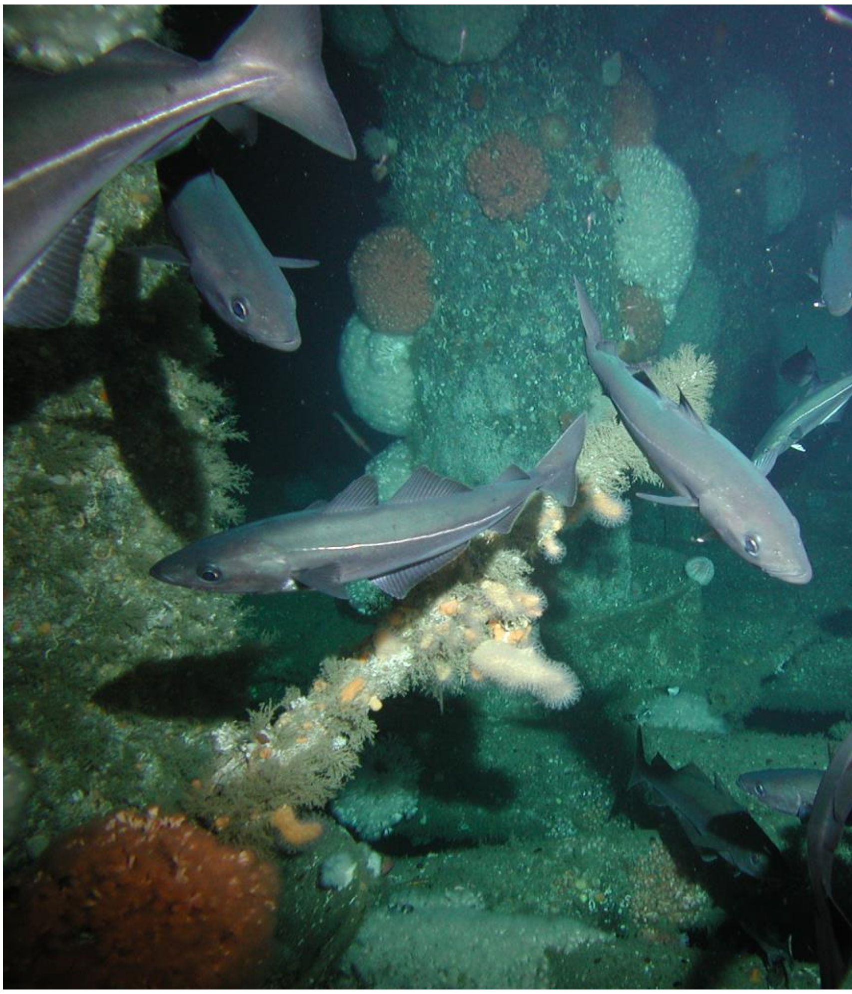
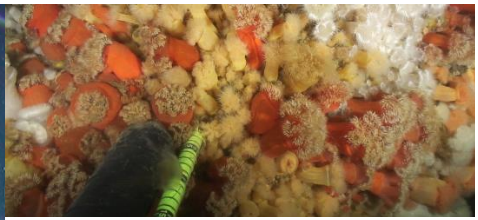
SUMMARY REPORT

ANCHOR • PROJECT





Project Deliverable

Prepared for INSITE's Independent Scientific Advisory Board and INSITE Sponsors

Version 1 – September 2017

Cover Image Credits

Larger image –

The protected stony coral *Lophelia pertusa* and other marine growth epifauna occurring with dense aggregations of the fish *Pollachius virens* around North Sea oil and gas installations. Original photograph courtesy of Lundin Britain Ltd. Reproduced from "Cold-Water Corals: The Biology and Geology of Deep-Sea Coral Habitats", by J.M. Roberts, A. Wheeler, A. Freiwald, and S. Cairns, Cambridge University Press, 2009.

Smaller image –

File photo North Sea marine growth.

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TITLE

ANChor:
Appraisal of Network Connectivity between North Sea oil and gas platforms

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SUMMARY

The ANChor project applied cross-cutting scientific techniques phased over the project (**model build-up**, **simulation**, **optimisation**) to illustrate the potential for oil and gas installations in the North Sea to create its own hard substrate system and the magnitude of effects this has had on the wider regional ecosystem. ANChor focussed on 5 animal species native to the North Sea including the blue mussel *Mytilus edulis*, the barnacle *Chirona hameri*, the stony coral *Lophelia pertusa*, the soft coral *Alcyonium digitatum*, and the anemone *Metridium senile*. This selection ensured that ANChor covered a range of species with different dispersal abilities so that a deeper understanding of how connectivity is mediated by the animals themselves.

Model-build-up involved scenario-testing effects of the North Atlantic Oscillation on larval dispersal, leading to ANChor's early decision to adopt the base-case scenario under a "low flow" regime to conservatively estimate connectivity. Real industry marine growth data from 66 distinct oil and gas structures across the North Sea were analysed to identify representative species, determine what depths these animals typically live on the structures and on which ones. Computer **simulations** that tracked the movements of virtual larvae were run using high-resolution oceanographic models configured with species-specific larval behaviours seeded from oil and gas installations in the North Sea that met each species' depth-criteria. For the protected coral *L. pertusa*, these simulations were run across a range of NAO states just to demonstrate the potential for these structures to act as sources for downstream natural populations. Larval tracks were used to estimate connectivity metrics and construct maps of connectivity between structures but also to the wider North Sea ecosystem. These maps were used for **optimisations**, which found the most coherent set of oil and gas structures that would keep the man-made network connected. The final part of the optimisation phase is now underway, with decommissioning scenarios being run to understand effects of management options on network structure, particularly with respect to the structures identified as part of the coherent set.

Simulations delivered evidence for both INSITE objectives and can provide bespoke information for operators and regulators. First, results showed that oil and gas structures have not only formed an inter-connected system of hard substrate ecosystems even under a low flow regime, but that connectivity highly depended on species' biology. Second, populations on oil and gas structures have the potential to affect regional ecosystems downstream, particularly protected species of coral on platforms that have the potential to reach naturally occurring populations in the deep sea, continental shelf, fjords and even a coral marine protected area in Norwegian waters. New network maps and optimisation approaches were developed that can be used to provide much needed information on importance of structures as part of the industry regulatory processes.

RATIONALE

Living and non-living resources in the North Sea have been exploited for millennia, and the region is rapidly undergoing climate change including warming sea surface temperatures and acidifying oceans. North Sea ecosystem dynamics will be tracking shifts in resource exploitation as well as climate change, but the cumulative ecosystem impacts at the scale of the North Sea are not well understood. The large-scale distribution of oil and gas infrastructure on the seafloor of the North Sea offer unique *in situ* “observatories” from which this scientific understanding can advance, as these structures may now be playing a significant role in the structure and functioning of the North Sea ecosystem.

In line with the more specific goals of the INSITE programme, the ANChor project set out to understand whether these structures now form a novel inter-connected hard substrate ecosystem in the North Sea, and what magnitude these structures are having on the wider regional ecosystem and its resilience to climate change and man-made impacts. ANChor also explored new approaches to optimise how one would keep networks of hard substrate ecosystems connected under future decommissioning scenarios. The method relies on the idea of a Pareto Front. Solutions that lie on this front are termed Pareto optimal, where improvement can only be made at additional cost, and whereby reducing cost inevitably produces a worse outcome.

PRODUCTS FOR SPONSORS

ANChor’s results can provide new products to help sponsors meet regulatory requirements such as Environmental Impact Assessments, Environmental Assessments and Comparative Assessments, etc., but also for sponsors to meet any of their own needs.

ANChor’s suite of maps for each species is bespoke for each of the 8 INSITE Phase I sponsors. Each map shows the potential ecological connectivity of the sponsor’s full suite of structures across their North Sea offshore asset portfolio (see section on Bespoke Connectivity Maps for Sponsors). Should a sponsor wish, ANChor can now provide each sponsor with all data for a specific structure as well. This information illustrates the potential for 5 representative marine growth species from a particular structure to disperse to other oil and gas structures, and thus the importance of that structure in the whole hard substrate network.

ANChor also analysed real marine growth data from structures. Permissions to use these are still being sought, however, these maps based on actual observations from the sponsor’s structures are also available at the sponsor’s request.

METHODS

The ANChor team comprised a multidisciplinary group of experts that ensured the project applied a combination of methods to achieve its contributions towards INSITE objectives.

Phase 1: Model build-up

Marine Growth Inventory Compilation (BMT Cordah and University of Edinburgh)

BMT Cordah maintain an internal unpublished reference database of marine growth on offshore platforms. The first year of ANChor was therefore an intensive period of compilation and quality assurance of remotely operated vehicle (ROV) and diver video/images using these data (*N*=57 surveys, 2 from the same structure, therefore *N*=56 distinct structures; Appendix Table 1). Additional data were added from a literature review and private samples held at the University of Edinburgh (*N*=9; Appendix Table 2) and analysis of marine growth on a structure (*N*=1) that was collected directly at the operator's office during ANChor. This yielded data on 5 representative marine growth species down to species-level (important in order to be confident in assigning life history traits that affect the virtual larval simulations), distributional depth ranges on the structures, and an inventory of a total of 66 distinct North Sea structures that were used to inform the virtual larval simulations conducted in ANChor.

However, ANChor's new marine growth inventory database cannot yet be made publicly available at this time, with the database having to be anonymised in the ANChor project and any ANChor output in order to maintain operator and structure anonymity until all permissions are secured. Each operator with surveys in BMT Cordah's inventory were contacted to request permission to publish and share the locations, names of structures, and depth distribution of the 5 species on each structure. To date, 3 operators have not responded, while most were happy to share data. One operator was happy to share data but requested to see drafts of any outputs first to give them time to review, and another has requested a non-disclosure agreement that is now underway. Another operator was happy to share data but only that which is already in publicly available documents.

Compilation of Life History Traits (University of Edinburgh)

Life history information for selected marine growth species (post-larval or propagule duration, time to competency, timing of larval or propagule release, vertical migration behaviour) was compiled from the literature in order to make the simulations biologically realistic (Table 1; Appendix Table 3). This also allowed ANChor to consider the more academic question around how life history traits mediate connectivity.

Table 1: Life history trait matrix that informed ANChor's virtual larvae simulations.

	Lophelia	***Alcyonium***	***Mytilus***	***Chirona***	***Metridium***
Total # particles released	61180	166376	408408	283374	218736
Pre-competency period (days)	32	10	20	10	15
Competency period (days)	28	8	10	8	7
Planktonic larval duration (days)	60	18	30	18	22
Spawning season	Jan-Feb	Dec-Jan	Apr-Sep	Mar-May	Aug-Sep
References	www.marlin.ac.uk/biotic; Larsson et al., 2014; Strömberg, 2016	www.marlin.ac.uk/biotic; Hartnoll, 1975	www.marlin.ac.uk/biotic; Sprung, 1984; Fuchs and DiBacco, 2011	www.marlin.ac.uk/biotic; Rainbow, 1984; DiBacco et al., 2011; Miller et al., 2013 compiled data from various sources; these are mostly observations from other barnacle species including *Semibalanus balanoides*	www.marlin.ac.uk/biotic; Scott and Harrison, 2007 for the anemones *Entacmaea quadricolor* and *Heteractis crispa*

Scenario-testing different ocean states **(University of Edinburgh, Heriot-Watt University)**

It was suspected early on that the North Atlantic Oscillation (NAO) would affect connectivity patterns. In western Europe and the North Sea, sub-decadal variability in large-scale air-sea interactions create different annual positive/negative states of the NAO (Reintges et al., 2017) that could profoundly affect network connectivity by increasing/decreasing the strength and direction of westerly winds and the import of Atlantic waters into the North Sea. Effects of inter-annual NAO variability were examined using virtual larval simulations, seeding larvae from marine protected areas (MPAs) in UK waters including North Sea MPAs with oil and gas installations. At this time, ANChor's high-resolution 1.8km NEMO model had not been configured, so the coarser resolution POLCOMS 7km Atlantic Margin Model (AMM) was used (see Fox et al., 2016 for more details). To test effects of NAO state on larval dispersal, Pearson's correlation coefficients between numbers of larvae crossing a section of the North Sea each year and the NAO index were calculated. All calculations were implemented in Python code using matplotlib, shapely and scipy packages.

Phase 2: Simulation

Biophysical model experiments (National Oceanography Centre)

ANChor's study area was constrained to the greater North Sea region. A published list of offshore oil and gas installations (OSPAR, 2015) was used to generate an initial list of structures. Using information from the marine growth survey analyses, a final list of structures for each species was selected to run the experiments from, based on whether the mean depth range of the species was less than the water depth of the structure, e.g., structures more shallow than 80 m water depth were not used in the *Lophelia* experiments (mean depth 80-113m, Table 2).

Table 2: Details on how larvae were seeded for the simulations across the different species.

	L. pertusa	*A. digitatum*	*M. edulis*	*C. hameri*	*M. senile*
# Structures meeting depth criteria	308	732	733	591	733
# Particles seeded in total	61180	166376	408408	283374	218736
Depth range seeded (m)	80-113	15-52	4-24	28-89	6-55

Connectivity maps and metrics were compared across species to determine what effects species' biology has in dispersal patterns from oil and gas structures.

Virtual larval experiments released from oil and gas structures (National Oceanography Centre)

The Nucleus for European Modelling of the Ocean (NEMO) Atlantic Margin Model 1/60° (AMM60) was used to run the virtual larval simulation experiments in ANChor. AMM60 is an ocean circulation model of the northwest European shelf with approximately 1.8 km horizontal resolution. It has 51 hybrid-σ-vertical fields, realistic bathymetry from GEBCO, and both atmospheric (ERA-interim) and tidal (TPXO7.2) forcing (Guihou et al., in prep.).

NEMO-AMM60 was integrated with the Larval TRANSport Lagrangian model LTRANS v2 (Schlag and North, 2012). LTRANS v2 ran offline with the NEMO-AMM60 hydrodynamic predictions, and was integrated with realistic larval behaviours from Table 1. Due to the early resulting knowledge from Phase 1 (model build-up) about potential effects of the NAO on connectivity, it was decided to run the model using the year 2010 (a negative NAO with reduced current strength in the North Sea) as a base-case scenario of connectivity, which would produce the most conservative network. The exception to this rule was that for the protected coral species *L. pertusa*, experiments were run across an NAO cycle (2010, 2011, 2012) that covered a strong negative (2010) to positive states (2012).

All particle tracking experiments were run using the high performance computing ARCHER facility. Two installations were considered connected if larvae from one structure became competent to settle within a 1 km radius of the other structure. These data were compiled into a connectivity matrix of numbers of larvae connecting them for each pair of structures. The full particle trajectories for *L. pertusa* were also mapped out alongside data on Norwegian coral areas due to the global conservation interest of this species in order to determine the magnitude that oil and gas structures may have on naturally occurring ecosystems downstream.

Network analyses (University of Edinburgh)

Ecosystem-relevant metrics of network connectivity were conducted with the Python script package Networkx based on pairwise connectivity matrices from the dispersal experiments for each species in 2010, and in the case of *Lophelia*, across 3 years (2010-2012):

(1) Network topology: illustrated groups of highly connected structures;
(2) In- and out-degree: measures numbers of larvae coming in and leaving a structure from other structures;
(3) Centrality: measures how important individual structures are in terms of being the most well-connected to other well-connected structures;
(4) Betweenness: identifies structures that act as bridges between otherwise disconnected groups of structures.

Phase 3: Optimisation (University of Edinburgh, Heriot-Watt University)

Fox et al. (2017, in review) present a method for selecting optimal sub-networks based on optimisation algorithms that balance multiple criteria (e.g. costs of structure removal with the potential ecological benefits as proxied by connectivity measures) connectivity-based functions of the network. The results presented in this Summary Report apply to the network connectivity associated with a model species with passive (i.e., no behaviours) larvae and lifespan of 15 days, but calculations are now underway using the individual species' connectivity matrices generated in Phase 2 - simulations. Data are gridded simply to better illustrate the method. Pareto optimal solutions for this initial simplified approach were found using the Python code http://code.activestate.com/recipes/578230-pareto-front/ and plotted using the matplotlib package.

RESULTS

Connectivity of ecosystems on oil and gas structures

Species-specific differences

Topology maps created from the connectivity matrices illustrated the potential connectivity of the 5 species on oil and gas structures across the North Sea, with various degrees of clustering of highly connected structures (Figure 1), which has a strong inverse relationship with planktonic larval duration (Figure 2).

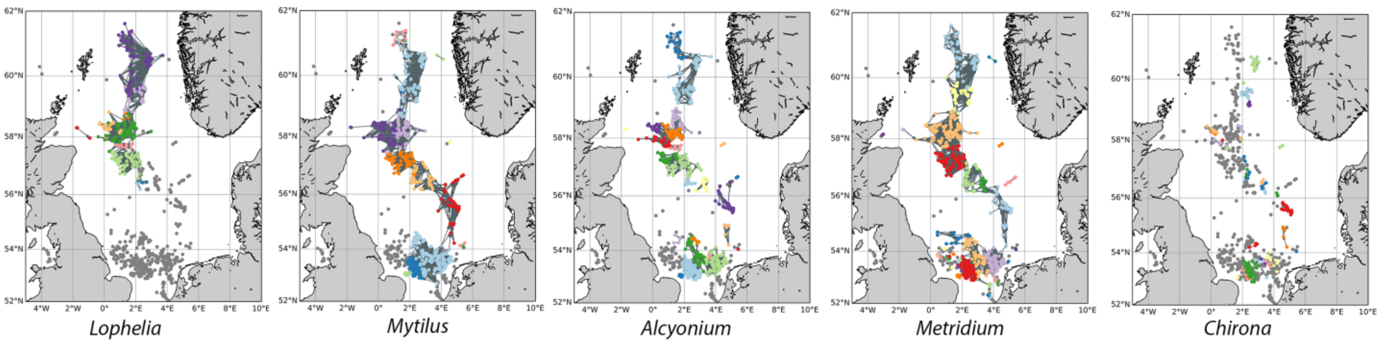


Figure 1: Connectivity of structures across the North Sea, showing links between structures as grey lines, with colour-coded clustering of the most highly connected structures (left to right: high connected to least connected species).

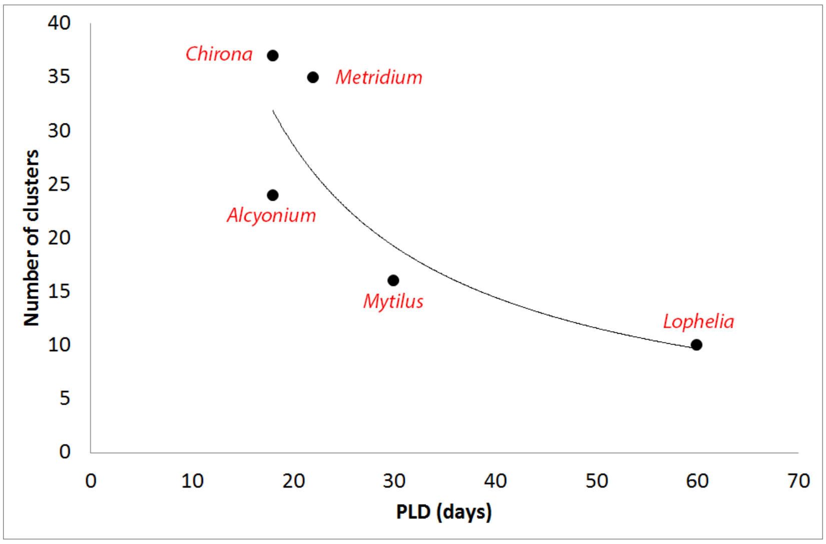


Figure 2: Number of clusters in the North Sea was strongly and inversely related to planktonic larval duration.

Structures acted as important bridges, but only for 2 species. Those in the southern North Sea were more important for keeping populations of *Alcyonium* connected (Figure 3). For *Lophelia* with its restricted northern distribution, structures in its southernmost range were more important (Figure 3).

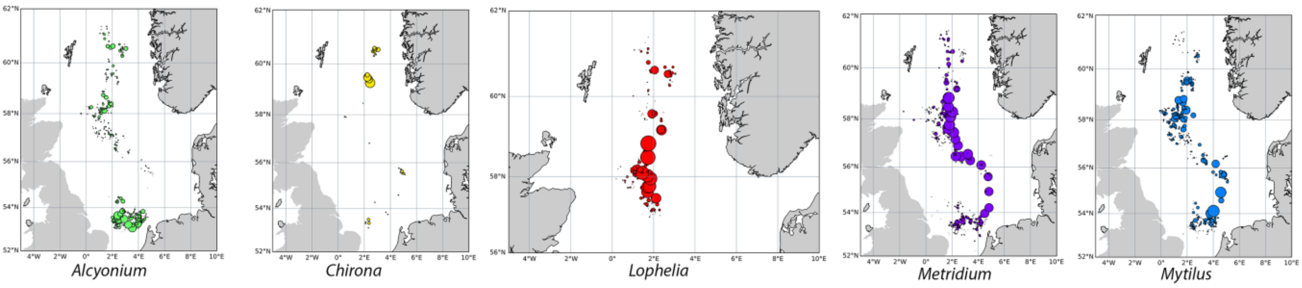


Figure 3: Betweenness of structures across species, with size of circle indicating importance of that structure as a bridge keeping the network connected. Circle size differed mostly for the 2 coral species, *Alcyonium* and *Lophelia*, indicating that some structures act as key bridges keeping coral networks connected.

