhardt and Griffing (2001), Tkachenko (2005) and Guerin (2009). Through adjustment of 'image colour threshold' and 'selection tolerance', individual 'image

masks' were produced for each fouling category, as per Guerin (2009). Obsolete areas (e.g. open water) were deleted and omitted from analysis. Individual masks were then selected and, using the 'count tool' and 'record measurements log', the number of pixels covered by each mask was determined. Once all masks had been quantified, percentage cover of each fouling category was calculated.

Fish and motile invertebrate assemblages

To quantify motile invertebrate and fish assemblage, *species richness (S)*, *abundance (N)* and *diversity (H')* were investigated. ROV footage was divided into ten 5 m depth bands, as above. At each depth band, five minutes of footage was viewed and any individuals observed were identified to lowest possible taxonomic group, as per Hughes et al. (2010) and Söffker et al. (2011), and enumerated. Individuals which were too distant from the ROV or too small to be accurately assigned a functional group were omitted from analysis, as per Guerin (2009).

Data analysis

In order to investigate fouling category, motile invertebrate and fish assemblage dynamics, α-diversity analysis, as described by Magurran (2004) was applied to both percentage cover and count data to calculate assemblage *species richness (S)*, *abundance (N)* and *diversity (H')* within depth bands and installations.

Data were tested for normality using Kolmogorov-Smirnov tests at the $P < 0.05$ level. To test null hypotheses that there were no significant differences in median fouling category *S* and *H'* between depth bands at both Installations, Kruskal-Wallis and Mann-Whitney U tests were performed on non-normal or continuous data, and Student t-tests and F-tests on normal data assuming equal variances.

Prior to performing fouling community analysis, data were standardised using a square root transformation. Upon determining if there was a difference in similarity of fouling assemblages between depth bands at each installation and between installations, three Multi-Dimensional Scaling (MDS) ordination analysis tests were applied to a corresponding Bray-Curtis similarity matrix.

To determine if fouling community similarity was different significantly between depth bands or installations, three Analysis of Similarity (ANOSIM) tests were applied to corresponding Bray-Curtis similarity matrices (Clarke and Warwick, 1994). In order to elucidate which fouling category expressed largest contribution to defining assemblage structure within and between installations and depth bands, three separate Similarity of Percentages (SIMPER) analysis tests were also performed. All statistical analysis was completed using PRIMER v. 6.0.

RESULTS and DISCUSSION

We found that both installations supported a range of diverse taxa; from reef-dependent species, to transient pelagic species. A list of all taxa observed at both installations is presented in Table S2.

Sessile fouling assemblages

At Installation A, there were three reasonably clear clusters of similarity (Fig. 3A) corresponding to infralittoral assemblages (0-15 m), circalittoral communities (15-45 m) and epi-benthic assemblages (45-50 m). Difference in fouling assemblage similarity between depth bands was statistically significant (ANOSIM, Global $R = 0.624$, $P = 0.001$). A pairwise comparisons of depth bands revealed that epi-benthic assemblages (45-50 m) were significantly different from all other depth bands ($P < 0.05$), circalittoral communities (15-45 m) were significantly different from all other depth bands ($P < 0.05$) and also that infralittoral assemblages (0-15 m) were significantly different from all other depth bands ($P < 0.001$); however, all other comparisons where not significant ($P > 0.05$). Infralittoral assemblages between 0-5 m expressed lowest richness amongst depth bands, dominated by macroalgae and mussels comparable to findings by Houghton (1978), Forteath et al. (1982), Southgate and Myers (1985), Whomersley and Picken (2003), Guerin et al. (2007) and Guerin (2009). Mussels are superior spatial competitors in wave-exposed habitats (Denny and Helmuth, 2009), often significantly reducing assemblage *S* and *H'* (Gosling, 1992), concordant with these findings. Mussels also increase structural heterogeneity, and, in combination

with increased light intensity at 0-5 m, provide ideal habitat for macroalgae (Terry and Picken, 1986). Due to ROV operational limitations close to the surface (see Guerin *et al*., 2007), it is likely that inconspicuous organisms were underrepresented. As such, *S*, *N* and *H'* should be interpreted as conservative levels of true α-diversity indices.

Assemblages between 10-15 m at Installation A expressed one of the highest *S* and *H'* of all depth bands. Macroalgae were most influential in defining the community, expressing an average abundance of 71% and contributing 50.0% of total similarity, followed by mussels (average abundance = 68%) contributing 47.6% of overall similarity (Table S3). Algal abundance declined with depth, in contrast to increased abundance of *M. senile*, which dominated below 15 m. Whilst mussels and algae still comprised a significant portion of the assemblage, reduced wave exposure and light intensity are likely to have diminished their competitive advantage, resulting in a reduction in abundance. Structurally-complex organisms, particularly *M. senile* which is vulnerable to disturbance (Bucklin, 1987), increased in prominence. The transitional nature of 10-15 m, between both abiotic and biotic-mediation dominated zones, facilitates coexistence of taxa from both assemblages contributing to increased *S* and *H'*. Increased structural complexity due to conductor guides at the shallowest horizontal elevation at 11 m may also contribute to elevated *S* and *H'* by increasing available ecological niches, thus accommodating greater organism richness and diversity (Menge, 1976). Increased *S* and *H'* may also be attributed to GVI footage favouring structurally-important elements, including the conductor guides at 11 m, resulting in disproportionate coverage of certain areas; however, as six still images were collected at each depth band using a random stratified technique, as per Whomersley and Picken (2003), inherent structural bias was minimised.