For the sake of brevity in the Summary Report, only out-degree maps are shown here as these illustrate which structures are most important in supplying larvae to other structures, rather than just which ones receive the most from other platforms. Out-degree illustrated how over small spatial scales, the importance of structures as larvae "sources" was highly variable (Figure 4). The only larger scale pattern was that "sources" tended to be more in the longitudinal middle of the North Sea, whereas structures in the periphery (located closer to land) tended to be less important as larval sources for other structures.

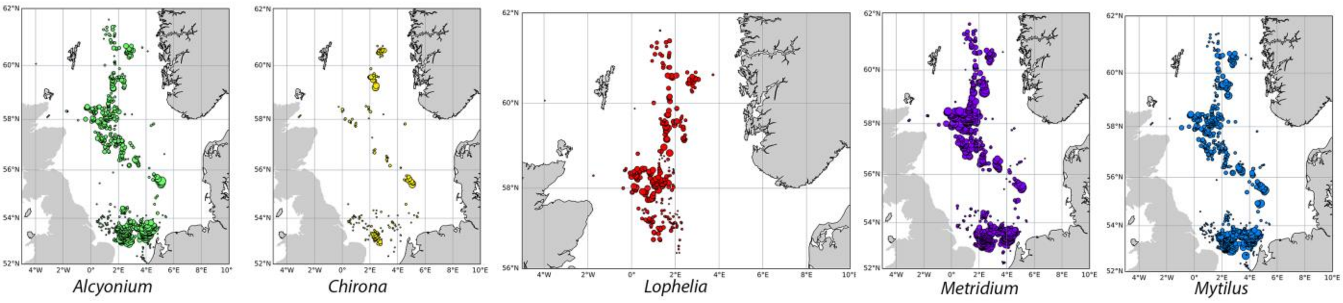


Figure 4: Out-degree of structures, with circle size indicating the importance of a structure as a source of larvae for other structures.

Across NAO states

Connectivity between MPAs with *Lophelia pertusa* showed a positive relationship with NAO state (see Results in Fox et al., 2016), with populations in the Atlantic connecting to North Sea populations, with the Norwegian Boundary Sediment Plain MPA connecting downstream to Scandinavia under strong positive NAO conditions (Fox et al., 2016). These results are not shown here in this Summary Report for the sake of brevity but they were used to set the year to 2010 in the virtual larval simulations. Instead, new results are presented showing how the man-made *Lophelia* network of oil and gas structures changes with NAO state, and how this network connects to naturally occurring populations downstream. Here, the network topology shows an increase in numbers of connections west to east, and a loss of connections in the north (Figure 5).

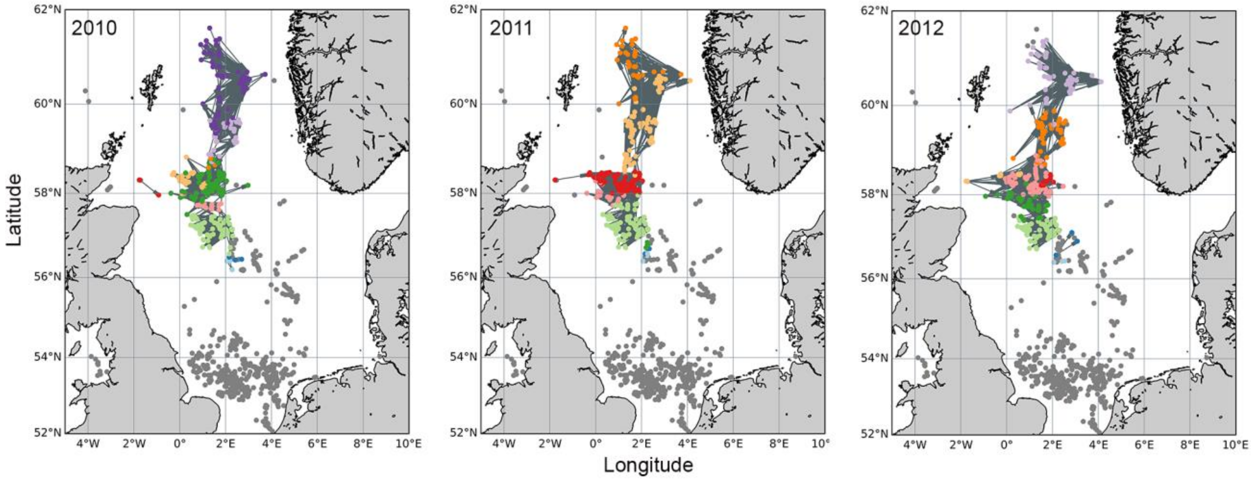


Figure 5: Network topology showing colour-coded clusters of highly connected North Sea installations configured for the protected stony coral *Lophelia pertusa* spanning a strong negative (2010) to positive NAO state (2012).

Plots of in-degree (Figure 6a) showed a lot of spatial heterogeneity in which clusters of installations received larvae relative to others (Figure 2a). However, in-degree became more equitably distributed across installations by 2012 (Figure 2a) when the network topology could be seen to have become more connected as west to east transport had increased (Figure 5).

Spatial trends in out-degree were less pronounced than in-degree, with the same clusters of installations generally supplying similar numbers of larvae to other structures over the time period 2010-2012 (Figure 6b). There was a weak but increasing trend in the southernmost installations and a single northern installation supplying more larvae by 2012 (Figure 6b), but on the whole, out-degree became even more equitable across clusters as west to east transport increased (Figure 5).

The extent to which installations were connected to other highly connected structures (centrality) strongly varied across years. This trend manifested itself as relative increases in the centrality metric in the southernmost installations, wherein these structures became far more highly connected by 2012 relative to structures further north where any signal of high centrality had dissipated (Figure 6c).

The relative importance of installations as bridges linking the different clusters (betweenness) strongly varied across years. Betweenness was highest in 2010, when the most southerly installations dominated as important bridges (Figure 6d). In 2011 and 2012 during the positive NAO spin-up, installations generally became more connected (Figure 5), making the network less dependent on installations that could bridge otherwise disconnected clusters.

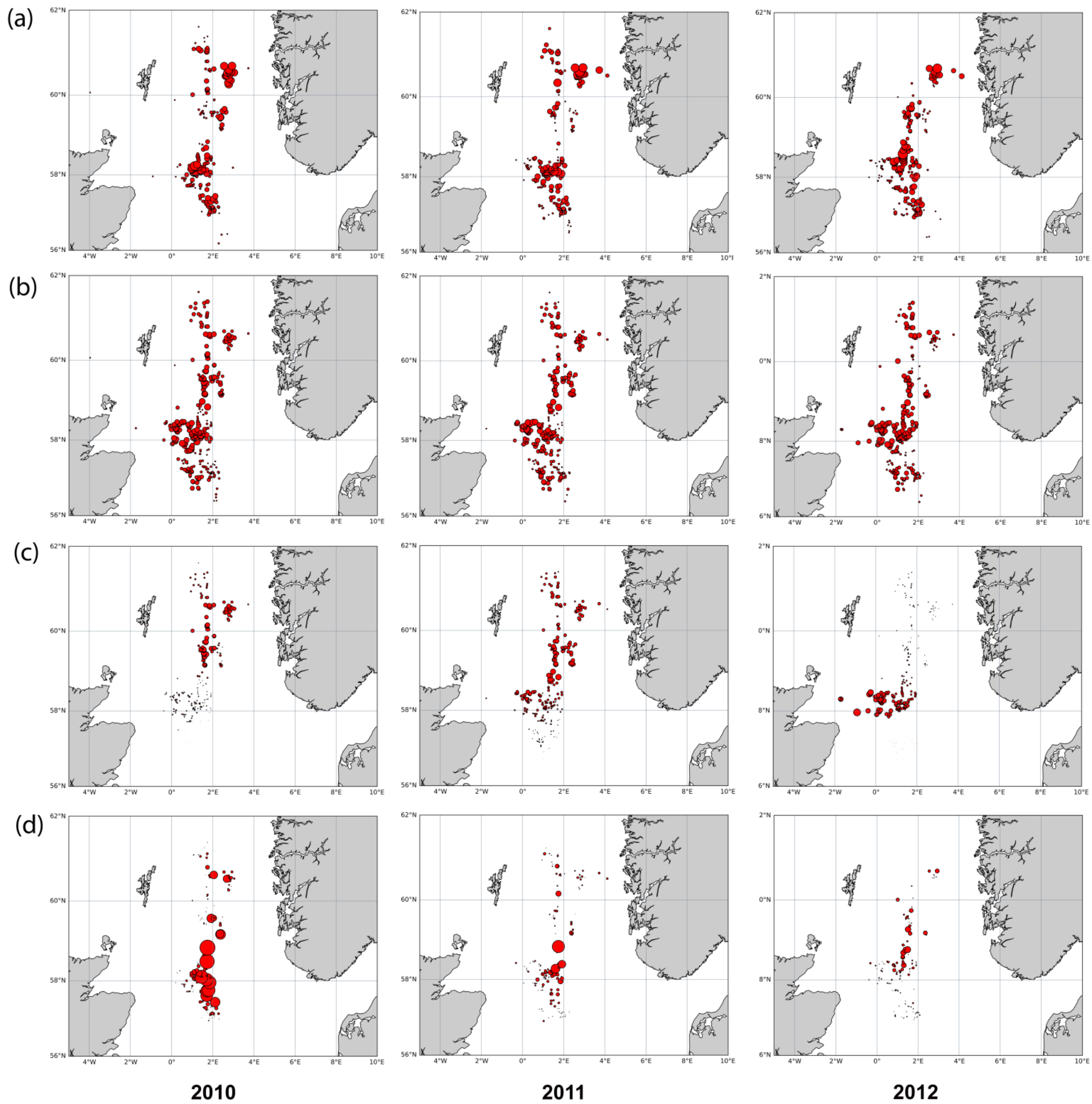


Figure 6: Metrics or (a) in-degree, (b) out-degree, (c) centrality, and (d) betweenness for the man-made network of *Lophelia pertusa* populations on oil and gas installations in the North Sea spanning a strong negative (2010) to positive NAO state (2012).

Optimal networks to maintain connectivity

The iterative Pareto solution approach identified an optimal set of gridded areas that, if kept in place and not removed, would keep the man-made network well connected. The optimal set found 40 areas, then next solution jumping up to 75 areas because the northern North Sea is not well-connected to the south, thus the next way to improve the network is to start including these well-connected northern sites (Figure 7).

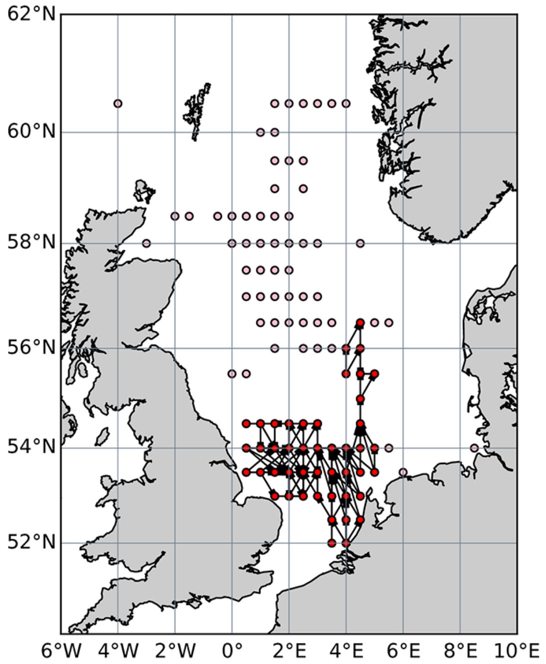


Figure 7: Optimal networks to keep a man-made network of hard substrate systems well connected. The best network retains many areas in the southern North Sea (left), the next best solution needing to include a total of 75 areas taking in the well-connected network in the north (right).

Impacts on the wider regional North Sea ecosystem

Maps of simulated particle trajectories in 2010, 2011, and 2012 illustrated the potential for larvae to reach distant geographic locations in the North Sea and beyond, crossing international borders from Great Britain to Norway. Simulated larvae became competent to settle over large geographical areas, particularly in 2012 (Figure 8) when larvae reached a variety of natural coral ecosystems including those in the deep sea, the continental shelf and in fjords (Figure 8).

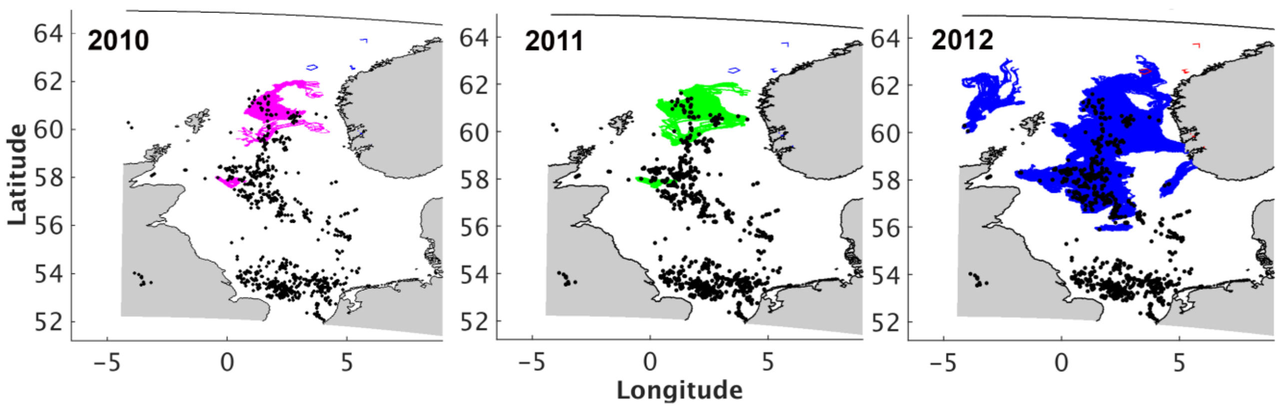
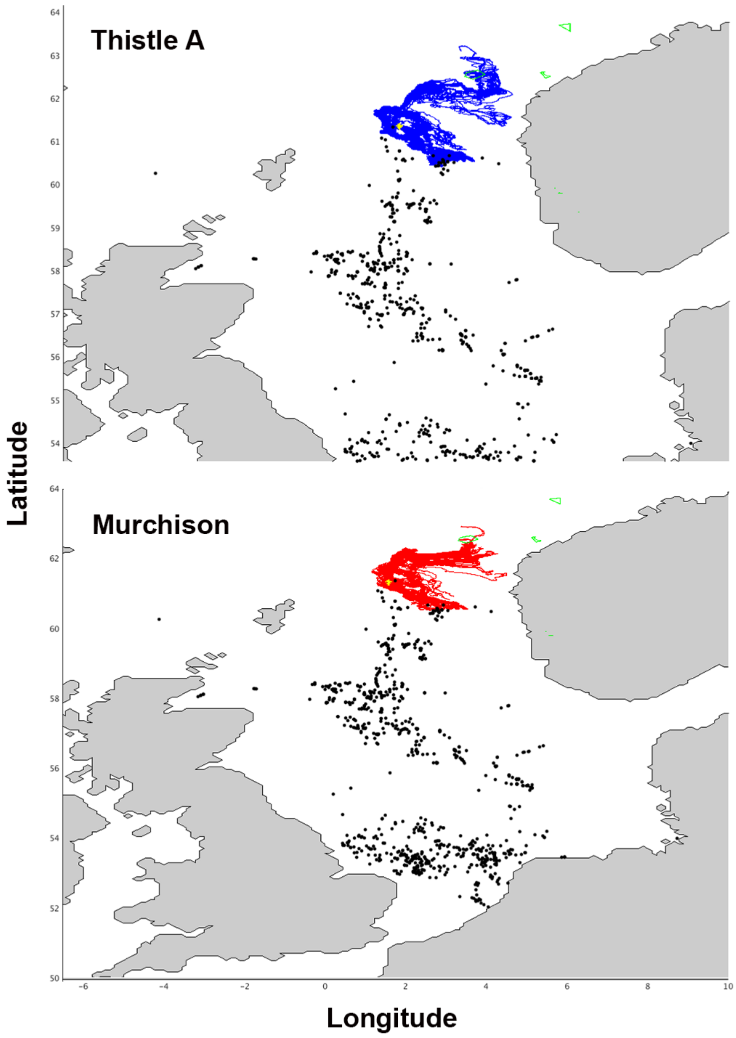


Figure 8: Larval trajectories from oil and gas structures supply larvae into areas with naturally occurring coral populations, particularly as the NAO becomes more positive from 2010 to 2012.

Exceptionally, in 2012, larvae seeded from two platforms (Murchison and Thistle Alpha) became competent to settle over Norway's Aktivneset coral marine protected area (Figure 9). To validate the possibility that platform corals from these two structures actually existed on the structures, ground-truthed observations of *Lophelia pertusa* colonising the Murchison and Thistle Alpha platforms were confirmed by inspection of unpublished industry ROV video and previous



publications (Gass and Roberts, 2006, 2011; CNRI, 2014; Shell UK Limited, 2017).

Figure 9: In 2012, larvae seeded directly from the Thistle A (top) and Murchison (bottom) platforms directly supply larvae in one generation into Norway's Aktivneset coral marine protected area designated to restore coral cover. Black dots are all oil and gas structures, the coloured clouds (blue and red) represent the larval trajectories. Small green polygons are Norwegian MPAs.

DISCUSSION

ANChor delivered supporting evidence for man-made structures having created a new type of hard substrate ecosystem in the North Sea that is also likely to positively impact naturally occurring ecosystems downstream. An optimisation approach was also developed (and is currently being fine-tuned) to illustrate the ideal network to keep in place on the seafloor that would keep the new man-made ecosystems connected.

ANChor delivery against INSITE objectives

To what extent, if any, the man-made structures in the North Sea represent a large inter-connected hard substrate system

Even under ANChor's base-case scenario of a low-flow regime in the North Sea, computer simulations illustrated the potential for several common species on oil and gas structures to form inter-connected networks. These ranged from highly connected ecosystems (the coral *Lophelia pertusa* and the mussel *Mytilus edulis*) to more fragmented rather dis-connected populations (e.g., the barnacle *Chirona hameri*). Of the species found throughout the North Sea (i.e., excluding *L. pertusa*), only *M. edulis* seemed to be highly connected, with the soft coral *Alcyonium digitatum* and the anemone *Metridium senile* to a lesser extent. In these latter two species, networks became more disconnected into northern, central and southern North Sea clusters.

Connectivity differences were strongly related to both species' phenology (i.e., spawning time) and biology (i.e., planktonic larval duration or PLD), with both *L. pertusa* and *M. edulis* having the longest PLD (60 and 30 days, respectively), and *C. hameri* having one of the shortest PLDs (18 days) but also being spawned in the spring (March to May) as opposed to the winter months (December to January) when the coral *Alcyonium digitatum* spawns but which also has an identical PLD (18 days). Notably both phenology and biology are likely to change under future climate change scenarios, with many marine species showing changes in reproductive timing with warming sea temperatures (Poloczanska et al., 2016): spring-blooming species tend to become reproductively mature earlier, while autumn-winter spawners tend to show a delay in reproductive activity. For winter spawners like *Lophelia* and *Alcyonium*, this could mean reduced dispersal potential in the future. Currently, A. digitatum in the North Sea appears to be panmictic (highly-connected), likely as a result of long-distance dispersal being facilitate by its winter spawning period when strong wind-driven currents can transport larvae a long way away (Holland et al., 2017). But in a warmer ocean, populations may become more fragmented because spawning, embryogenesis and larval development will then be taking place when the strong winter wind-driven currents will have slowed.

Using these networks, ANChor developed a new optimisation method that finds the balance between the costs of structure removal from the ecological benefits of leaving structures in place. The first set of experiments (using passive particles) showed an optimal network of about 40 areas in the southern North Sea that would keep the man-made network connected but keep economic costs of removal down. The next best network to keep in place included 75 areas, because the method then found the next most highly connected network, which happened to be in the northern North Sea. Work to make the optimisations species-specific is now underway, with plans beyond ANChor to continue making the optimisations more realistic e.g., by refining estimates of removal costs and therefore the ANChor team is open to any INSITE sponsor's interests in helping to develop these.

The magnitude of the effects of man-made structures compared to the spatial and temporal variability of the North Sea ecosystem, considered on different time and space scales

Larval trajectories for the protected coral species *Lophelia pertusa* showed the capacity for ecosystems on man-made structures to benefit ecosystems downstream that have been degraded by human impacts and climate change. This capacity was robust across climate states proxied by the NAO, with the furthest most dense connections happening in a year when current strength would have been strongest. Even in low-flow conditions, trajectories carried larvae into areas with known naturally-occurring coral ecosystems. By 2012 under what was assumed to be the strongest current strength, larvae reached a range of coral ecosystems in the Norwegian EEZ including those in the deep-sea, on the continental shelf and slope, and in coastal fjords. Most notable was the direct supply of larvae in just a single generation into a Norwegian coral marine protected area from the Murchison and Thistle A platforms. Corals on both platforms have been verified. The Aktivneset coral MPA was designated to protect coral ecosystems from further fisheries degradation, the wider region also being impacted by climate change. The partial removal of Murchison (as an OSPAR derogation case) is unlikely to have impacted this role, with corals located on the structure that remains, and that was still within the range of ANChor's experiments.

OUTREACH

ANChor has delivered 8 oral presentations at national and international workshops and symposia; the first model build-up paper has been published (Fox et al., 2016), with 2 manuscripts on simulations ready for near-term submission in October (Henry et al., a&b, in preparation), and a 4th manuscript on the optimisations having already been submitted in August 2017 (Fox et al., submitted). These are listed below:

Presentations

September 2016 – Challenger Society for Marine Science Conference, Liverpool, UK

September 2016 – Special Interest Group, Challenger Society for Marine Science Conference, Exeter,

October 2016 – MASTS Conference, Glasgow, UK

November 2016 – Shelf ReCover Project Coral Restoration Symposium, Barcelona, Spain

February 2017 – ASLO (Association for the Sciences of Limnology and Oceanography), Honolulu Hawai'i

April 2017 – EGU (European Geosciences Union), Vienna, Austria

May 2017 – PISCES/ICES Climate, Oceans and Society Challenges and Opportunities Conference, Busan, Korea

September 201 – iMarCo meeting, Louvain-la-Neuve, Belgium

Manuscripts

Fox AD, Corne DW, Mayorga Adame CG, Polton JA, Henry L-A, Roberts JM (submitted) An efficient multi-objective optimisation method for use in the design of marine protected area networks. *Methods in Ecology and Evolution*

Fox A, Henry L-A, Corne DW, Roberts JM (2016) Sensitivity of marine protected area network connectivity to atmospheric variability. *Royal Society Open Science* 3: 160494.

Henry L-A, Fox AD, Mayorga Adame CG, Polton JA, Ferris J, McClellan F, McCabe C, Roberts JM (in preparation) Networks of oil rigs facilitate widespread dispersal of protected species. *Proceedings of the National Academy of Science*

Henry L-A, Fox AD, Mayorga Adame CG, Polton JA, Ferris J, McClellan F, McCabe C, Roberts JM (in preparation) Regional scale impacts of marine infrastructure on ecological connectivity. *Journal of Applied Ecology*

LEGACY OPPORTUNITIES

INSITE and ANChor helped make several opportunities happen that offer legacy opportunities, including:

- Collection of coral samples of *Lophelia* and associated epifauna during the decommissioning of Murchison and surveys at Ninian North; these rare new collections can be used for genetics and biodiversity analyses in future

- Ship- and ROV-time applied for with the Norwegians to collect *Lophelia* from the Aktivenest coral MPA for genetic analyses to validate ANChor's model

ACKNOWLEDGEMENTS

The ANChor team wishes to thank the sponsors of INSITE's Foundation Phase: support from BP, Centrica, CNR International, ExxonMobil, Marathon Oil, Shell, Talisman–Sinopec and Total made ANChor possible. ANChor would also like to thank various other operators who permitted us to view their marine growth data and who continue to work with us to gain permissions to share these. ANChor would like to thank INSITE's Independent Scientific Advisory Board for their guidance and to ANChor's mentor Associate Professor Torgeir Bakke for his mentorship. We are grateful to Eileen Rogerson for helping to disseminate ANChor outputs, and The ANChor team are especially grateful to INSITE's Programme Director Richard Heard for his leadership, expert advice and good humour.

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Appendix Table 1: Anonymised inventory of the distribution of ANCHor's 5 target species from marine growth surveys analysed by BMT Cordah (*N*=57). Reference number N=northern North Sea, C=central North Sea, S=southern North Sea, D=Dutch southern North Sea. Species abbreviations: MS=*Metridium senile*, LP=*Lophelia pertusa*, AD=*Alcyonium digitatum*, ME=*Mytilus edulis*, CH=*Chirona hameri*. NA=species not recorded during survey.

ANChor reference number	Max. depth surveyed (m)	Survey year	MS min. depth (m)	MS max. depth (m)	MS peak depth (m)	LP min. depth (m)	LP max. depth (m)	LP peak depth (m)	AD min. depth (m)	AD max. depth (m)	AD peak depth (m)	ME min. depth (m)	ME max. depth (m)	ME peak depth (m)	CH min. depth (m)	*CH max. depth (m)*	CH peak depth (m)
N1	137	2014	2	137	55	106	126	116	24	137	38	2	45	2-7	55	137	126
N2	90	2014	12	90	51	58	90	90	12	90	35	1	58	6	0	0	0
N3	89	2014	5	89	43	52	80	71	10	89	43	5	61	5	52	89	89
N4	141	2011	12	110	17, 60, 29	55	133	133	14	132	38	7	55	14	0	0	0
N5	87	2009	6	87	59	59	87	87	6	34	20-27	6	13	13	0	0	0
N6	153	2009	N/A	N/A	N/A	59	140	140	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
N7	138	2007	12	138	26	58	138	74	9	124	58	4	12	4	0	0	0
N8	40-96	1989	40	96	77	0	0	0	40	40	40	0	0	0	0	0	0
N9	100	1987	15	100	100	0	0	0	10	96	30	10	27	12	50	93	65, 68, 71
N10	140	1985	33	140	140	0	0	0	0	0	0	10	33	10	20	140	140
N11	159	1981	0	0	0	0	0	0	0	0	0	12	12	12	0	0	0
N12	34	1984	0	0	0	0	0	0	12	12	12	12	19	19	0	0	0

N13	100	1999	N/A	N/A	N/A	100	100	100	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
N14	100	2011	N/A	N/A	N/A	100	100	100	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
N15	155	2011	N/A	N/A	N/A	155	155	155	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
C1	80	2012	4	83	51	0	0	0	0	0	0	4	46	6	0	0	0
C2	121	2012	7	121	24	0	0	0	14	95	28 and 90	7	121	7 to 13	0	0	0
C3	81	2009	8	81	26	0	0	0	32	81	75	8	81	8	8	81	69
C4	88	2000	11	88	23-30, 35, 45-50, 62, 65, 83, 87	0	0	0	14	20	14	5	5	5	0	0	0
C5	118	1995	41	118	118	0	0	0	0	0	0	13	13	13	0	0	0
C6	99	1994	6	99	40	0	0	0	12	99	12	6	6	6	0	0	0
C7	18	1994	3	18	10	0	0	0	5	18	12	2	9	3	0	0	0
C8	88	2015	5	88	35-68	0	0	0	62	88	68-84	0	40	0-15	0	0	0
C9	93	2015	3	93	15-18, 20-34, 40-47, 52-58, 67-74, 77, 78, 84, 88	0	0	0	88	92	88	3	20	3	0	0	0
C10	102	2012	1	102	17, 40, 50	74	97	97	17	102	98	1	24	1-3, 7	24	102	75, 82

S1	25	2015	4	25	25	0	0	0	0	0	0	4	21	4	0	0	0
S2	22	2015	4	22	22	0	0	0	4	4	4	4	18	4	0	0	0
S3	39	2015	2	39	11, 26, 33	0	0	0	6	39	13	1	7	5	0	0	0
S4	31	2015	1	31	27	0	0	0	25	31	25, 31	1	18	7	0	0	0
S5	42	2015	5	40	5	0	0	0	3	42	30	1	10	30	10	42	38
S6	24	2014	2	24	21	0	0	0	0	0	0	1	19	2	0	0	0
S7	20	2014	1	20	16-20	0	0	0	0	0	0	1	15	1-2	0	0	0
S8	36	2014	5	36	19	0	0	0	6	36	36	5	22	5	0	0	0
S9	31	2013	2	31	28	0	0	0	0	0	0	2	27	2-3	5	24	7
S10	27	2013	2	27	26-27	0	0	0	7	15	12	2	20	6	0	0	0
S11	38	2013	1	38	27,28, 31	0	0	0	0	0	0	1	29	1	0	0	0
S12	34	2012	1	34	25,27	0	0	0	3	4	3	1	13	8	0	0	0
S13	22	2012	7	22	19	0	0	0	0	0	0	1	16	1	0	0	0
S14	21	2012	3	21	16,19	0	0	0	0	0	0	0	18	1	0	0	0
S15	24	2012	1	24	19,21	0	0	0	12	12	12	1	24	1	0	0	0
S16	24	2012	2	24	16,20	0	0	0	0	0	0	1	14	1-3	0	0	0
S17	26	2011	2	26	20	0	0	0	0	0	0	1	20	8	0	0	0
S18	25	2011	8	25	18	0	0	0	0	0	0	1	10	1	0	0	0

S19	29	2011	3	29	26	0	0	0	0	0	0	2	19	17	0	0	0
S20	30	2011	2	30	28	0	0	0	3	3	3	2	17	2	0	0	0
S21	25	2011	1	25	17, 21,23	0	0	0	0	0	0	1	18	1	0	0	0
S22	34	2010	2	34	25	0	0	0	6	6	6	1	18	1	0	0	0
S24	31.5	1990	3	32	26	0	0	0	3	32	18	3	20	3	0	0	0
S25	31	1990	4	31	14-26	0	0	0	4	31	18	4	14	4	0	0	0
S26	24	1990	6	24	24	0	0	0	6	24	16-20	6	20	6	0	0	0
S27	18	1990	4	18	12,14	0	0	0	4	18	16	4	10	4	0	0	0
D1	40	2014	3	11	4	0	0	0	5	40	21	3	11	4	0	0	N/A
D2	28	2012	12	28	N/A	0	0	N/A	0	0	N/A	2	23	N/A	0	0	N/A
D3	33	2012	3	33	N/A	0	0	N/A	0	0	N/A	3	13	N/A	0	0	N/A
D4	43	2012	3	43	N/A	0	0	N/A	23	43	N/A	0	0	N/A	0	0	N/A
D5	43	2012	2	42	N/A	0	0	N/A	27	43	N/A	2	12	N/A	0	0	N/A
D6	38	2012	2	38	N/A	0	0	N/A	7	38	N/A	2	2	N/A	0	0	N/A

Appendix Table 2: Inventory of marine growth surveys from the literature with observations of *Lophelia pertusa* and from physical samples of *L. pertusa* collected from North Sea oil and gas structures (*N*=9).

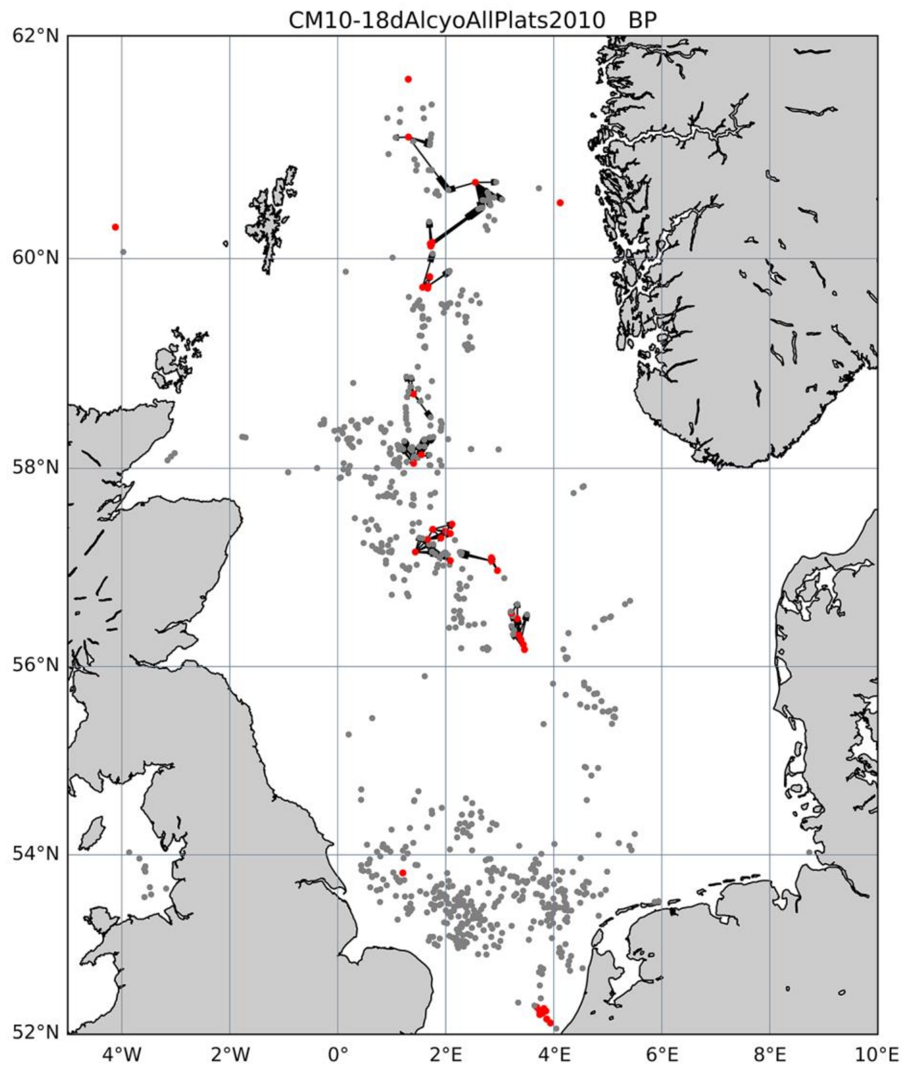
Structures	Latitude	Longitude	Block	Depth of platform (m)	Data source
Eider	61.357333	1.161333	211/16	158	Gass & Roberts 2006
Magnus	61.62	1.307	211/12a/7a	186	Gass & Roberts 2006
Tern Alpha	61.276167	0.919	210/25	167	Gass & Roberts 2006
Brent A	61.035000	1.705278	211/29	142	Gass & Roberts 2006
Claymore A	58.449318	-0.253607	14/19	111	Gass & Roberts 2006
Cormorant North	61.240556	1.149444	211/21	160	Gass & Roberts 2006
Heather A	60.953611	0.94	41761	144	Gass & Roberts 2006
Tartan A	58.369847	0.073606	15/16	142	Gass & Roberts 2006
Dunlin A	61.274289	1.595847	211/23	151	Gass & Roberts 2006
Thistle A	61.363036	1.579761	211/18	160	Gass & Roberts 2011
Brent D	61.1325	1.736167	211/29	142	Brent decommissioning plans

Appendix Table 3: Detailed notes and literature review on life history traits compiled for each species considered in ANChor's virtual larval tracking experiments.

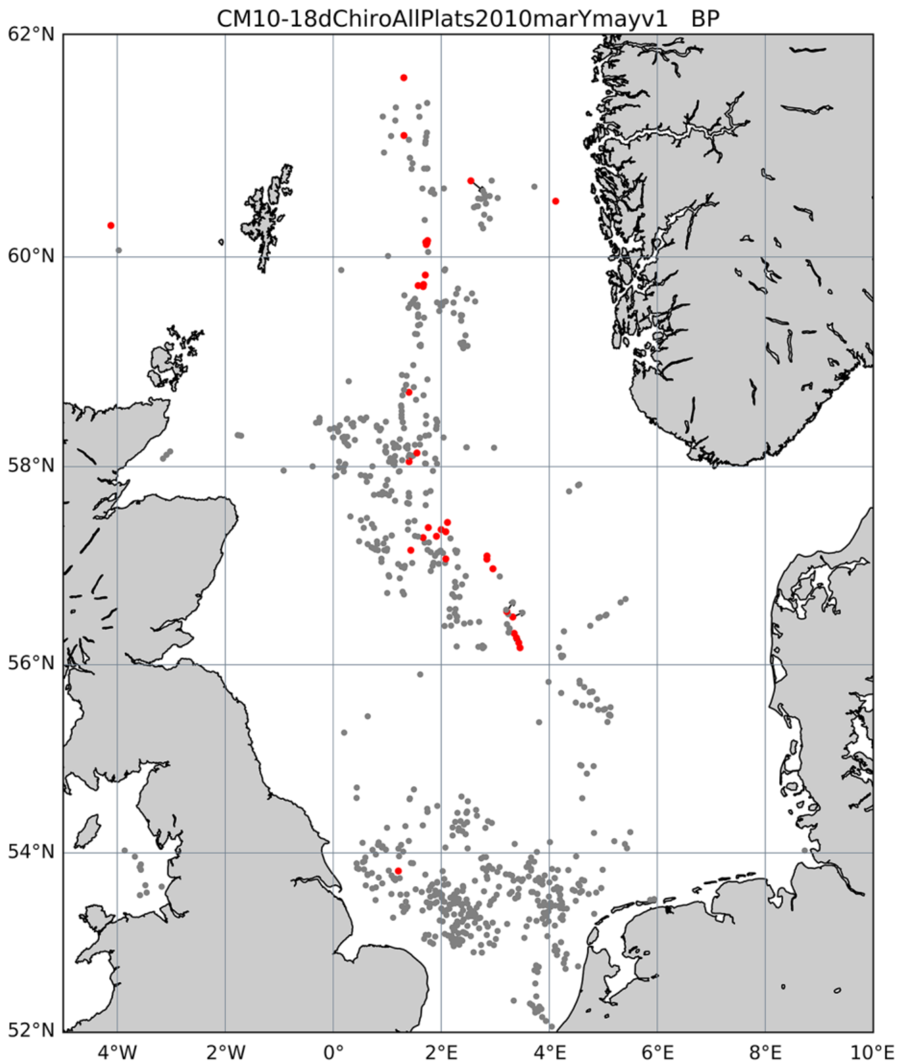
Traits	***M. edulis***	***L. pertusa***	***A. digitatum***	***M. senile***	***C. hameri***
Sexual reproductive mode	gonochoristic	gonochoristic	gonochoristic	gonochoristic	hermaphroditic
Reproductive season	April to September	January to February	January to February	August to September	larvae bloom in spring, may be year-round
Lifespan (years)	21-50	>100	21-50	11-20	assumed 1-2 years
Developmental mode	planktotrophic	planktotrophic	lecithotrophic	planktotrophic	planktotrophic
Fertilisation	external	external	external	external	
Age at maturity	1-2 years		2-3 years		under 1 year
Embryo buoyancy		Short-lived neutrally buoyant blastula, then larvae swim	neutrally buoyant, float for 7 days		
Swimming behaviour (vertical)	yes: vertical migration with swim speeds 0.5 to 7mm/s	yes, vertical migration, up to 0.5mm/s	yes	yes, no ref. for speeds	cyprid larvae swim and drift horizontally in surface waters
Swimming behaviour (horizontal)	yes; horizontal migration swim speeds 1.25-3.3mm/s			yes, no ref. for speeds	cyprid larvae sink vertically, maybe 0.44-0.54 cm/s
Larval dispersal potential	>10km	>10km	>10km	>10km	>10km, assumed from *Balanus crenatus*
Larval duration	1-6 months	8 weeks, but can live for 1 year	2-10 days, but can live for 35 weeks	1-6 months	11-30 days, assumed from *Balanus crenatus*
Notes	Larvae maintain position in the water column using cilia to swim continuously for up to several weeks where they aggregate at the water surface. Larval depth seems restricted by thermoclines and haloclines, so in stratified waters, larvae are able to settle at deeper depths when the time comes. Larvae likely swim upwards and sink back downwards in a helical pattern.	Larvae start as passive, then swim over the first 14 days at peak speeds up to 0.5mm/s (up to >40 m/day). *In vitro*, larvae accumulate at the tank surface until about day 30, when they sink and become competent to settle.	Larvae are neutrally buoyant for up to 7 days then swim, but there are no references for swim speed yet	Larvae said to swim but there are no references about this yet	Nauplii larvae metamorphose into cyprid larvae within 24 hours

BESPOKE CONNECTIVITY MAPS FOR SPONSORS

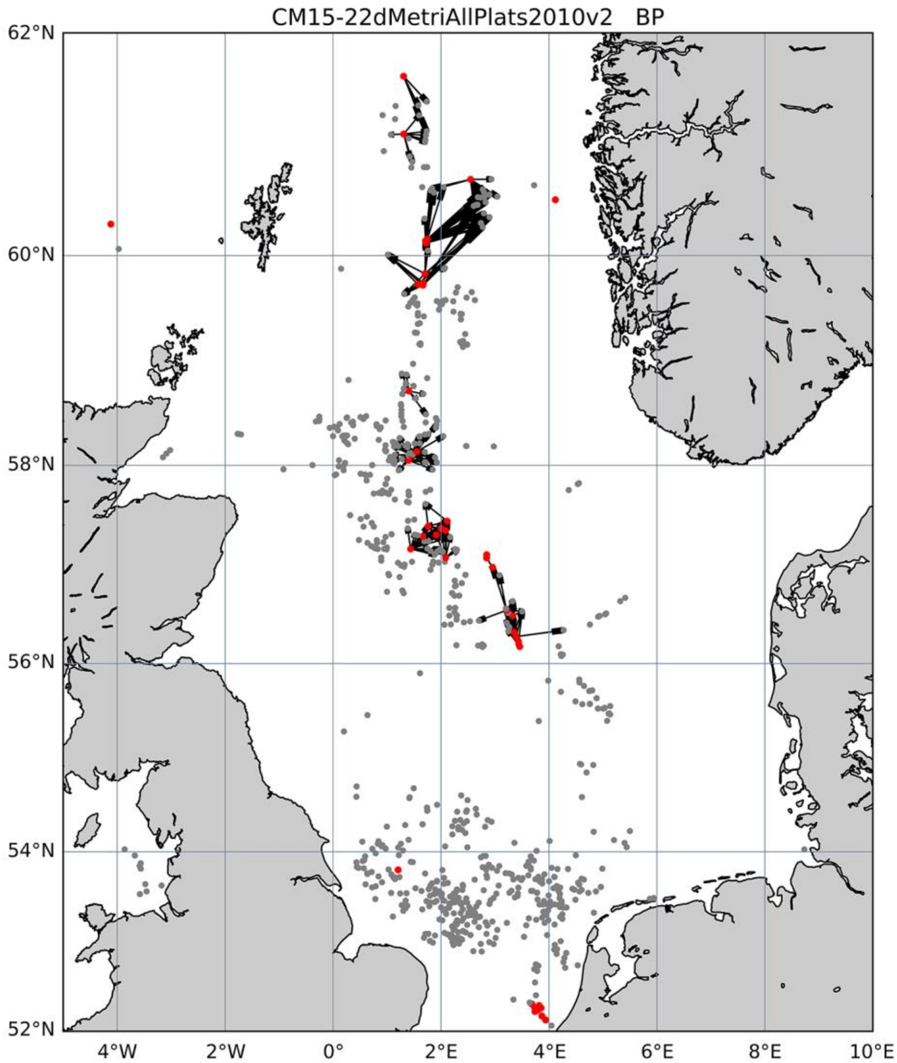
BP's network for the soft coral *Alcyonium digitatum*