Assemblages present between 15-45 m at Installation A were dominated by *M. senile* (Table S3), resulting in very low *S* and *H'*. *M. senile* express facultative asexual reproduction employing both sexual broadcast spawning and asexual pedal laceration (Bucklin, 1987). Pelagic planktotrophic larvae enable establishment of isolated areas and asexual reproduction facilitates rapid colonisation (Shick, 1991). Once established, *M. senile* supresses larval recruitment of other species by preying upon planktonic larvae (Mercier et al., 2013; Sebens and Koehl, 1984), and has been shown to smother juvenile recruits through pedal locomotion (Nelson and Craig, 2011; Turner et al., 2003). As such, *M. senile* is ubiquitous amongst North Sea fouling communities (Forteath et al., 1982; Guerin, 2009; Guerin et al., 2007; Roberts, 2002; Schrieken et al., 2013; Whomersley and Picken, 2003), often present as a dominant spatial competitor and significant structuring force (Guerin et al., 2007; Nelson and Craig, 2011; Whomersley and Picken, 2003). In contrast to 15-45 m, *S* and *H'* for the epibenthic assemblages at 45-50 m were much higher (Table S3). At this depth, static infrastructure interferes with local hydrodynamics increasing flow (Dahlberg, 1983), resulting in greater scour, burial and suspended sediment around the footings. Increased flow can deform anthozoan polyps (Patterson, 1984) and, combined with greater turbidity, reduce suspension-feeding efficiency, possibly contributing to the marked reduction in *M. senile*. Barnacles are also active suspension-feeders; however, their cirral fans are more tolerant of turbidity (Riisgård and Larsen, 2010) enabling assemblage domination at 45-50 m.

At Installation B, there are two distinct clusters of similarity, one of which corresponds to the 40-45 m samples and the other to the 45-50 m samples, in addition to one outlying 40-45 m sample (Figure 3B). Consequently, dissimilarity in depth band fouling assemblages was statistically significant (ANOSIM, Global $R = 0.908$, $P = 0.018$). Four types of fouling category accounted for 92.9% of the total 51.3% similarity within 40-45 m samples. *M. senile* were most influential, expressing an average abundance of 48.0% contributing 36.2% to overall similarity, followed by mussels, then fouling scars and barnacles (Table S4). Five fouling categories contributed 100.0% of the total 82.9% similarity within 45-50 m samples. Fouling scars were most significant with an average abundance of 66.0% which contributed 34.6% to overall similarity, followed by exposed metal, then biofilm, *M. senile* and finally egg masses (Table S4). Hydroids and mussels are pioneering colonisers (Whomersley and Picken, 2003), attributable to r-selected reproductive strategies (Moate, 1985; Thompson, 1979), in which high fecundity, rapid growth, young sexual maturity and high larval dispersal potential are inherent. Hydroid and mussel dominance is typical of young offshore fouling communities (Whomersley and Picken, 2003), concordant with Installations B's limited time *in situ*. Nevertheless, hydroids are short-lived and

poor spatial competitors (Moate, 1985) so as time *in situ* increases, *M. senile* is expected to dominate, as observed on Installation A. *Mytilus edulis* is not usually documented below 18 m (Page and Hubbard, 1987), so their abundance at 40-45 m suggests that some individuals settled whilst legs were at shallower depths, probably at different locations prior to Installation B being 'jacked down'. Indeed, Wanless et al. (2010) suggest relocation of temporary O&G infrastructure may allow recruitment and development at different locations and depths, which may support re-population although may also facilitate establishment of invasive species.

The two Installations (A and B) are compared in Fig. 3C. There are four relativity distinct clusters of similarity corresponding to 40-45 m and 45-50 m samples at Installations A and B (Figure 3C). Dissimilarity between installation fouling assemblages was statistically significant (ANOSIM, Global $R = 0.949$, $P = 0.001$). At 40-45 m, hydroids and mussels were more abundant at Installation B, whereas, *M. senile* were more dominant at Installation A. Installation B can be considered ephemeral habitat due to frequent operational relocation and as already discussed, opportunistic r-selected species, including hydroids and mussels, dominate young fouling communities. At 45-50 m, egg masses were more dominant at Installation B; however, barnacles were more abundant at Installation A. Barnacles are sessile and iteroparous, typically spawning between February and April with peak settlement between May and June (Barnes and Barnes, 1954; Crisp, 1962; Rainbow, 1984). Whilst larvae may have reached Installation B at the time of the GVI in April, newly settled cyprids would have been too small (<3 mm) (Barnes and Barnes, 1954) to detect on ROV footage. Barnacles seen on Installation A, however, had potential to accommodate yearlings and individuals recruited in previous years. Egg masses were predominantly those of *B. undatum*, which rely on hard substrata to affix egg masses (Valentinsson, 2002), typically spawning during late winter (Kideys et al., 1993; Smith and Thatje, 2013) after which eggs develop for 3-8 months (Kideys et al., 1993). As Installation B was sampled during April and Installation A during early December, variation in abundance was not surprising. Nevertheless, it would also appear that installations can act as vectors for *B. undatum* reproduction, providing evidence of production over merely attraction, as discussed by Bohnsack (1989).