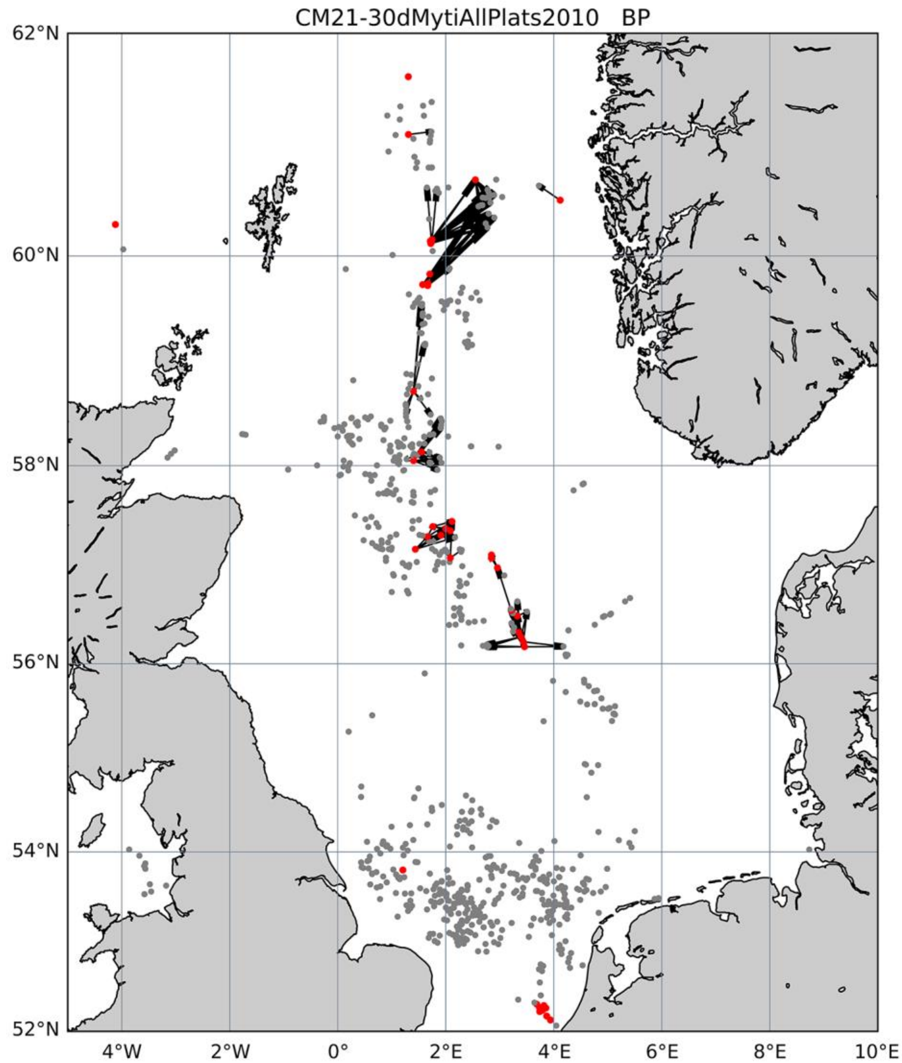
BP's network for the barnacle *Chirona hameri*



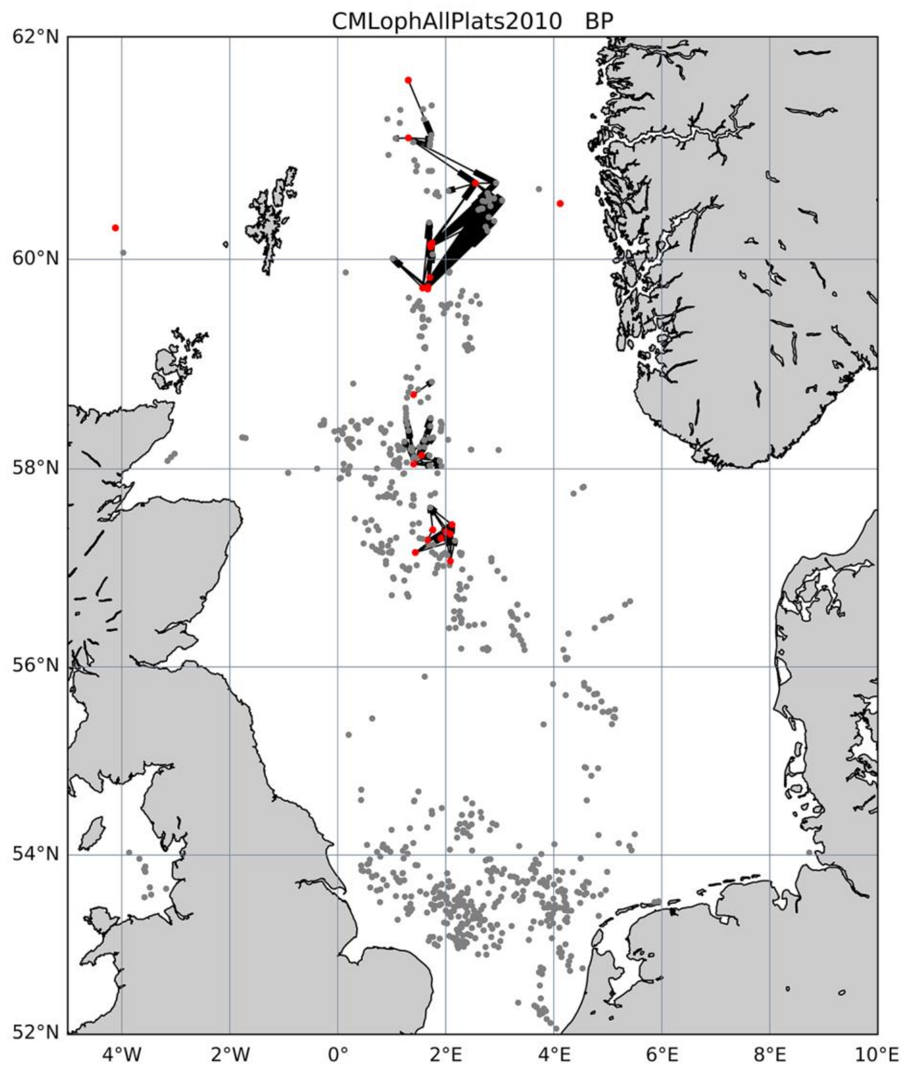
BP's network for the anemone *Metridium senile*



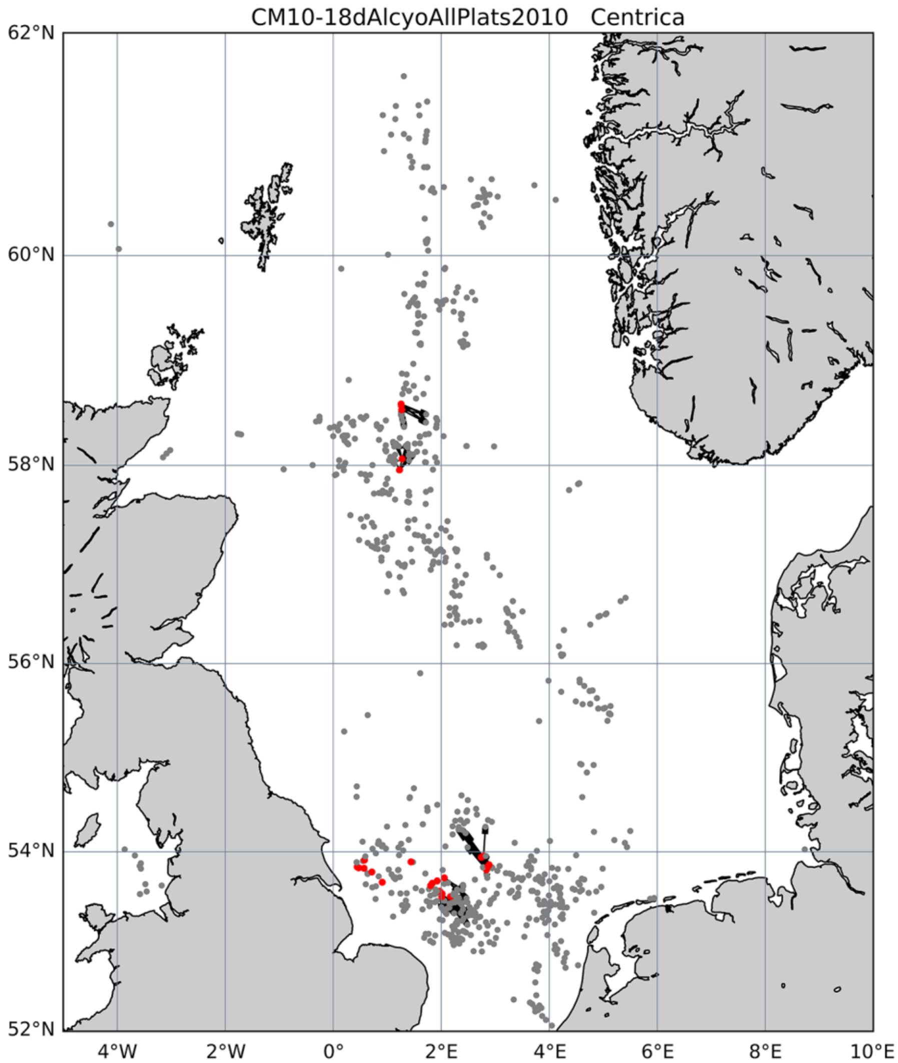
BP's network for the blue mussel *Mytilus edulis*



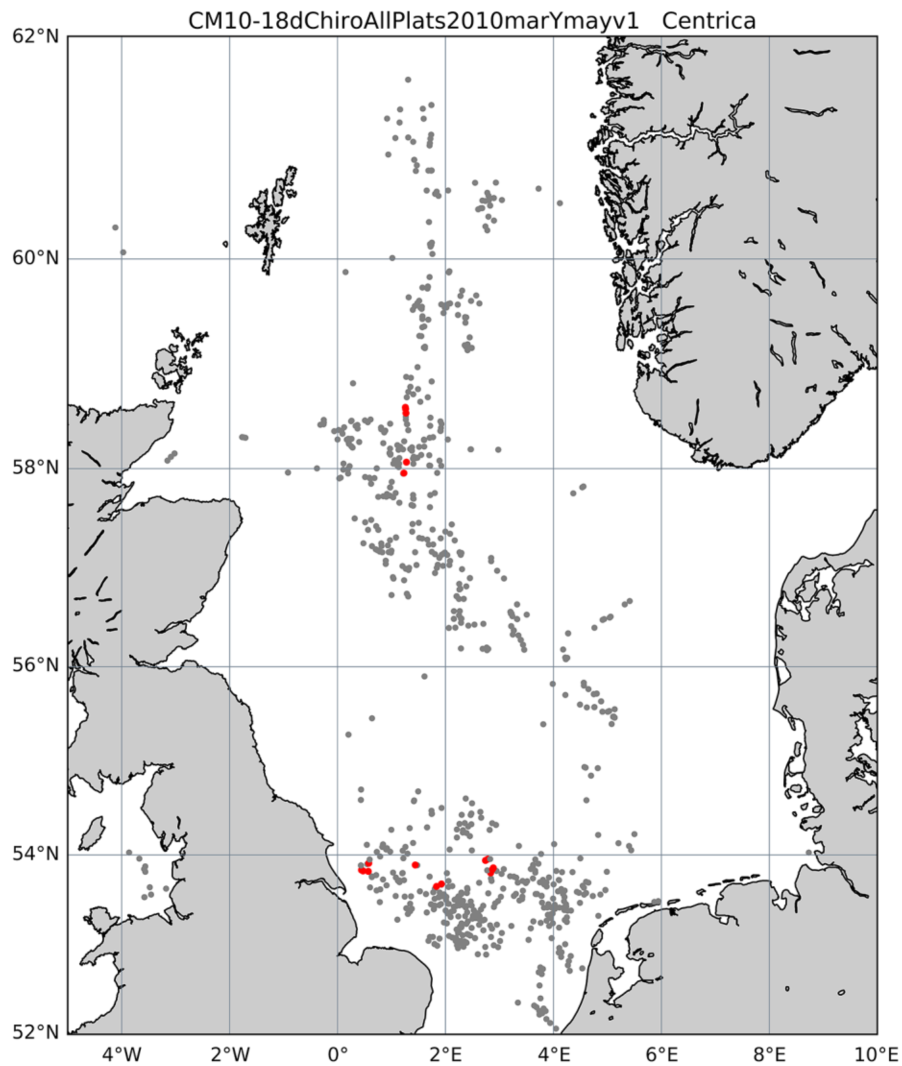
BP's network for the stony coral *Lophelia pertusa*



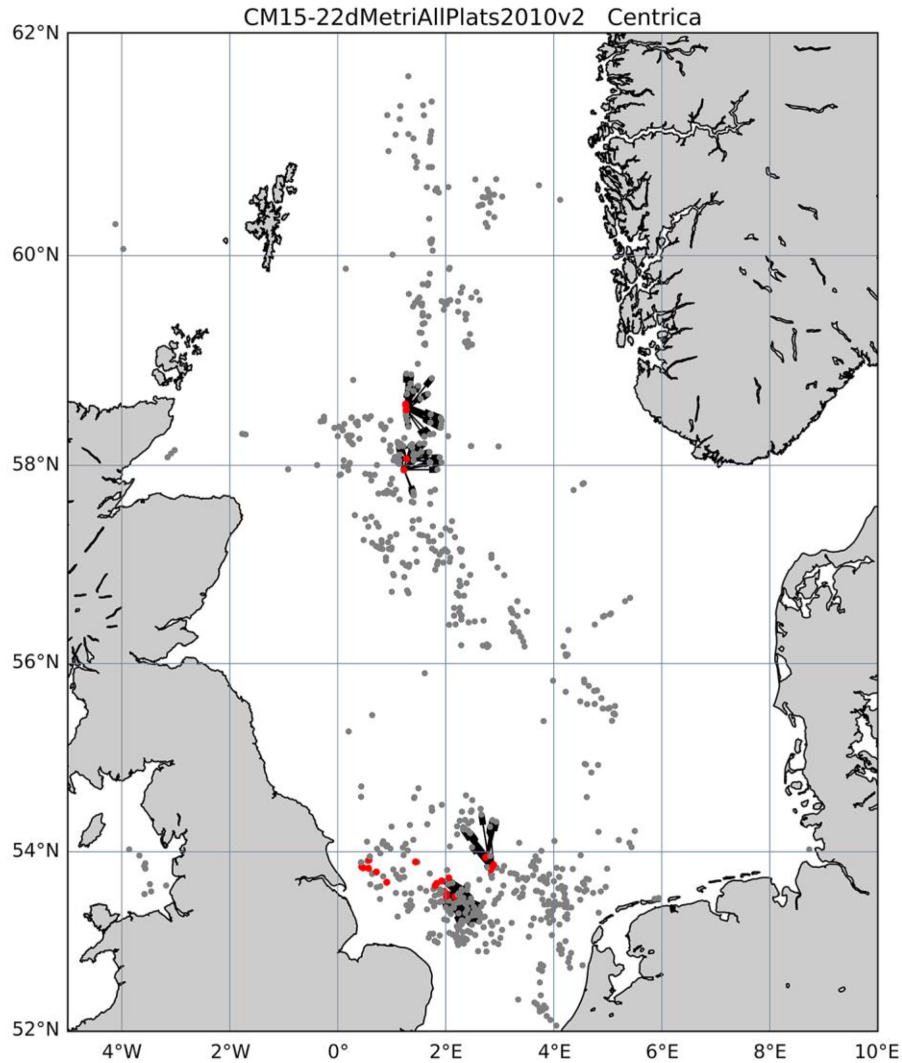
Centrica's network for the soft coral *Alcyonium digitatum*



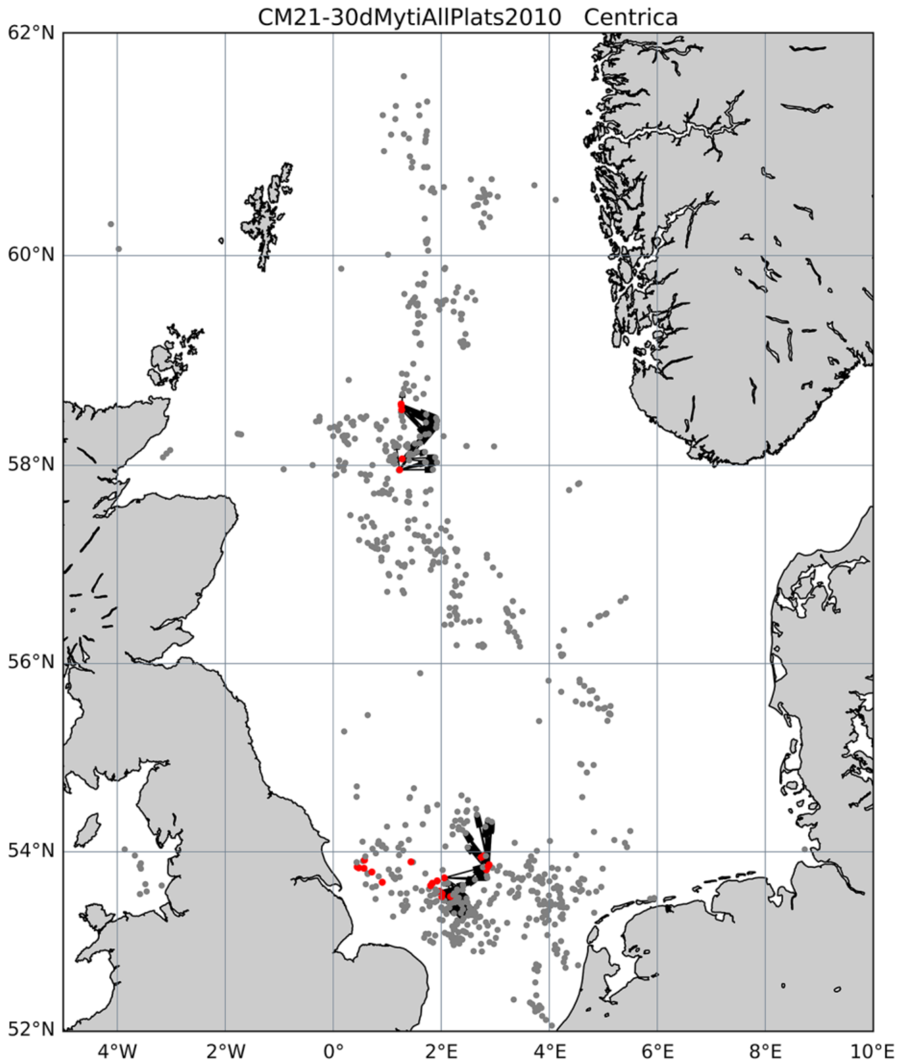
Centrica's network for the barnacle *Chirona hameri*



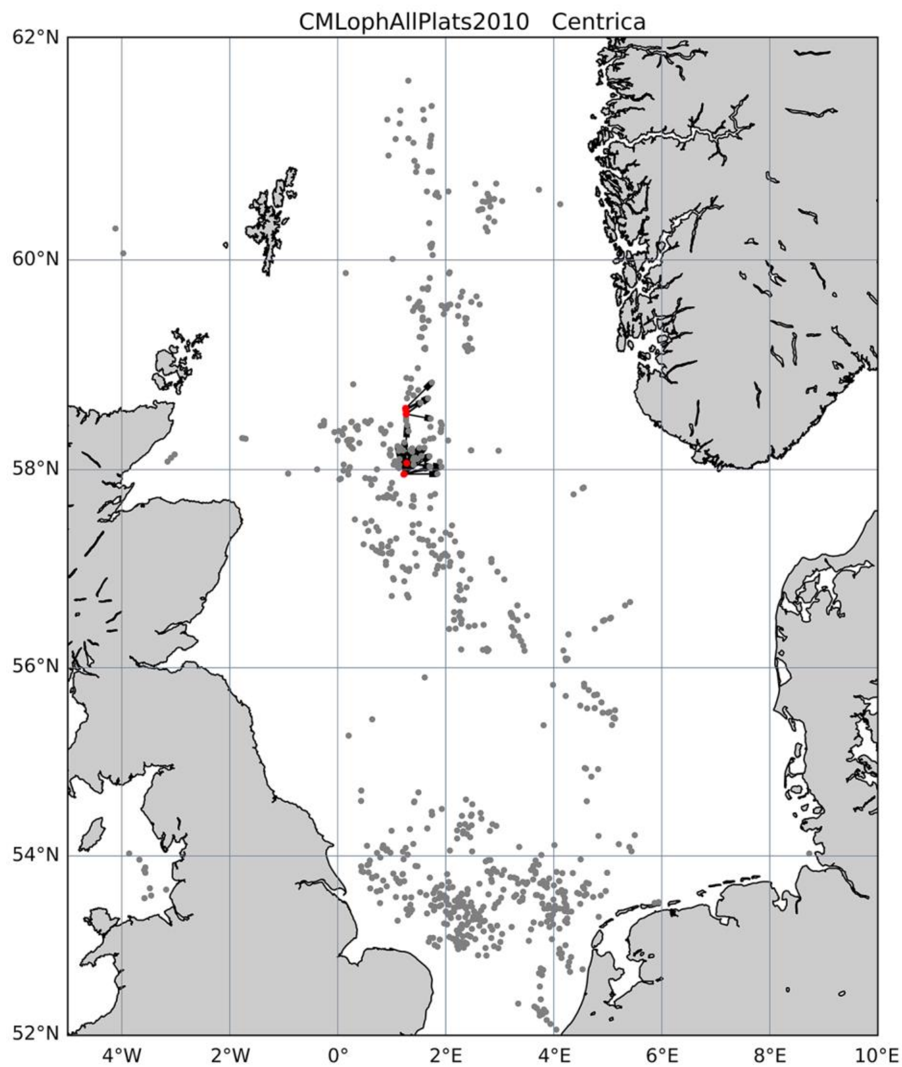
Centrica's network for the anemone *Metridium senile*



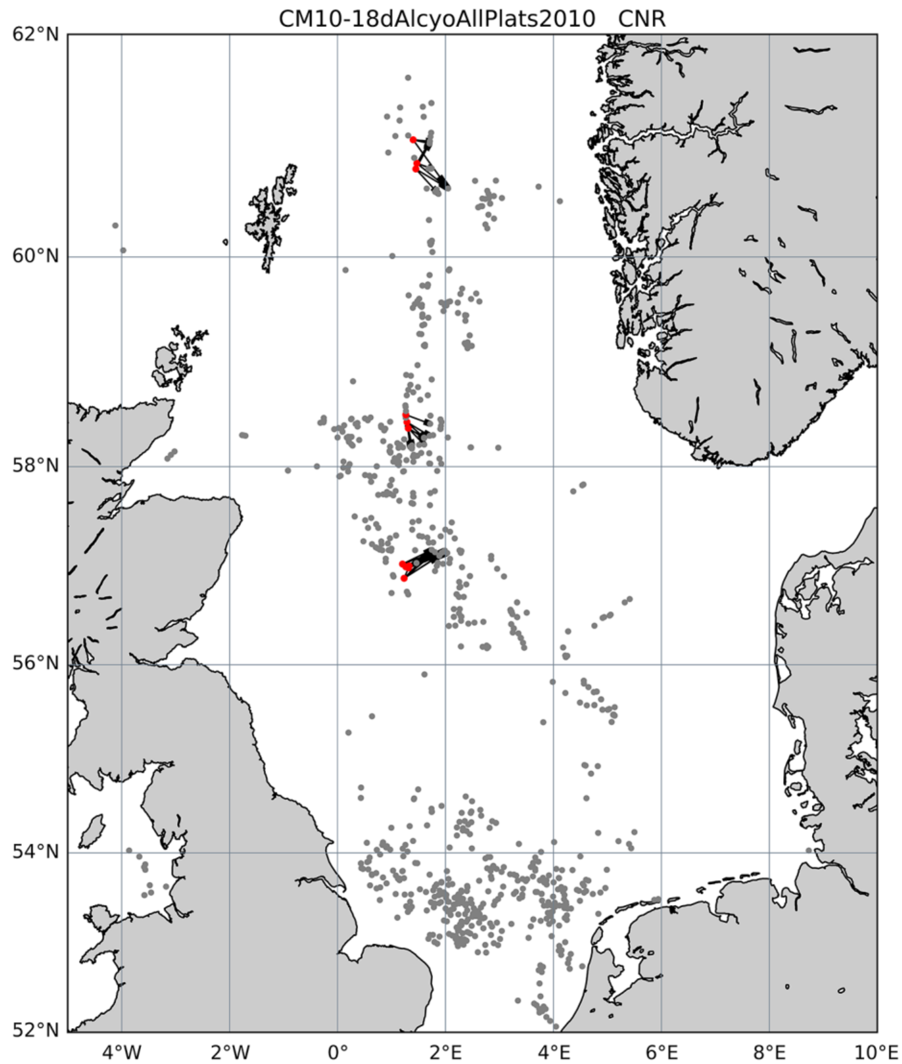
Centrica's network for the blue mussel *Mytilus edulis*



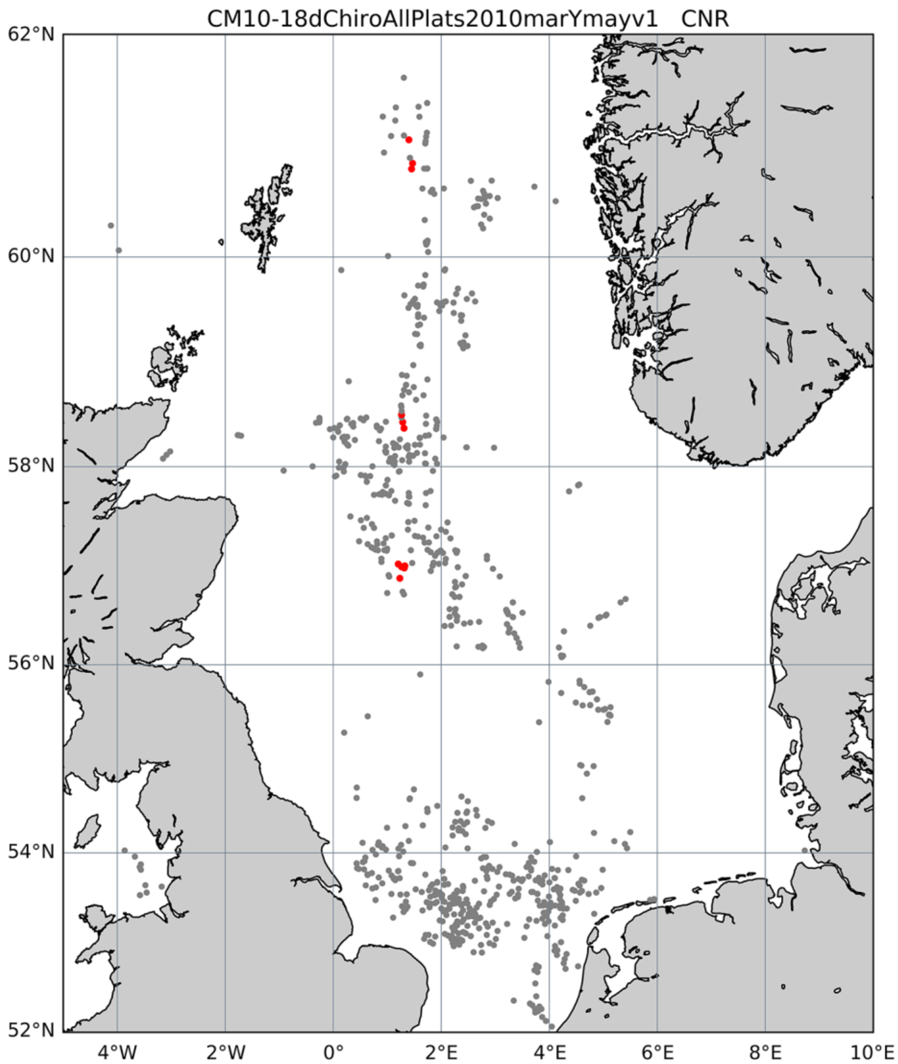
Centrica's network for the stony coral *Lophelia pertusa*



CNRI's network for the soft coral *Alcyonium digitatum*



CNRI's network for the barnacle *Chirona hameri*



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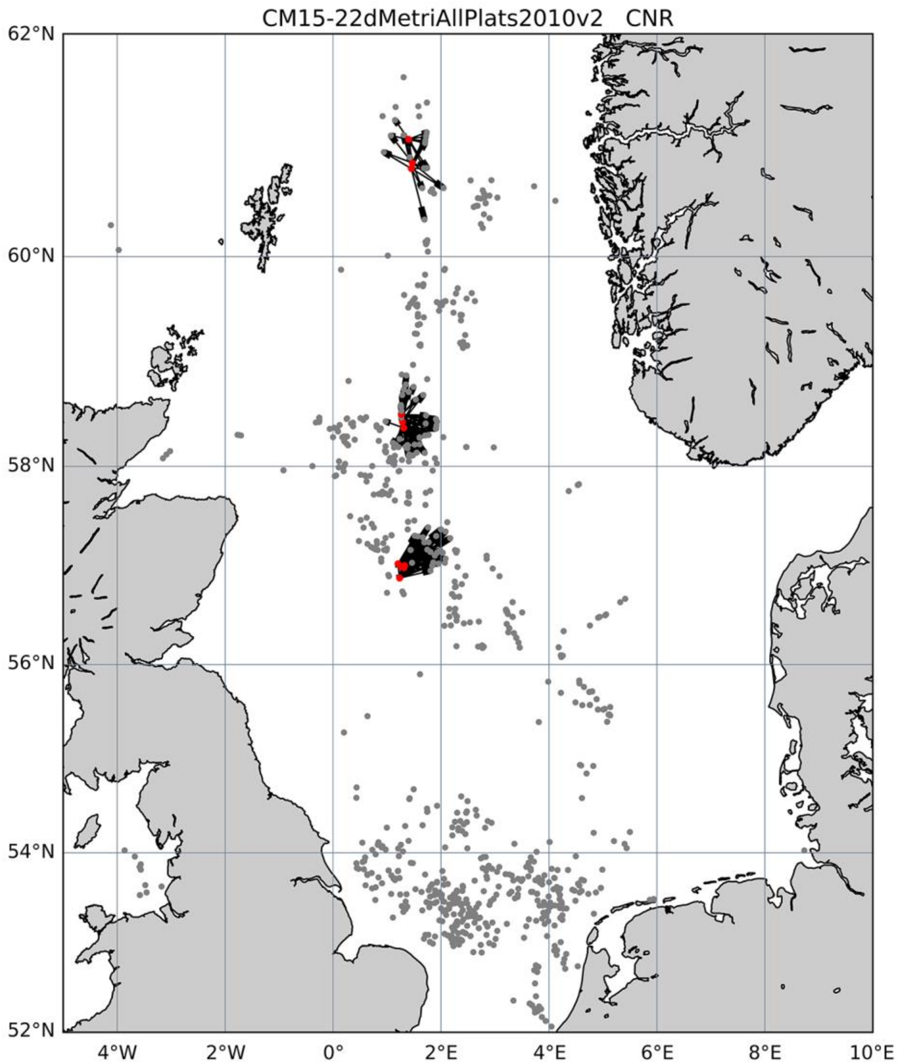

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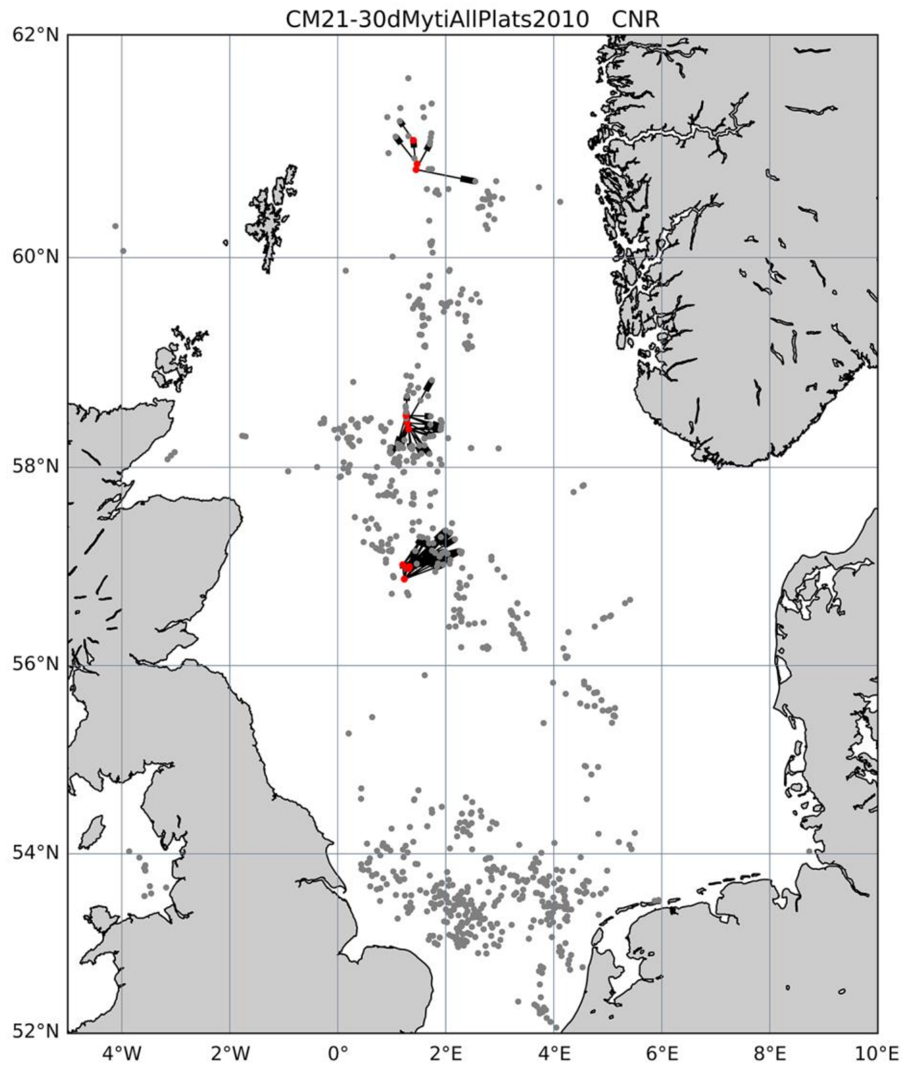
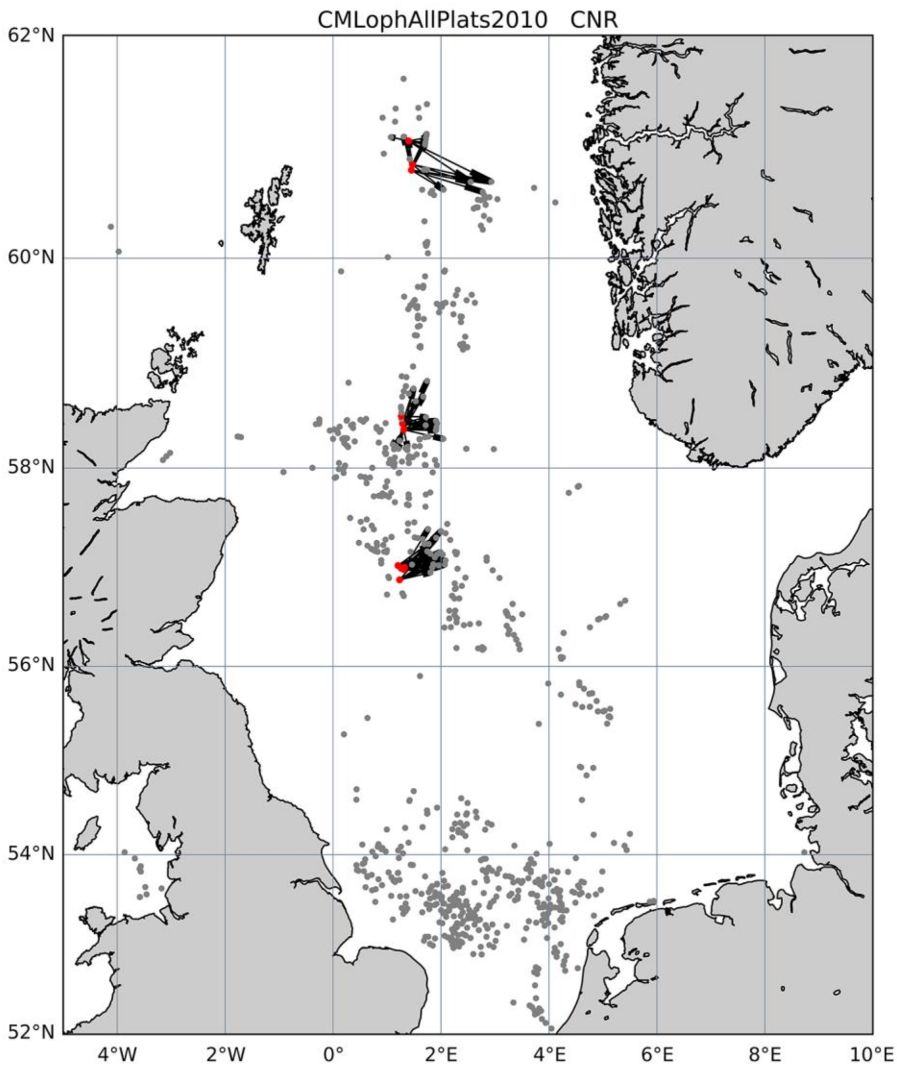
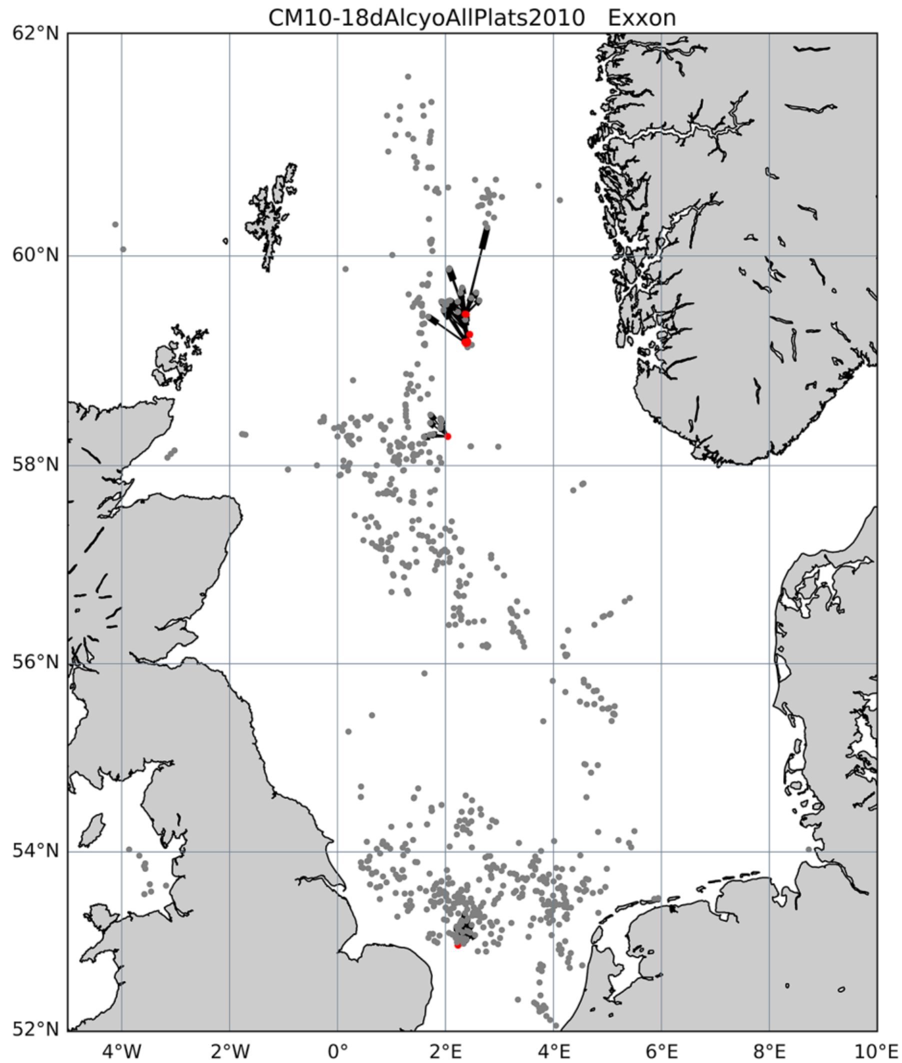


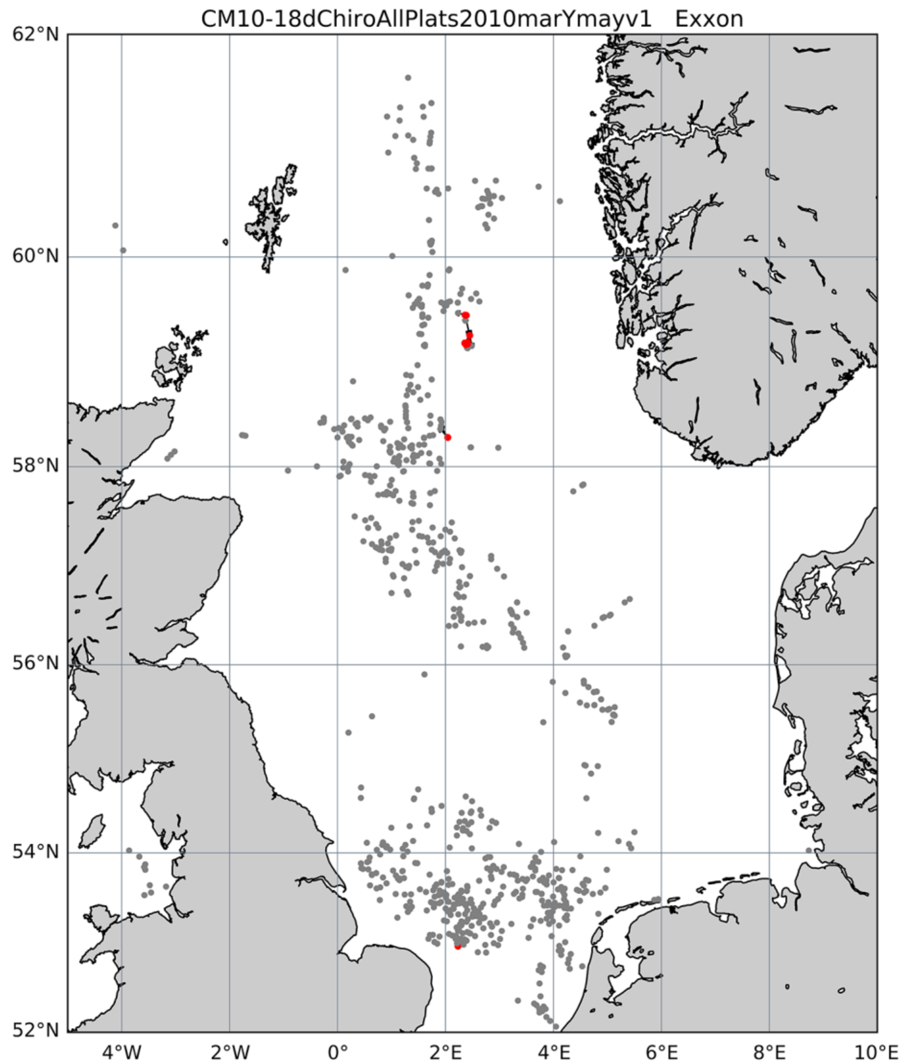
CNRI's network for the stony coral *Lophelia pertusa*