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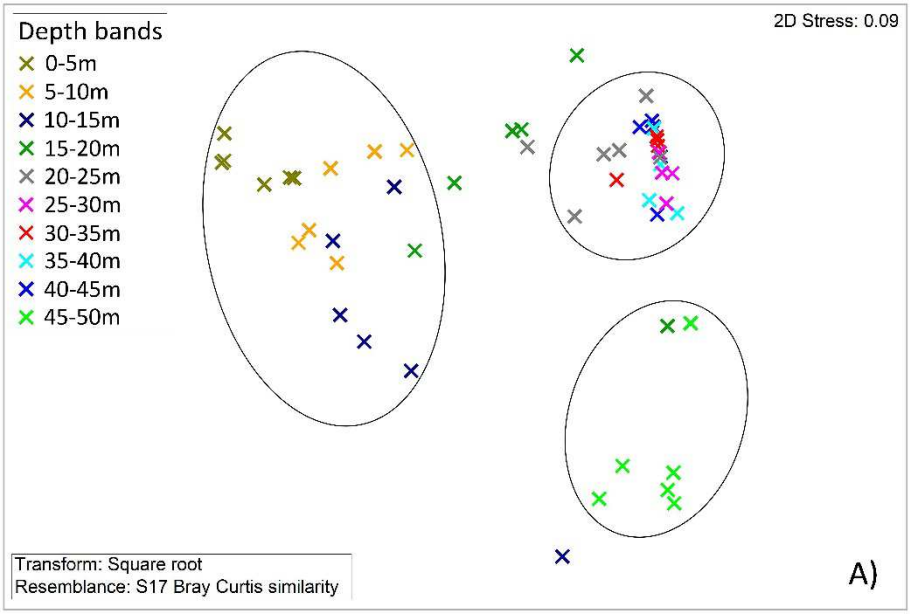
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5-10m
10-15m
15-20m
20-25m
25-30m
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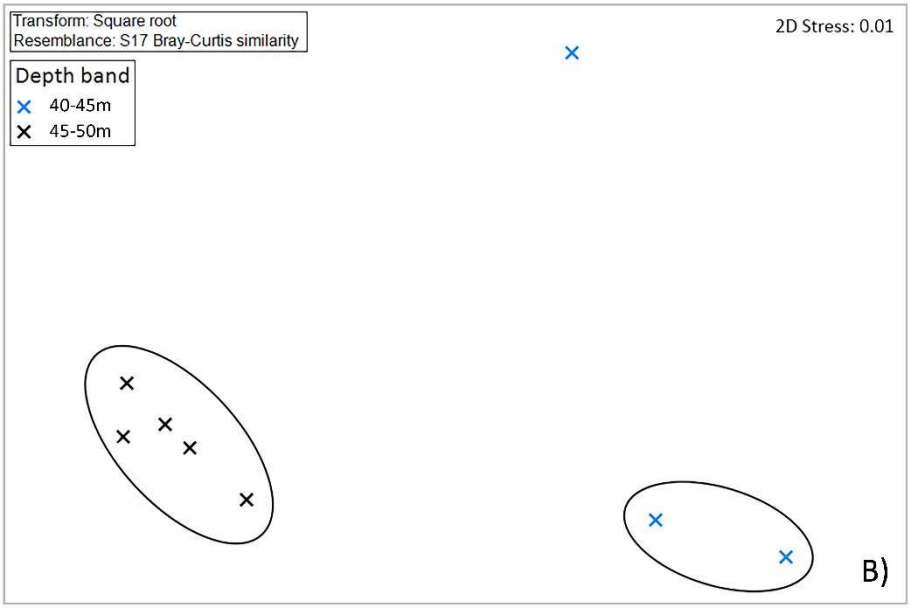
A)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Depth band
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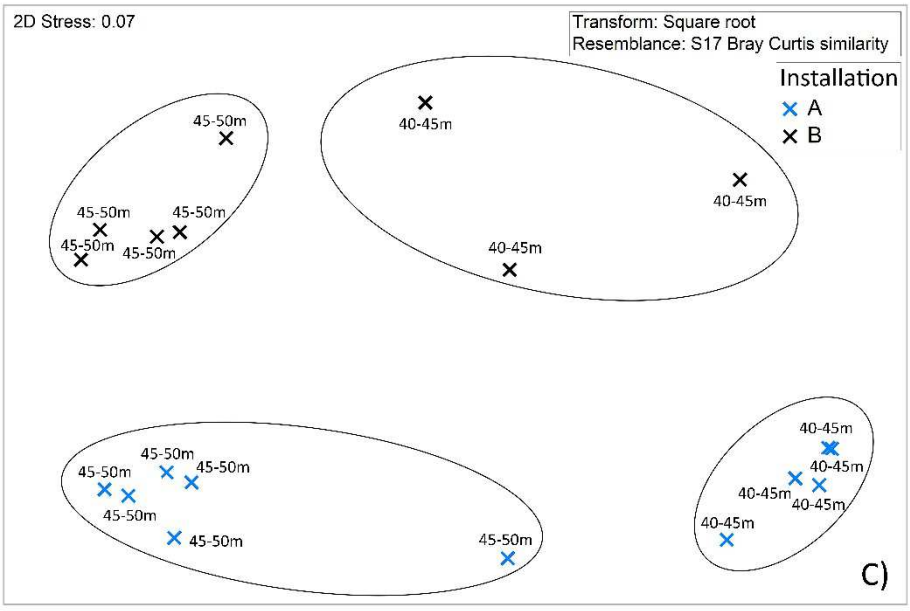
B)


2D Stress: 0.07
Transform: Square root
Resemblance: S17 Bray Curtis similarity
Installation
A
B
45-50m
40-45m
C)

295

Figure 3. MDS analysis on a Bray-Curtis similarity matrix of fouling assemblages present between: A) depth bands (0-50m) at Installation A; B) depth bands (40-50m) at Installation B; and C) depth bands (40-50m) at Installations A and B.

Figure 4 compares the percentage cover of sessile invertebrates between the two installations. At Installation B, at 40-45m, fouling scars, hydroids and mussels were all far more abundant than at Installation A, whereas, plumose anemones where more abundant at Installation A in this depth band. Between 45-50 m, fouling scars and egg masses were far more dominant at Installation B; however, barnacles were significantly more dominant at installation A (Figure 4).