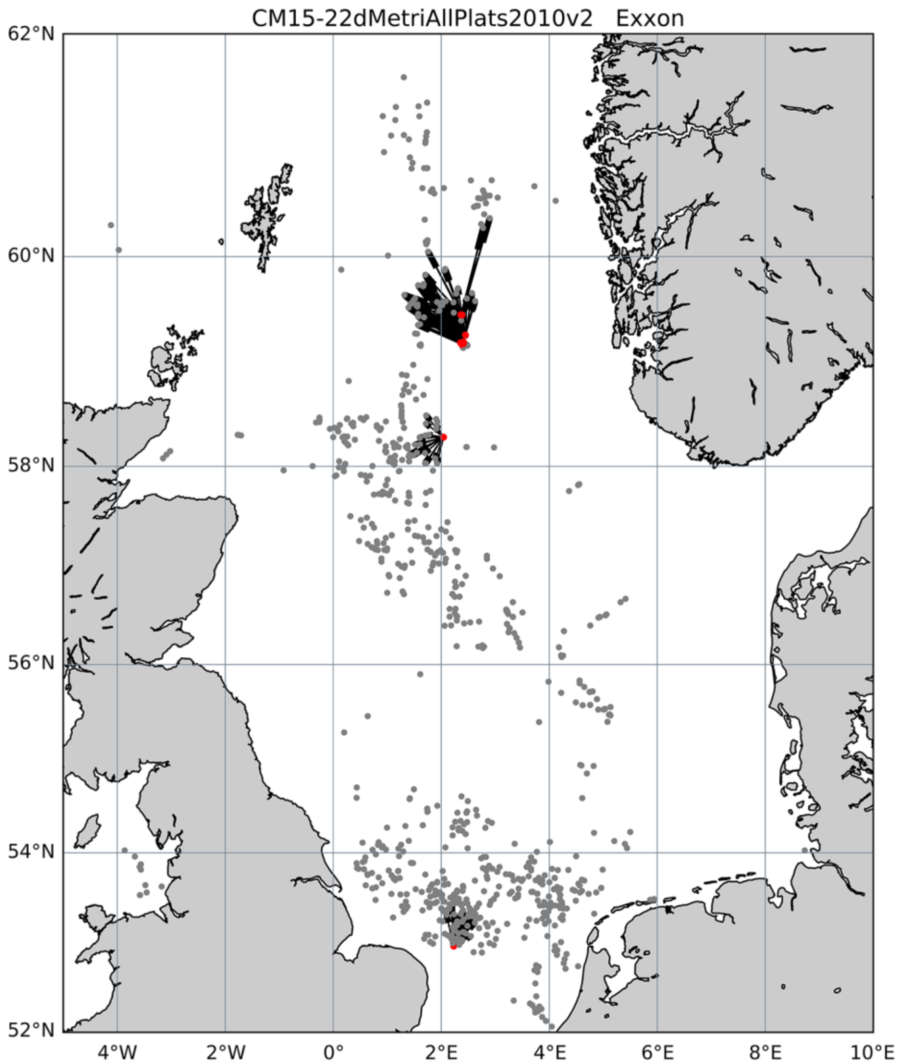
ExxonMobil's network for the soft coral *Alcyonium digitatum*



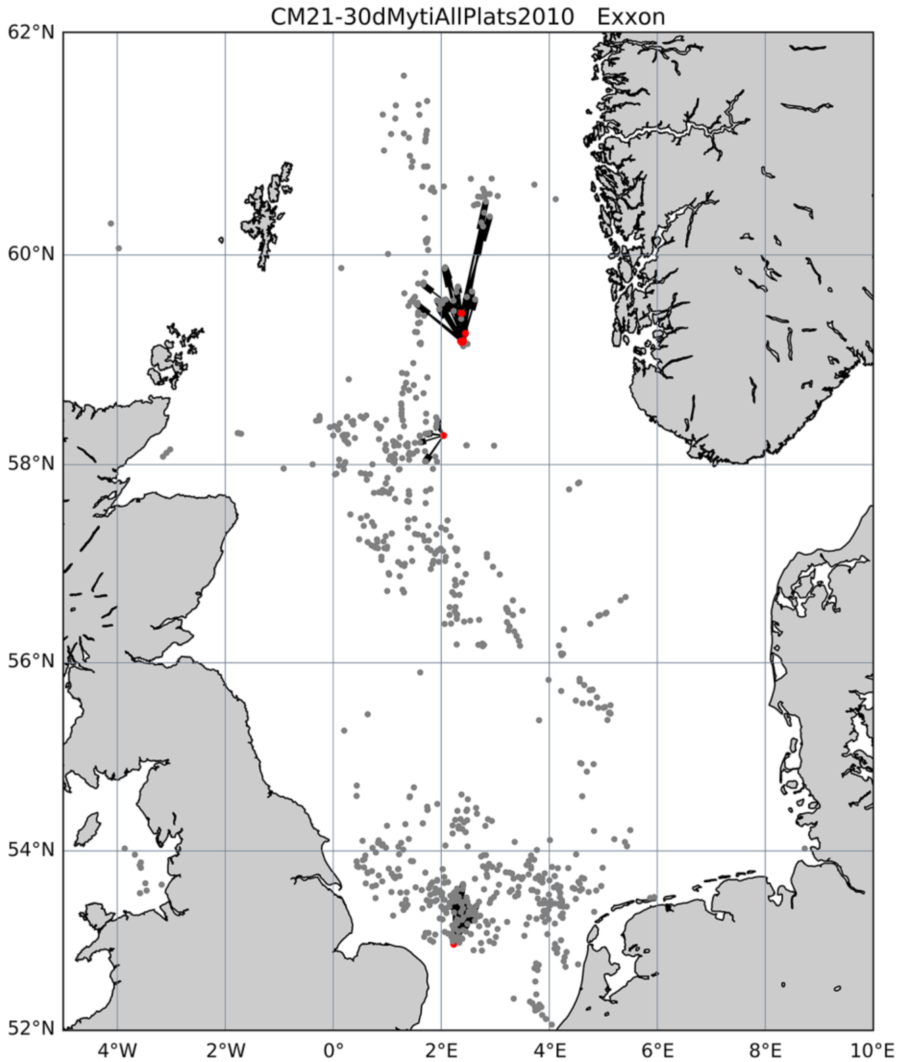
ExxonMobil's network for the barnacle *Chirona hameri*



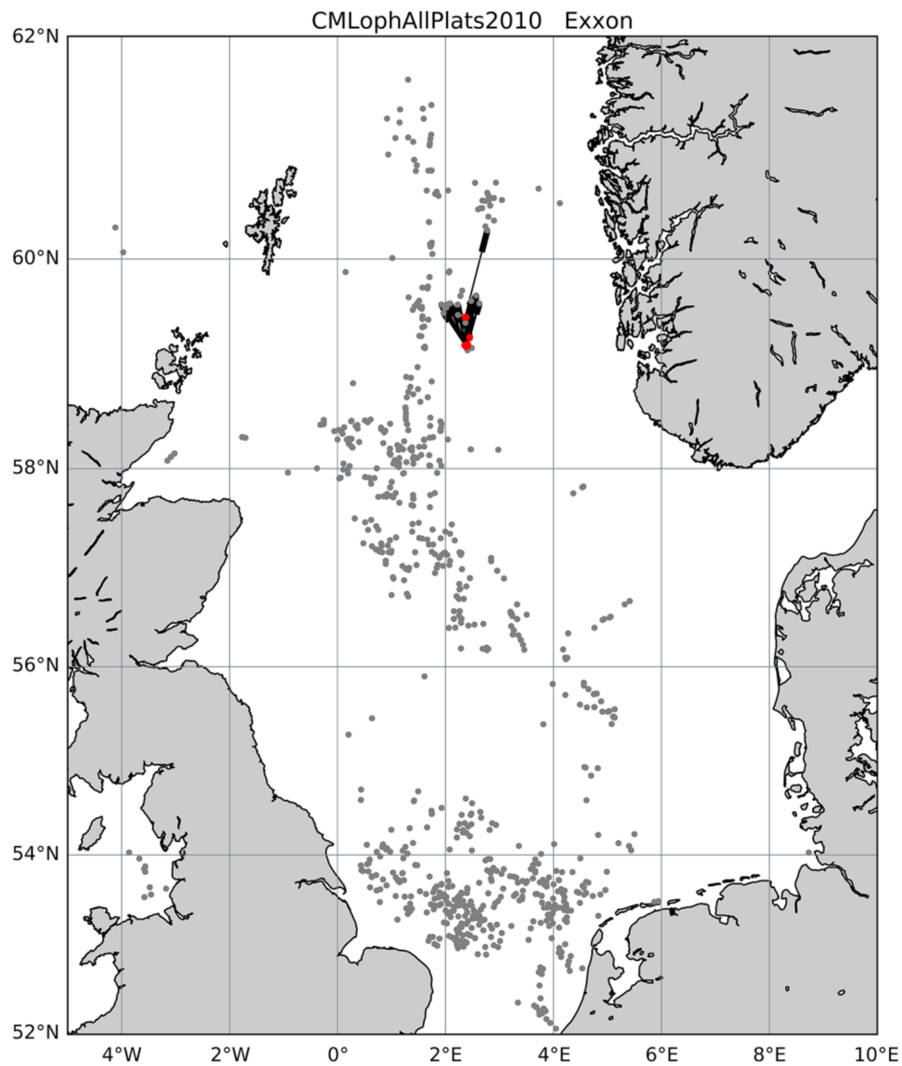
ExxonMobil's network for the anemone *Metridium senile*



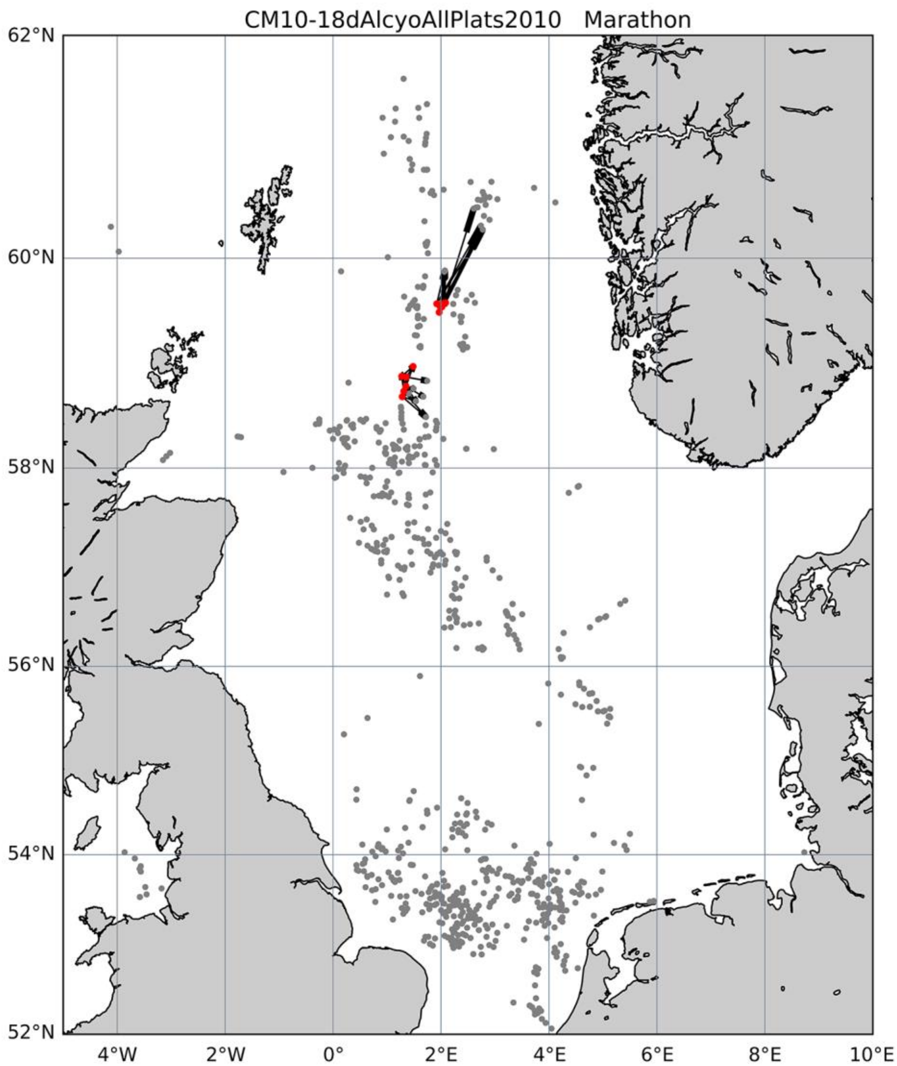
ExxonMobil's network for the blue mussel *Mytilus edulis*



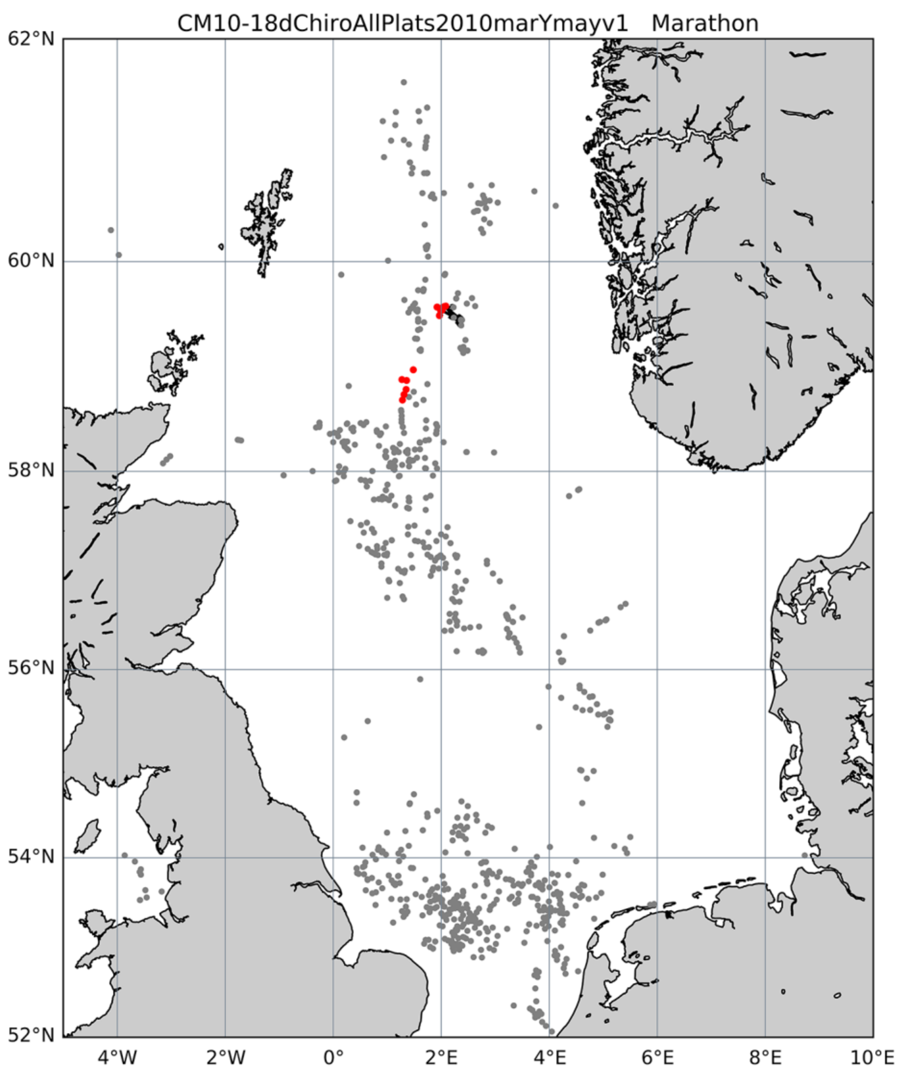
ExxonMobil's network for the stony coral *Lophelia pertusa*



Marathon's network for the soft coral *Alcyonium digitatum*



Marathon's network for the barnacle *Chirona hameri*



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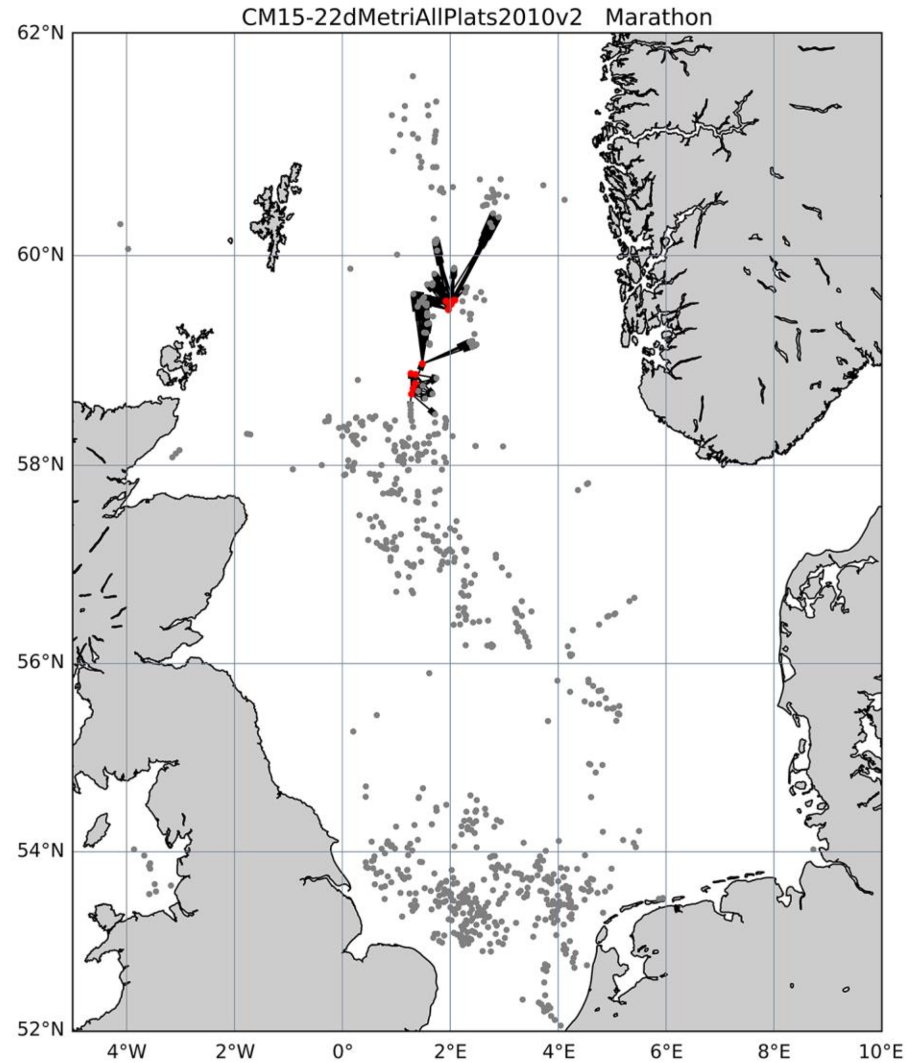