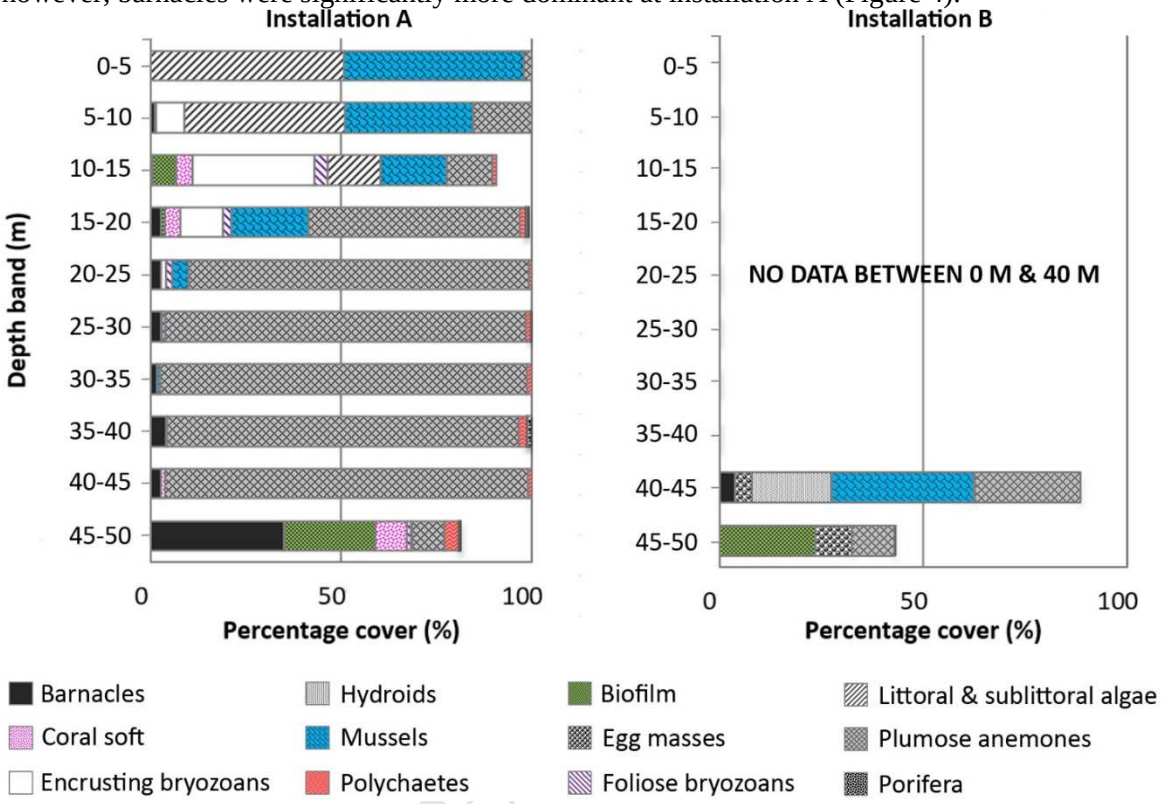


Figure 4. Mean percentage cover of sessile invertebrates present between depth bands (0-50 m) at Installation A and (40-50 m) at Installation B.

Motile invertebrate assemblages

At both Installations, the epibenthic community was dominated by *Asterias rubens, Echinus esculentus, Cancer pagurus* and *Pagurus bernhardus* sheltering amongst rock and beneath footings, followed to a lesser extent by *Ophiocomina nigra, Ophiothrix fragilis, Buccinum undatum* and *Eledone cirrhosa* (Figure 5). Most observed invertebrates were obligatory or facultative hard substrata species, similar to Krone et al. (2013a), which directly benefit from refuge (Krone et al., 2013a; Langhamer and Wilhelmsson, 2009; Page et al., 1999) and increased food availability (Krone et al., 2013b; Langhamer and Wilhelmsson, 2009) provided by such habitat.

Both installations provided substantial habitat heterogeneity compared to the relatively featureless sedimentary benthos. Shallower depth bands were utilised by motile invertebrates, predominantly *A. rubens, E. esculentus* and *C. pagurus;* however, abundance was negligible compared to epibenthic assemblages. Greatest motile invertebrate assemblage *species richness (S)*, *abundance (N)*, and *diversity (H')* occurred within the 45-50 m depth band at installation A (Table S5). At Installation B, highest motile invertebrate *S*, *N* and *H'* was also observed at 45-50 m; however, expressed marginally lower *S* and considerably lower *N* and *H'* than Installation A (Table S5). The epibenthic community was again dominated by *A. rubens*, closely followed by *P. bernhardus* and *B. undatum* with rare occurrences of *C. pagurus, E. esculentus, Pandalus montagui* and *Sepiola atlantica* (Figure 5). The second greatest *N* was expressed at Installation A

between 40-45 m; however, as only *C. pagurus* was observed (Figure 5) both *S* and *H'* were comparatively low (Table S5). Installation B at 40-45m conveyed slightly lower N, although, expressed greater *S* and *H'* as both *A. rubens* and, to a lesser degree, *Liocarcinus depurator* were present (Figure 5). At Installation A, 0-40 m motile invertebrate *S*, *N* and *H'* were significantly lower compared to that of 40-50 m (Table S5). *C. pagurus* expressed greatest abundance, observed between 5-40 m sheltering amidst anemones, sponges and soft corals, particularly amongst the undersides of horizontal members and nodes (Figure 5). *E. esculentus* was second most abundant, although, was only observed between 20-40 m on the newly installed conductor five (Figure 5). A single *A. rubens* was also observed at 15-20 m (Figure 5).