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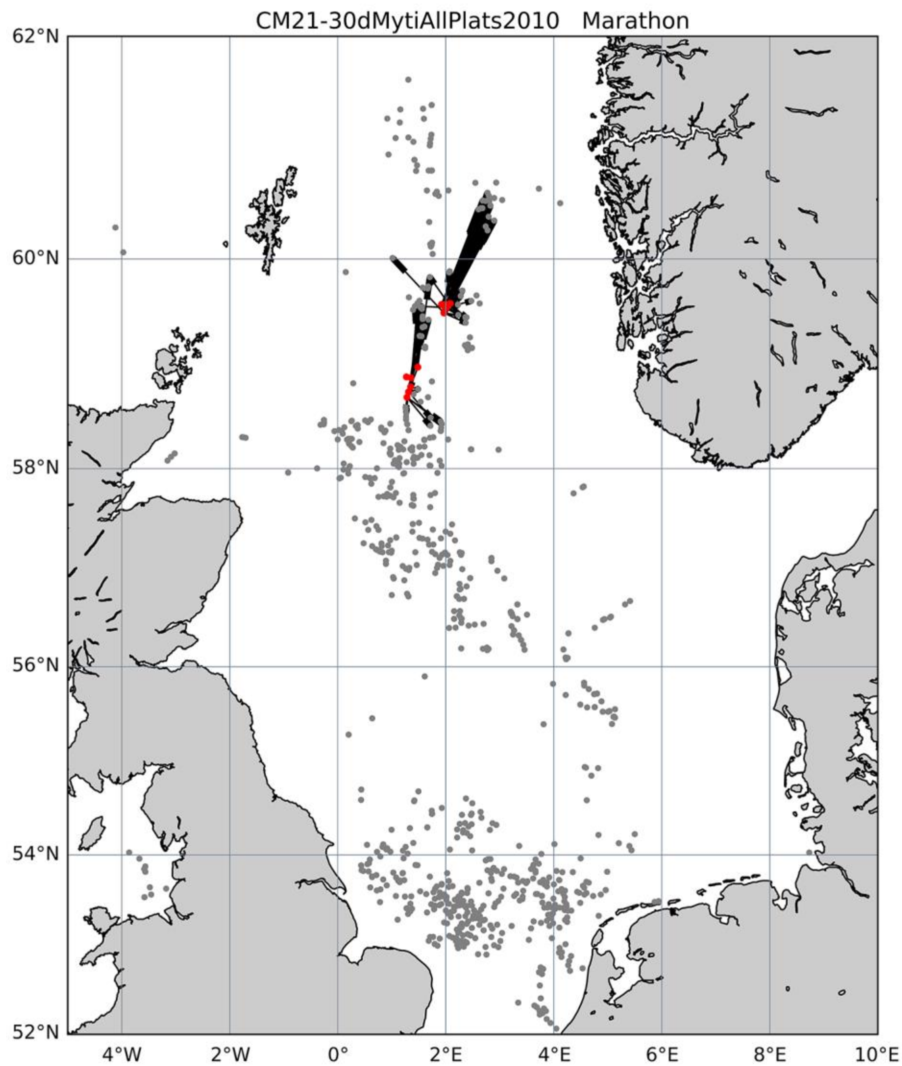

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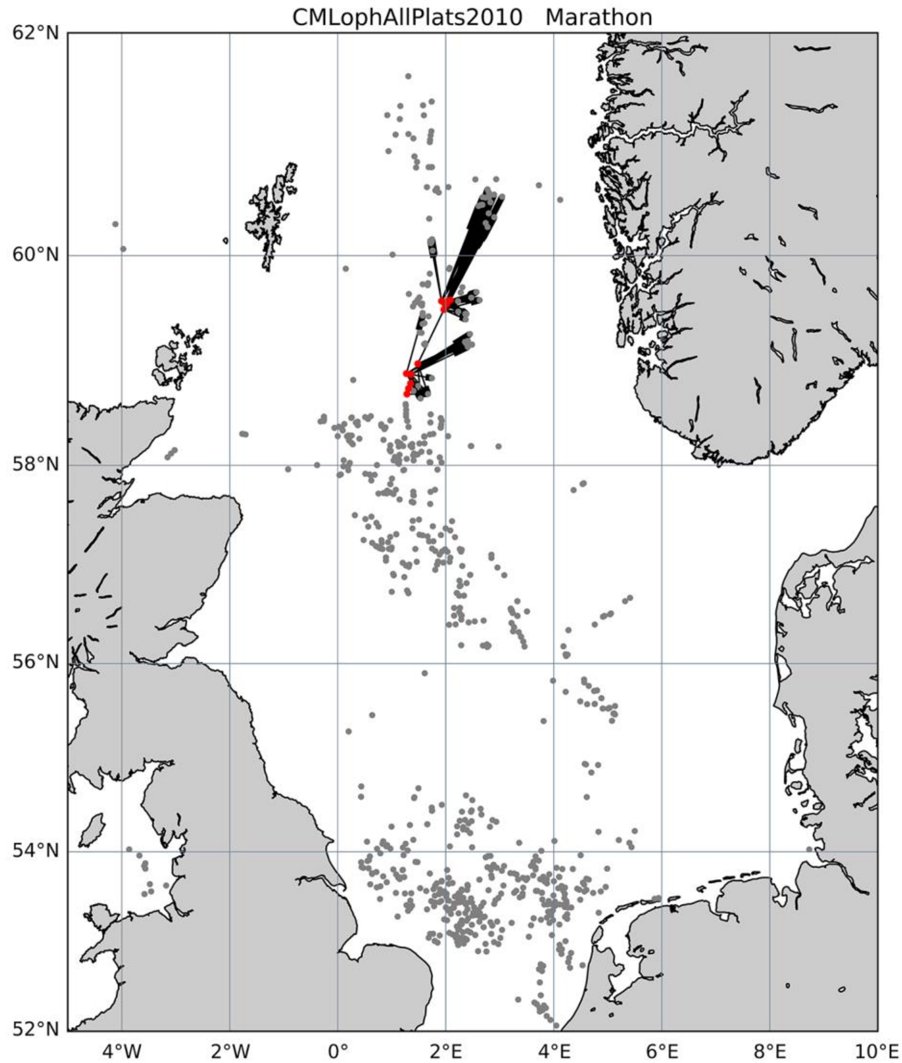
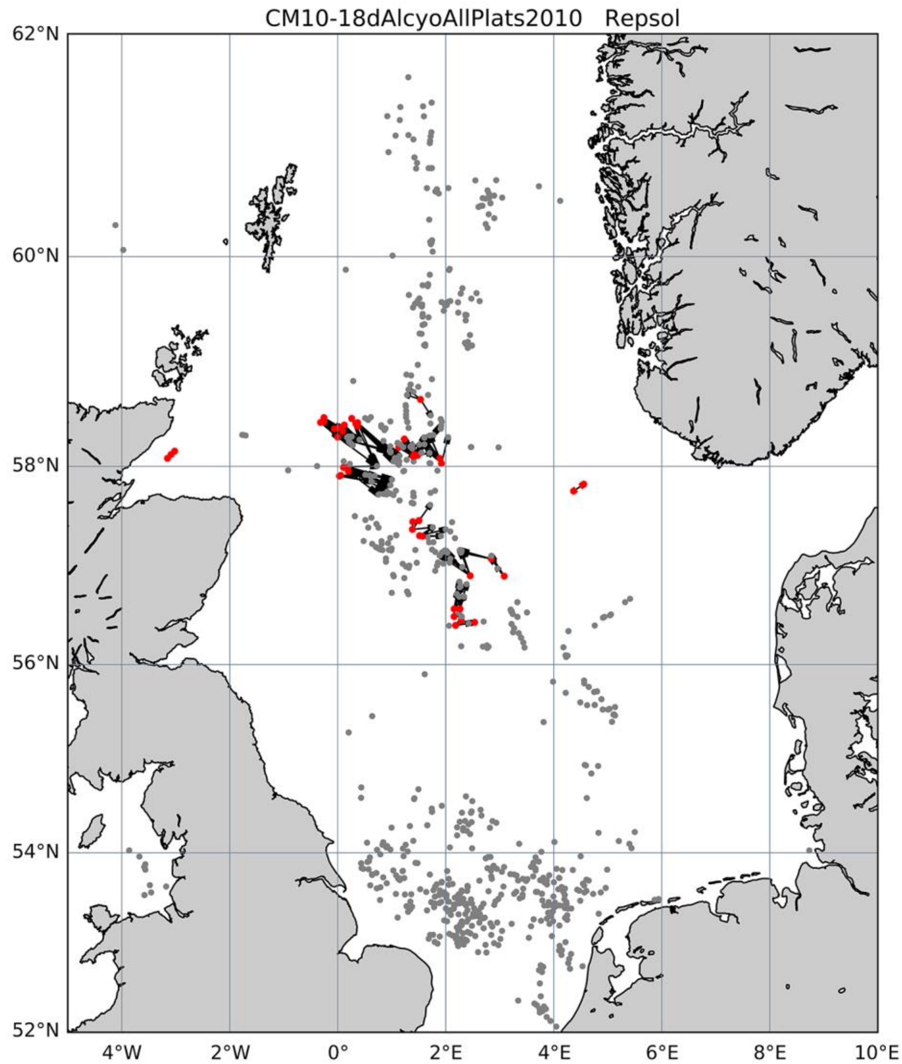
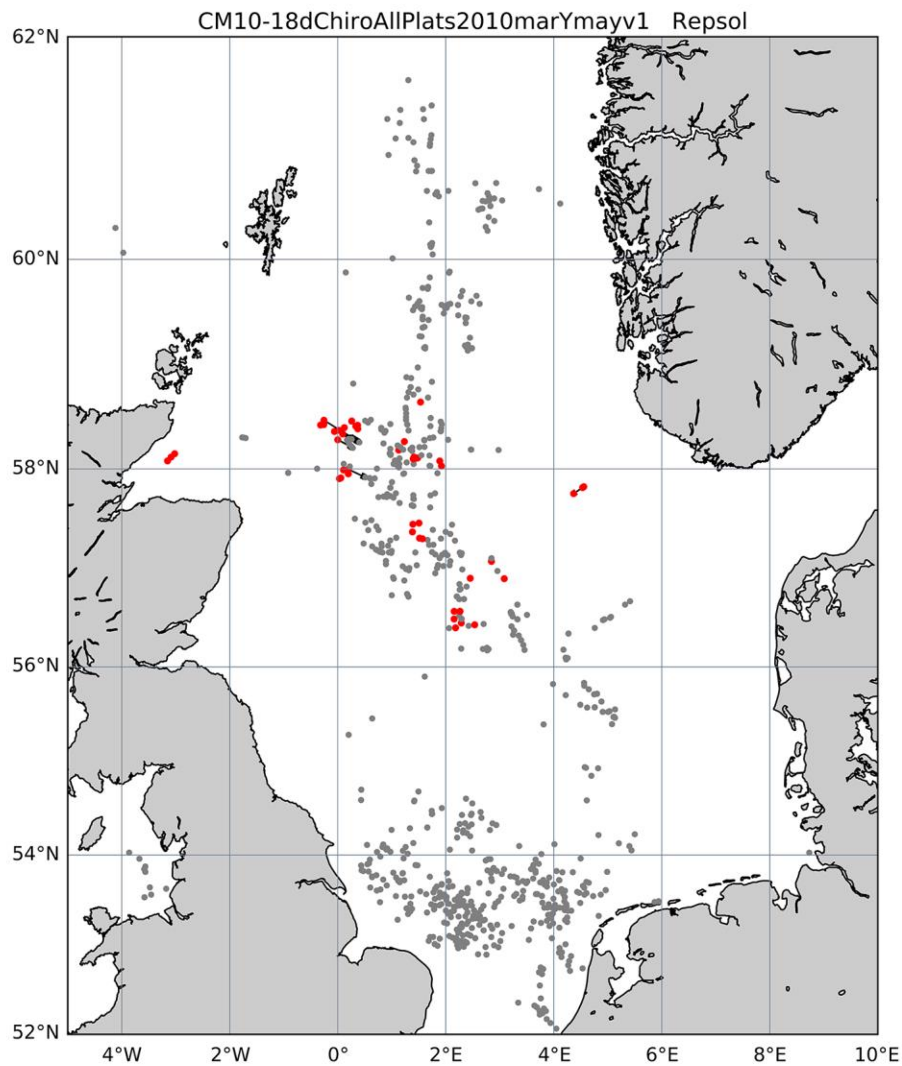


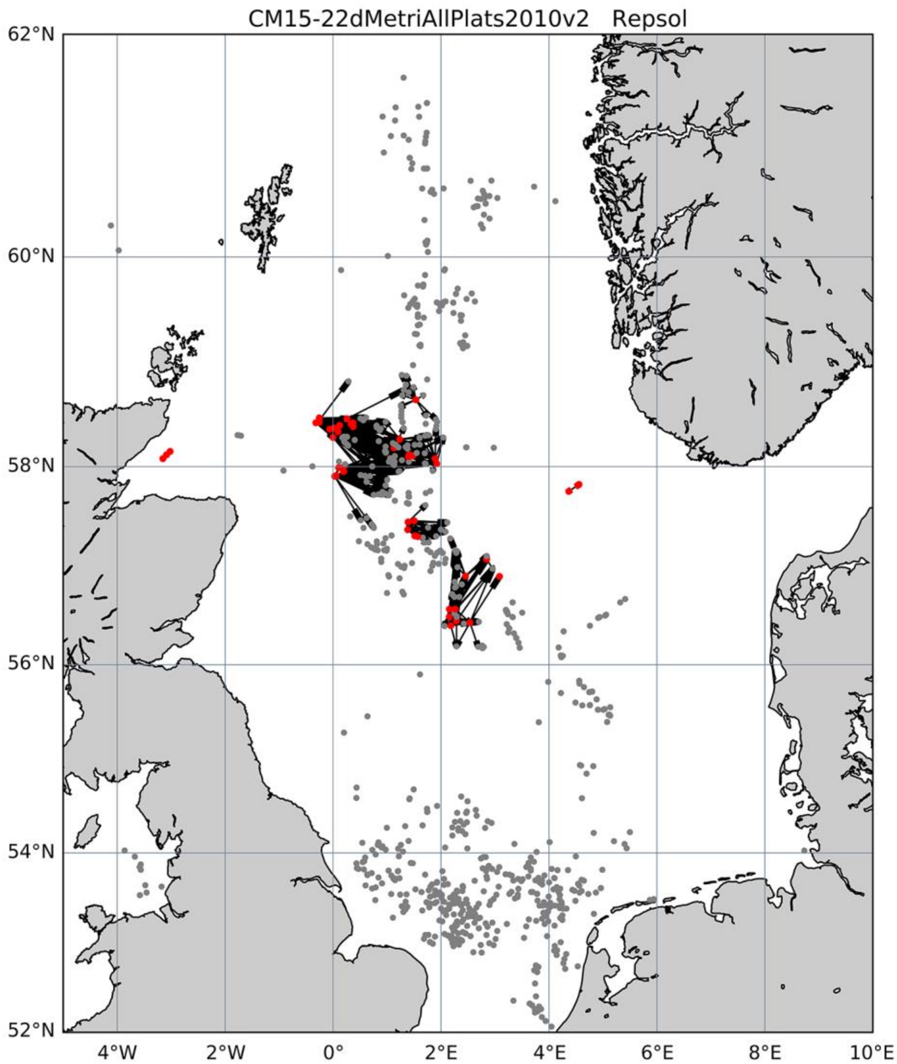
Repsol Sinopec's network for the soft coral *Alcyonium digitatum*



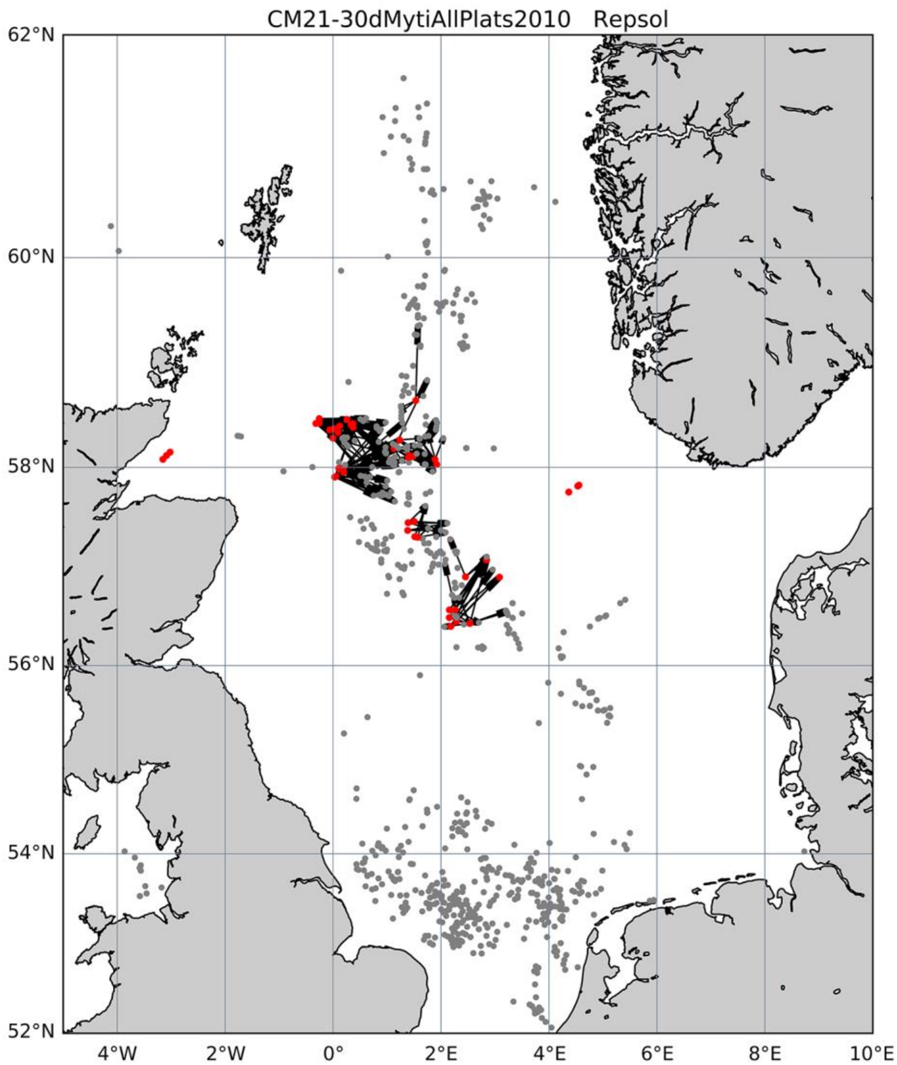
Repsol Sinopec's network for barnacle *Chirona hameri*



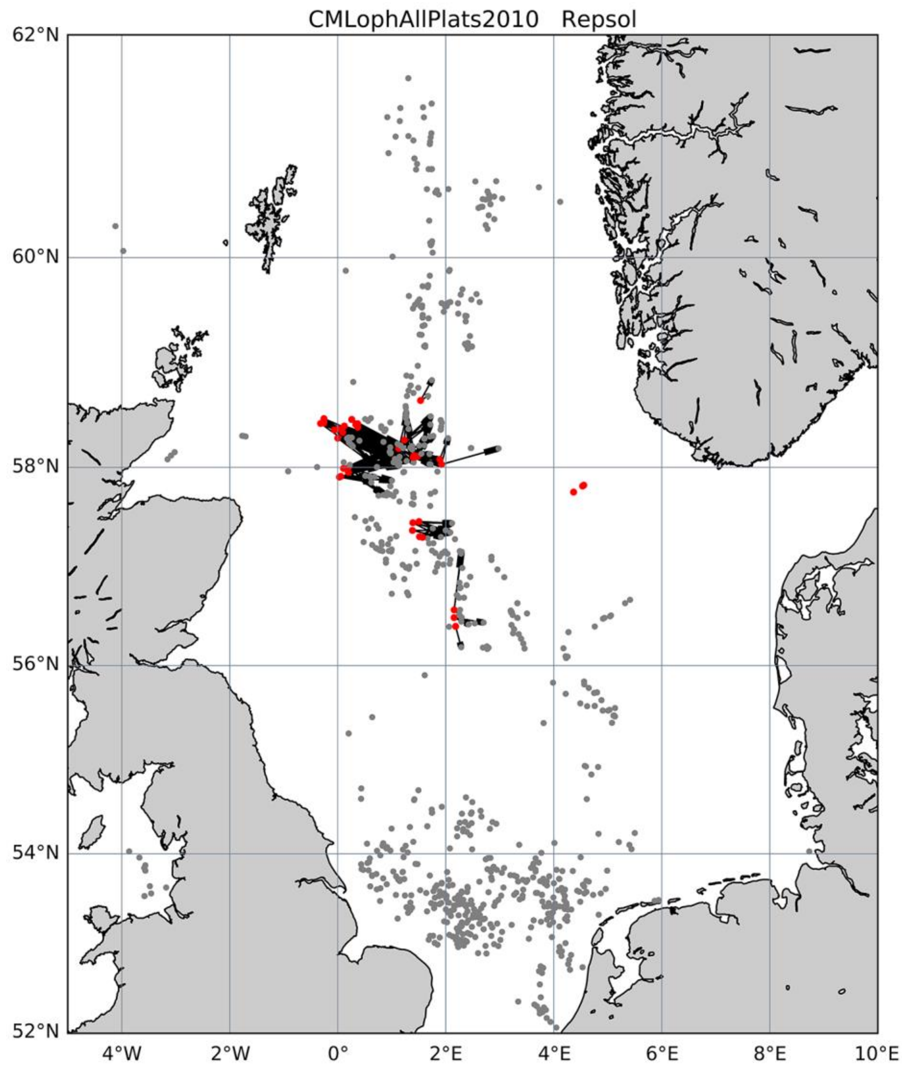
Repsol Sinopec's network for the anemone *Metridium senile*