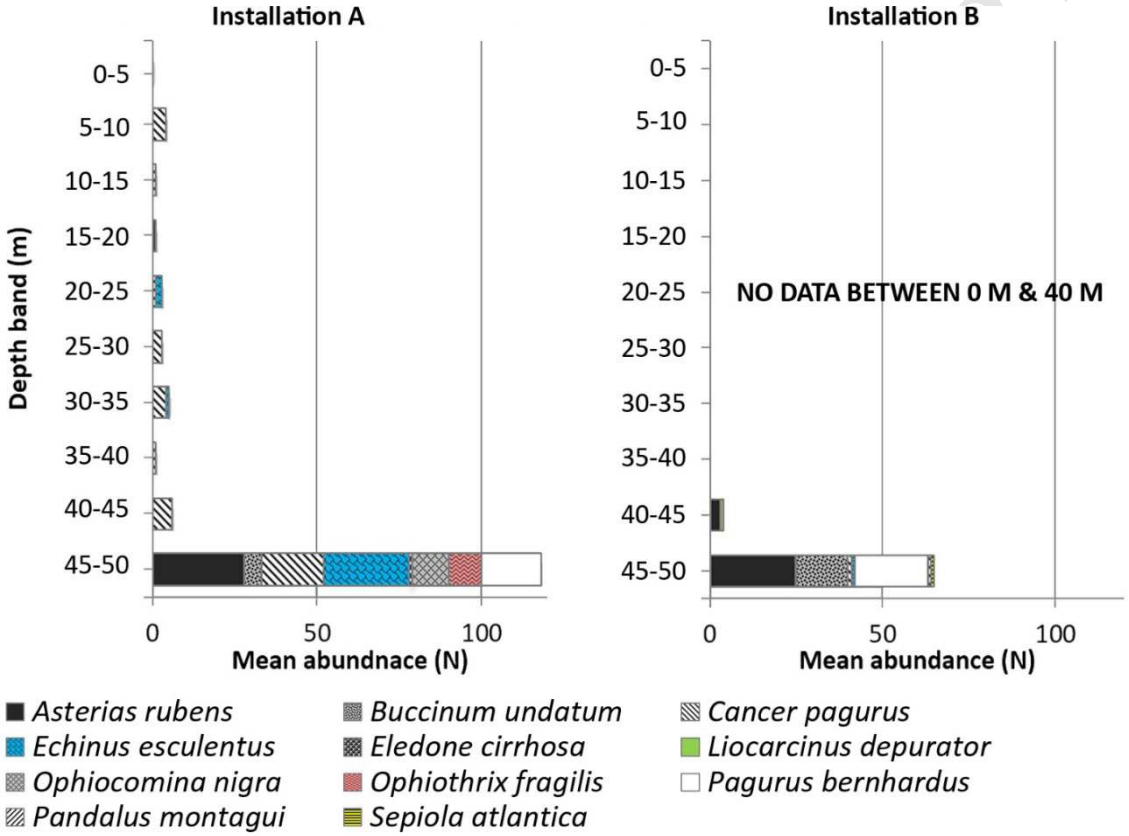


Figure 5. Mean abundance (N) of motile invertebrate species present at depth bands (0-50m) at Installations A and B.

Fish assemblages

The epibenthic fish community was dominated by shoals of *Gadus morhua* and to a lesser degree *Pollachius pollachius* and *Molva molva* all in close association with the footings and lower members. *Limanda limanda* were also seen in low numbers but were most frequently observed away from artificially placed rock areas upon soft sediment (Figure 6). Greatest fish assemblage *S*, *N* and *H'* was observed between 45-50 m at installation A (Table S6), followed by 45-50 m at installation B (Table S6). In the absence of artificially-placed rock, *L. limanda* were dominant, often observed in close association with spudcans. Juvenile *G. morhua* were also present in small numbers, always seen sheltering in close association with the Installation (Figure 6).

Differences in substrata around the installations is likely to drive the variation in fish assemblage abundance and diversity. Gadoid juveniles preferentially select structurally complex habitat (Sayer et al., 2005), which, in addition to jacket design and structurally complex fouling, was provided by artificially placed rock surrounding Installation A, whereas sedimentary substratum surrounding Installation B was more conducive to supporting *L. limanda*, an obligate sedimentary benthic species (Gibson, 1997). Abundance of juvenile gadoids supports suggestions

that installations may act as nursery areas (Claisse et al., 2014; Love et al., 2006; Sayer et al., 2005; Scarborough-Bull et al., 2008); however, without site fidelity studies, such as those by Jørgensen et al. (2002), a conclusive outcome remains tenuous. Observation of *C. lumpus* brooding eggs on Installation B does provide relatively unambiguous evidence of installations acting as vectors for reproduction and actively producing rather than merely attracting fish, as discussed by Bohnsack (1989) and Fujii *et al.* (2014).

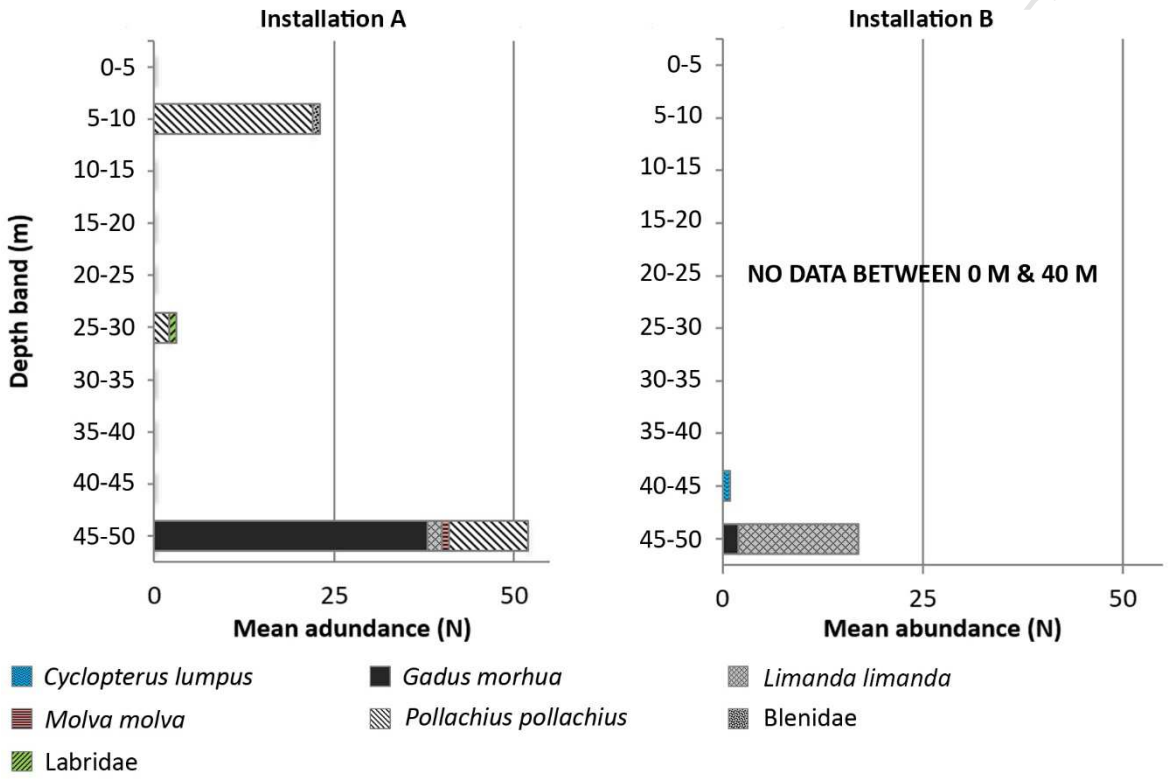


Figure 6. Mean abundance (N) of fish species present at depth bands (0-50 m) at Installation A and B.

On 25 November 2014, two *Cyclopterus lumpus* specimens were discovered simultaneously by crew, lying on the mezzanine deck of Installation A; one specimen was orange and one was blue (Figure S1). Unfortunately, the orange specimen was discarded by crew pre-examination, but the blue specimen was retrieved, and meristics and morphometrics taken using Vernier callipers (Mitutyo, Japan), as per Todd and Grove (2010). The specimen had been lying on deck for an unknown period and was thus slightly desiccated. Consequently, weight was not taken. Sex was also not determined internally. Crew believed both specimens had been caught at the water surface, and dropped onto the platform, by European herring gulls, *Larus argentatus*. Crew further commented that *C. lumpus* is 'common' around their platform, and fish are dropped regularly on deck by seabirds.

On 6 April 2014 a single male *C. lumpus* was observed tending to three separate broods of eggs affixed to horizontal members of Installation B within the 40-45 m depth band. The male expressed distinct orange/red colouration dorsally and blue ventrally, typical during spawning (Davenport and Thorsteinsson, 1989), whilst egg masses expressed white and orange colour variations (Figure 7). This observation of reproduction by *C. lumpus* at the O&G complex has implications for the potential role of the Installations as sites of fish *production* (sensu 'attraction vs production' debate).

C. lumpus is a cold water, marine, benthopelagic, oceanodromous fish (Coad and Reist, 2004; Cox and Anderson, 1922; Riede, 2004), valued commercially for its flesh and eggs (Davenport, 1985; Frimodt, 1995; Mitamura et al., 2011). *C. lumpus* are predominantly solitary

fishes with a strong homing instinct (Davenport, 1985). They migrate considerable distances in an annual cycle between deeper offshore waters in winter and shallower coastal waters in summer (Kennedy et al., 2015; Möller, 1977). On contact with seawater, eggs adhere to one another to form large, masses up to 26 cm x 10 cm x 10 cm (Zhitenev, 1970 cited in Davenport 1985).

To date, there are no records of *C. lumpus* spawning at such depth and distance from the coastline, and this is the first published evidence of this species using offshore structures as spawning sites. This finding provides evidence that offshore installations may act as vectors for reproduction and actively produce, rather than merely attract fish, as discussed by Bohnsack (1989) and Fujii et al. (2014).

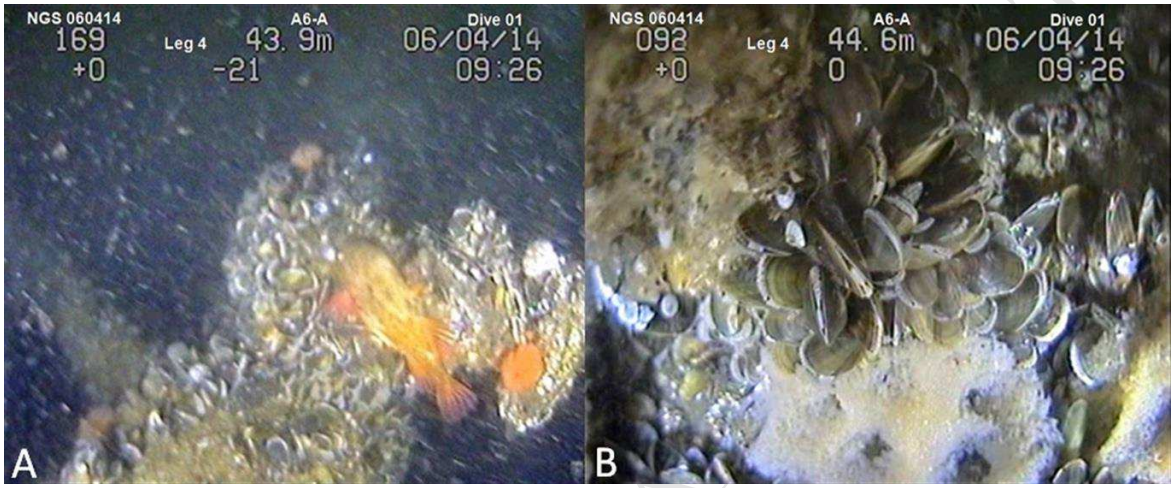


Figure 7. Still images extracted from ROV footage of Installation B. A = a single male *C. lumpus* guarding three broods of eggs; and B = close up of a single *C. lumpus* brood laid amongst a cluster of *Mytilus edulis.*

CONCLUSIONS

The Rigs-to-Reefs (RTR) paradigm remains controversial (Fowler et al., 2014; Jørgensen, 2012; Macreadie et al., 2012); however, a renaissance in RTR research is starting to elucidate intricacies and importance of installation ecology (Fujii and Jamieson, 2016; Macreadie et al., 2018; McLean et al., 2017; Pradella et al., 2014). The findings of this study show that certain well-placed installations support diverse sessile fouling communities which can provide food and refuge to considerable populations of motile invertebrates and fish. Findings confirm that gadoid juveniles and some obligate hard substrata-reproducing species utilise installations as vectors for reproduction, as suggested by Sayer et al. (2005). Installations surrounded by exclusion zones can act as *de facto* marine protected areas (Macreadie et al., 2011) which have potential to aid conservation of endangered sessile invertebrates (Bergmark and Jørgensen, 2014), ichthyofauna including sharks, and marine mammals (Todd et al., 2009a; Todd, 2016). Additionally, adjacent stocks of commercially-exploited species including *G. morhua*, *C. lumpus*, *C. pagurus* and *B. undatum*, may be augmented, as suggested by Sayer et al. (2005) and Fujii et al. (2014), potentially to the benefit of fishermen (Baine and Side, 2003).

Improved understanding of installation ecology provides the scientific basis for the formulation and implementation of environmentally beneficial decommissioning strategies (Macreadie et al., 2011); however, installation communities are inherently dynamic (Whomersley and Picken, 2003) and vary considerably between geographical location, depths, structural design and orientation (Forteath et al., 1982; Guerin, 2009; Guerin et al., 2007; Krone et al., 2013b; Southgate and Myers, 1985; Terry and Picken, 1986; Whomersley and Picken, 2003); therefore, derogation of current legislation should be considered case-by-case on the premise of multi-criteria evaluation (Fowler et al., 2018), taking into account environmental, social and economic outcomes, as suggested by Jørgensen (2012), Macreadie et al. (2012) and Fowler et al. (2014).

In summary, the oil and gas (O&G) Installation complex in the Dogger Bank Special Area of Conservation (SAC), in the North Sea, Germany, attracts and supports diverse and abundant invertebrate and fish populations, which vary due to depth and time *in situ*. The abundance of life

435 coupled with observations of organisms using installations as vectors for reproduction, notably the
436 first reported use of an anthropogenic structure for *C. lumpus* brooding, demonstrates potential
437 ecological benefit from the implementation of a rigs-to-reefs decommissioning regime (possibly
438 with implications for fisheries, ecotourism, and biodiversity) within the North Sea. Comparable
439 information from installations in different geographical locations is required to reinforce this
440 theory. To formulate a decommissioning strategy with the greatest ecological benefit, we
441 recommend: 1) further research using higher quality images allowing identification to species level
442 and quantification of smaller inconspicuous organisms; 2) investigating organism dependency over
443 both spatial and temporal scales; and 3) research into the role of these installations as vectors for
444 dispersal. The findings of this study should be considered upon review of North Sea installation
445 decommissioning legislation by OSPAR in 2018.
446
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451
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720 **SUPPLEMENTARY MATERIAL**

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722 **Table 1.** Fouling invertebrate categories in addition to key species, families, and orders.

Fouling category	Scientific name/category constituents
Barnacles	*Balanus balanus, Semibalanus balanoides* & *Balanus crenatus*
Biofilm	N.A.
Coral hard	*Lophelia pertusa*
Coral soft	*Alcyonium digitatum*
Egg masses	*Cyclopterus lumpus* & *Buccinum undatum*
Encrusting bryozoans	*Membranipora membranacea*
Exposed metal	Un-colonised areas of sub-surface structure
Foliose bryozoans	*Omalosecosa ramulosa* & *Flustra foliacea*
Fouling scars	Deceased calcified fouling (barnacles & tube worms), residual structures & blemishes
Hydroids	*Tubularia larynx*
Littoral & sublittoral algae	*Ulva lactuca, Ulva intestinalis, Cladophora rupestris* & *Polysiphonia* spp.
Mussels	*Mytilus edulis* & *Modiolus modiolus*
Other anemones	*Urticina* spp. & *Sagartia* sp.
Plumose anemones	*Metridium senile senile* & *Metridium senile pallidus*
Polychaetes	*Pomatoceros triqueter* & *Protula tubularia*
Porifera	*Suberites ficus* & *Myxilla* sp.

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725 **Table S2:** List of all taxa observed at installations A and B.

Phylum	Family, genus or species	Installation A	Installation B
Annelida	*Pomatoceros triqueter*	X	-
	Protula tubularia	X	-
Bryozoa	*Flustra foliacea*	X	-
	Omalosecosa ramulosa	X	-
	Membranipora membranacea	X	-
Chlorophyta	*Cladophora rupestris*	X	-
	Ulva lactuca	X	-
	Ulva intestinalis	X	-
Chordata	*Ammodytes tobianus*	-	X
	Anarhichas lupus	-	X
	Blenniidae	X	-
	Cyclopterus lumpus	-	X
	Gadus morhua	X	-
	Labridae	X	-
	Limanda limanda	X	X
	Molva molva	X	-
	Pollachius pollachius	X	X
	Solea solea	-	X
Cnidaria	*Alcyonium digitatum*	X	X
	Metridium senile senile	X	X
	Metridium senile pallidus	X	X
	Urticina sp.	X	-
	Sagartia sp.	X	-
	Tubularia larynx	X	X
Crustacea	*Balanus balanus*	X	X
	Balanus crenatus	X	X
	Cancer pagurus	X	X
	Liocarcinus depurator	X	-

	Necora puber	X	X
	Pagurus bernhardus	X	X
	Pandalus sp.	-	X
	Semibalanus balanoides	X	X
Echinodermata	*Asterias rubens*	X	X
	Echinus esculentus	X	X
	Ophiothrix fragilis	X	-
	Ophiocomina nigra	X	-
Mollusca	*Buccinum undatum*	X	X
	Eledone cirrhosa	X	-
	Modiolus modiolus	X	-
	Mytilus edulis	X	X
	Sepiola atlantica	-	X
Porifera	*Myxilla* sp.	X	-
	Suberites sp.	X	-
Rhodophyta	*Polysiphonia* sp.	X	-

Table S3. Results of SIMPER analysis outlining average abundance and contribution to overall similarity of key fouling categories in addition to overall similarity within samples at each depth band at Installation A. Shaded cells show average category abundance and non-shaded show percentage contribution to overall similarity.

	0-5m	5-10m	10-15m	15-20m	20-25m	25-30m	30-35m	35-40m	40-45m	45-50m
Algae	71.1%	65.0%	30.0%	-	-	-	-	-	-	-
	50.0%	41.1%	13.9%	-	-	-	-	-	-	-
Barnacles	-	-	-	-	-	-	-	-	15.0%	58.0%
	-	-	-	-	-	-	-	-	10.6%	31.6%
Biofilm	-	-	-	-	-	-	-	-	-	46.0%
	-	-	-	-	-	-	-	-	-	23.5%
Encrusting bryozoans	-	-	48.0%	-	-	-	-	-	-	-
	-	-	27.8%	-	-	-	-	-	-	-
Fouling scars	-	-	-	-	-	-	-	-	-	36.0%
	-	-	-	-	-	-	-	-	-	19.2%
Mussels	68.0%	58.0%	36.0%	37.0%	-	-	-	-	-	-
	47.6%	36.3%	20.7%	23.6%	-	-	-	-	-	-
Plumose anemones	-	36.0%	30.0%	73.0%	94%	97.0%	98.0%	96.0%	98.0%	-
	-	17.4%	17.5%	68.9%	85.7%	90.4%	88.4%	91.6%	88.0%	-
Overall similarity	89.3%	80.1%	49.4%	56.2%	77.9%	84.6%	90.6%	81.9%	88.6%	69.1%

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733 **Table S4.** Results of SIMPER analysis outlining average abundance and contribution to overall similarity of
734 key fouling categories in addition to overall similarity within samples at each depth band at Installation B.
735 Shaded cells show average category abundance and non-shaded show percentage contribution to overall
736 similarity.
737

	40-45m	45-50m
Algae	-	-
	-	-
Barnacles	18.0%	-
	12.5%	-
Biofilm	-	43.0%
	-	16.5%
Egg masses	-	29.0%
	-	15.1%
Encrusting bryozoans	-	-
	-	-
Exposed metal	-	35.0%
	-	17.5%
Fouling scars	31.0%	66.0%
	21.3%	34.6%
Mussels	48.0%	-
	22.9%	-
Plumose anemones	48.0%	32.0%
	36.2%	16.2%
Overall similarity	51.3%	82.9%

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740 **Table S5.** Alpha diversity indices of motile invertebrate assemblages present at depth bands (0-
741 50m) at Installation A and B.

	Species richness (S)		Abundance (N)		Diversity (H')	
	Installation A	Installation B	Installation A	Installation B	Installation A	Installation B
0-5m	0	-	0	-	0.00	-
5-10m	1	-	4	-	0.00	-
10-15m	1	-	1	-	0.00	-
15-20m	1	-	1	-	0.00	-
20-25m	2	-	3	-	0.64	-
25-30m	1	-	3	-	0.00	-
30-35m	2	-	5	-	0.50	-
35-40m	1	-	1	-	0.00	-
40-45m	1	2	6	4	0.00	0.56
45-50m	8	7	118	65	1.86	1.33

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744 **Table S6.** Alpha diversity indices of fish assemblages present at depth bands (0-50m) at Installation A and
745 B.

	Species richness (S)		Abundance (N)		Diversity (H')	
	Installation A	Installation B	Installation A	Installation B	Installation A	Installation B
0-5m	0	-	0	-	0.00	-
5-10m	2	-	23	-	0.18	-
10-15m	0	-	0	-	0.00	-
15-20m	0	-	0	-	0.00	-
20-25m	0	-	0	-	0.00	-
25-30m	2	-	3	-	0.64	-
30-35m	0	-	0	-	0.00	-
35-40m	0	-	0	-	0.00	-
40-45m	0	1	0	1	0.00	0
45-50m	4	2	52	17	0.76	0.36

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750 **Figure S1.** Photographs and measurements of *C. lumpus* specimen retrieved from Installation A. A = Lateral view
751 measuring posterior to anterior; B = lateral view measuring dorsal to ventral; C = posterior view measuring laterally; and
752 D = ventral sucker.
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Highlights

- Decommissioning of North Sea oil and gas infrastructure is a £40 billion liability
- We assessed fish and invertebrate habitat value of a North Sea oil and gas complex
- A diverse range of reef-dependent and transient pelagic species were observed
- Clear depth zonation occurred, helping inform *in situ* decommissioning strategies
- Evidence of reproduction suggests the complex was producing fish-invertebrates

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