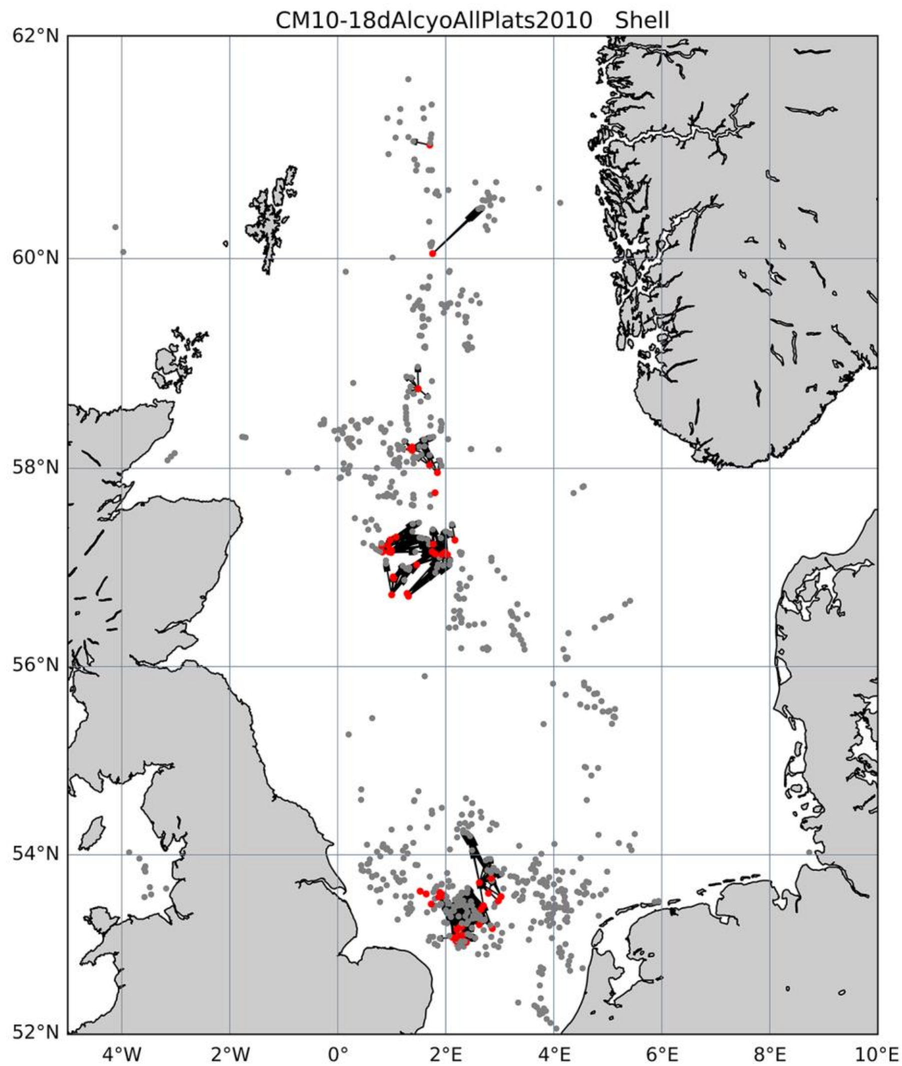
Repsol Sinopec's network for the blue mussel *Mytilus edulis*



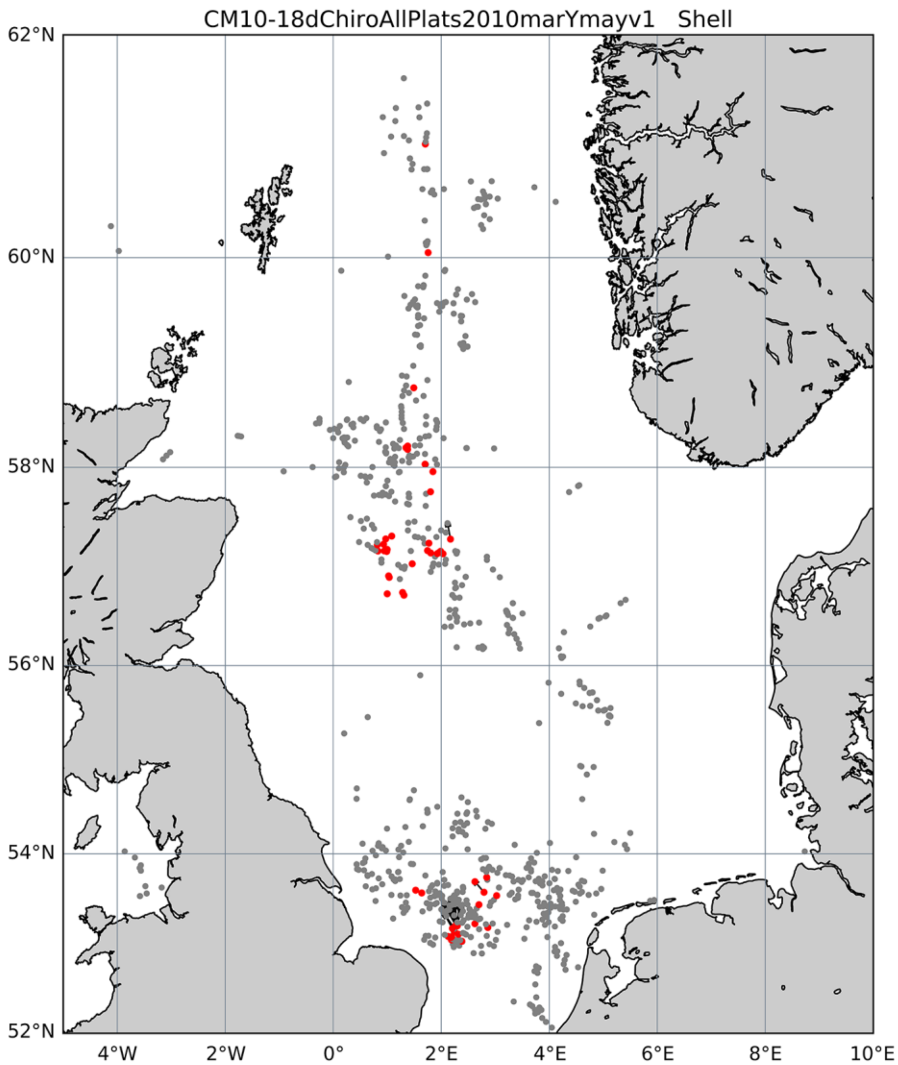
Repsol Sinopec's network for the stony coral *Lophelia pertusa*



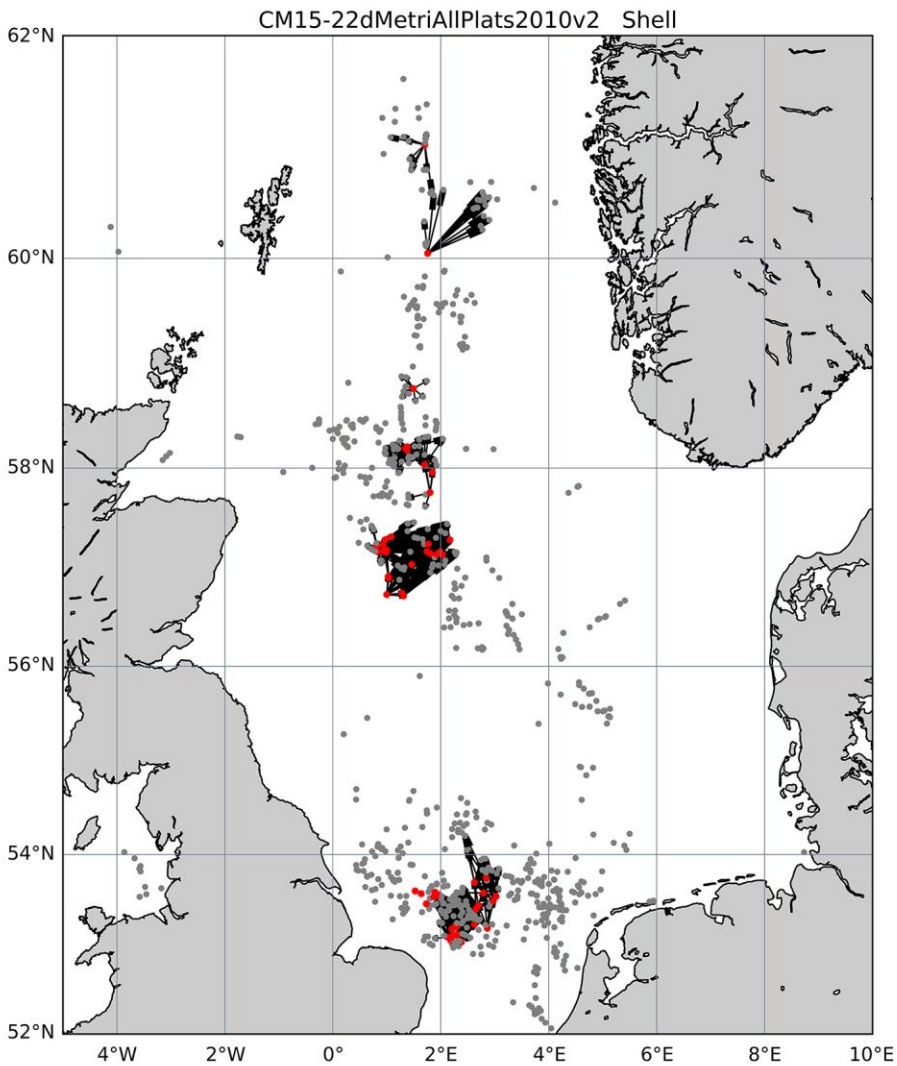
Shell's network for the soft coral *Alcyonium digitatum*



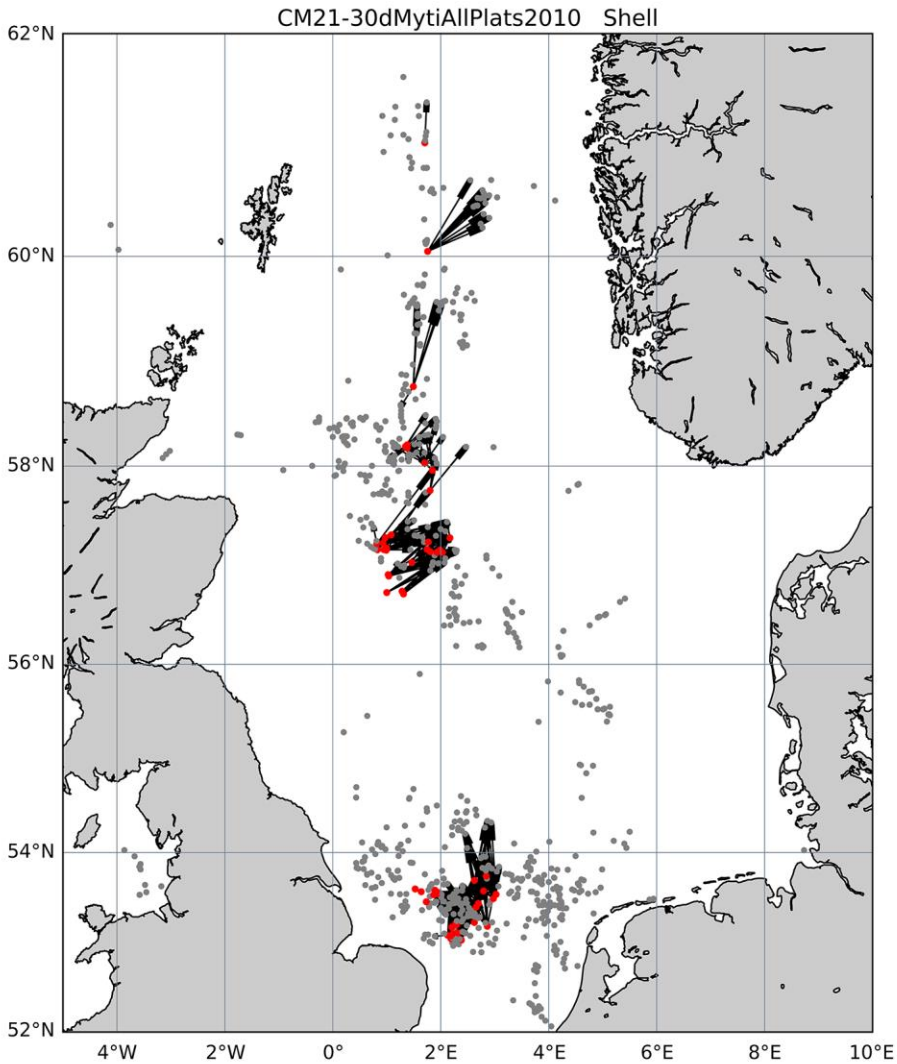
Shell's network for the barnacle *Chirona hameri*



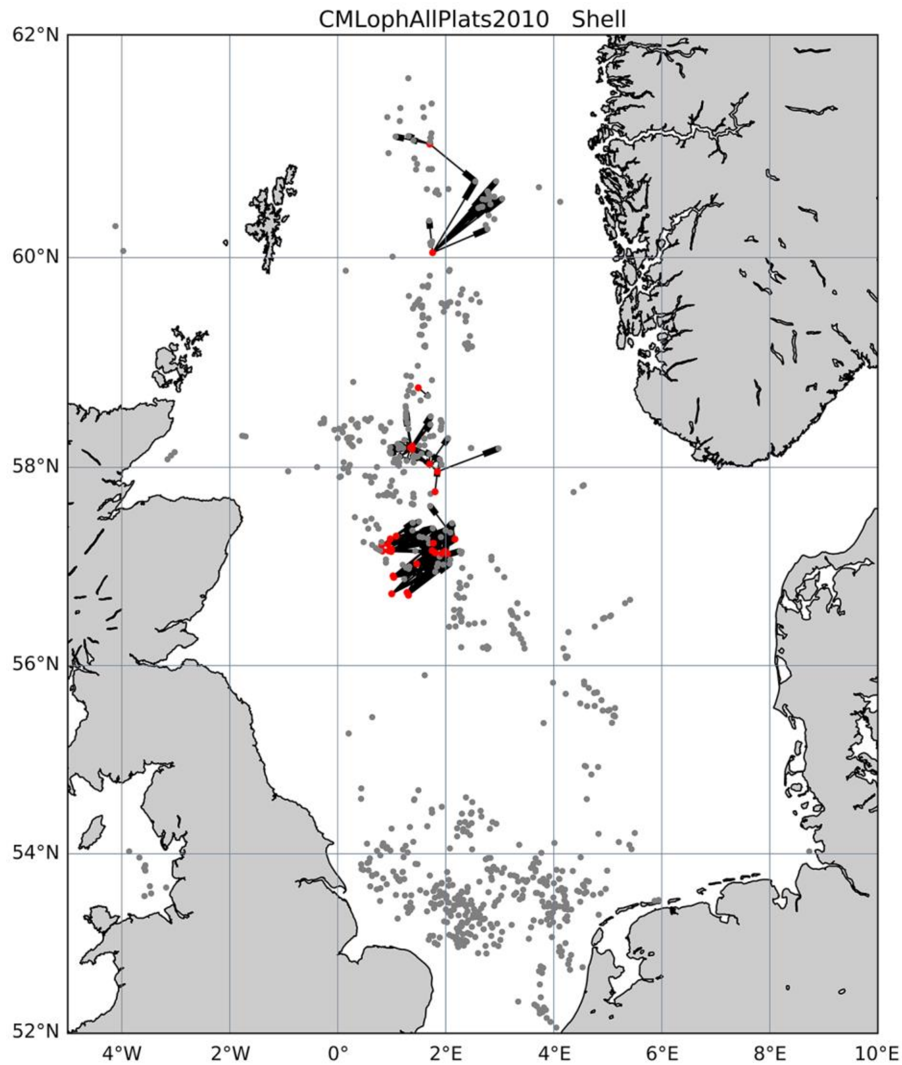
Shell's network for the anemone *Metridium senile*



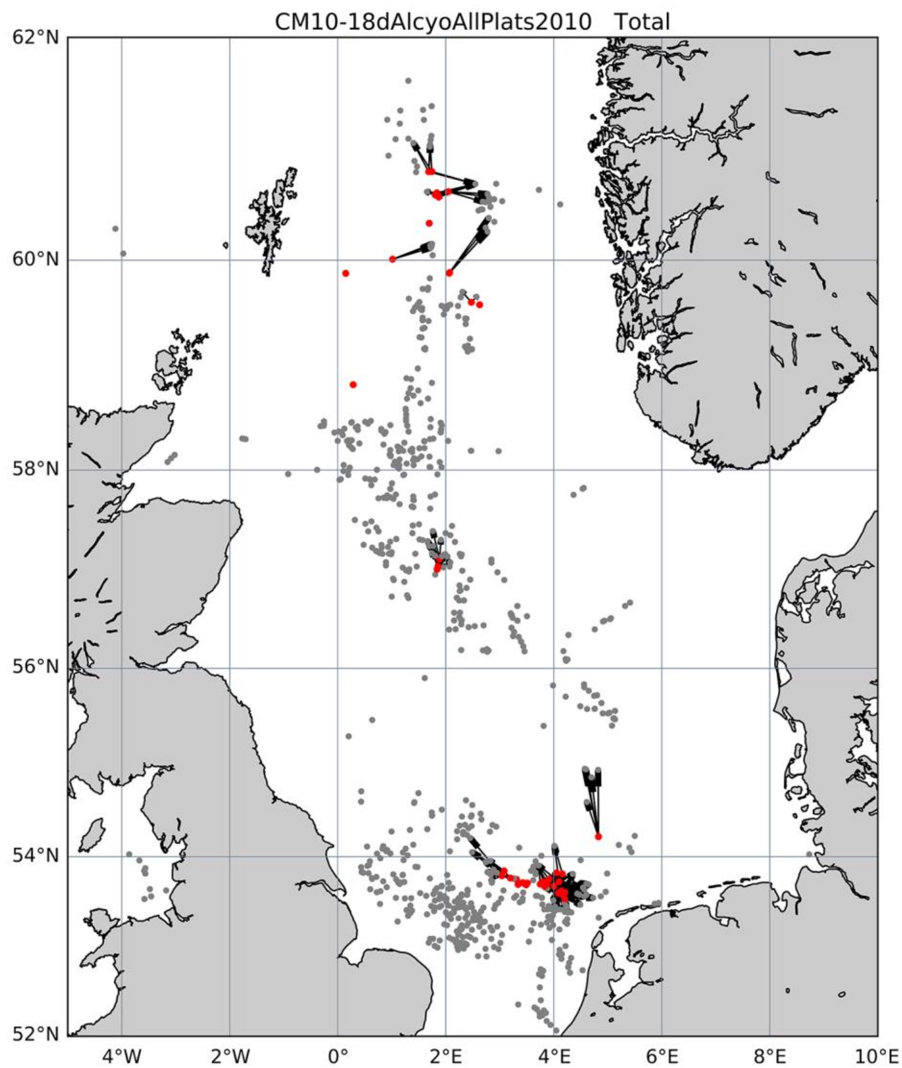
Shell's network for the blue mussel *Mytilus edulis*



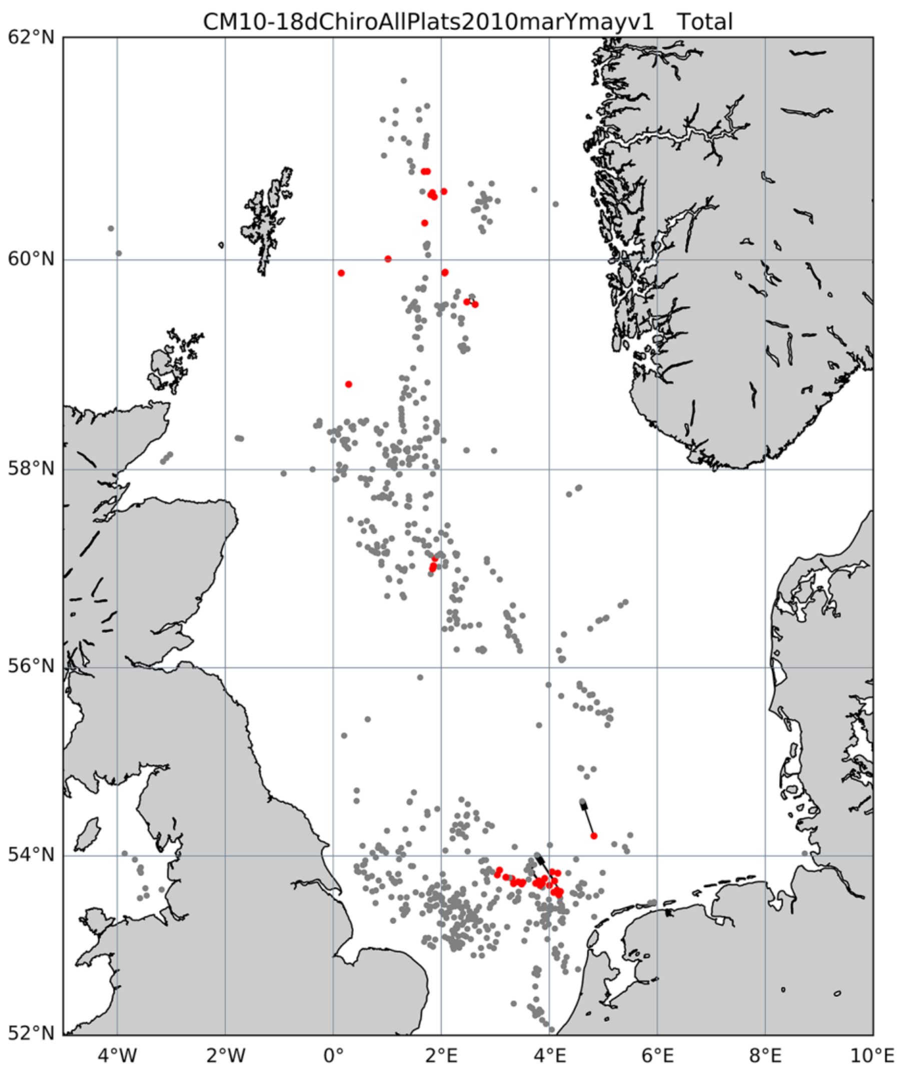
Shell's network for the stony coral *Lophelia pertusa*



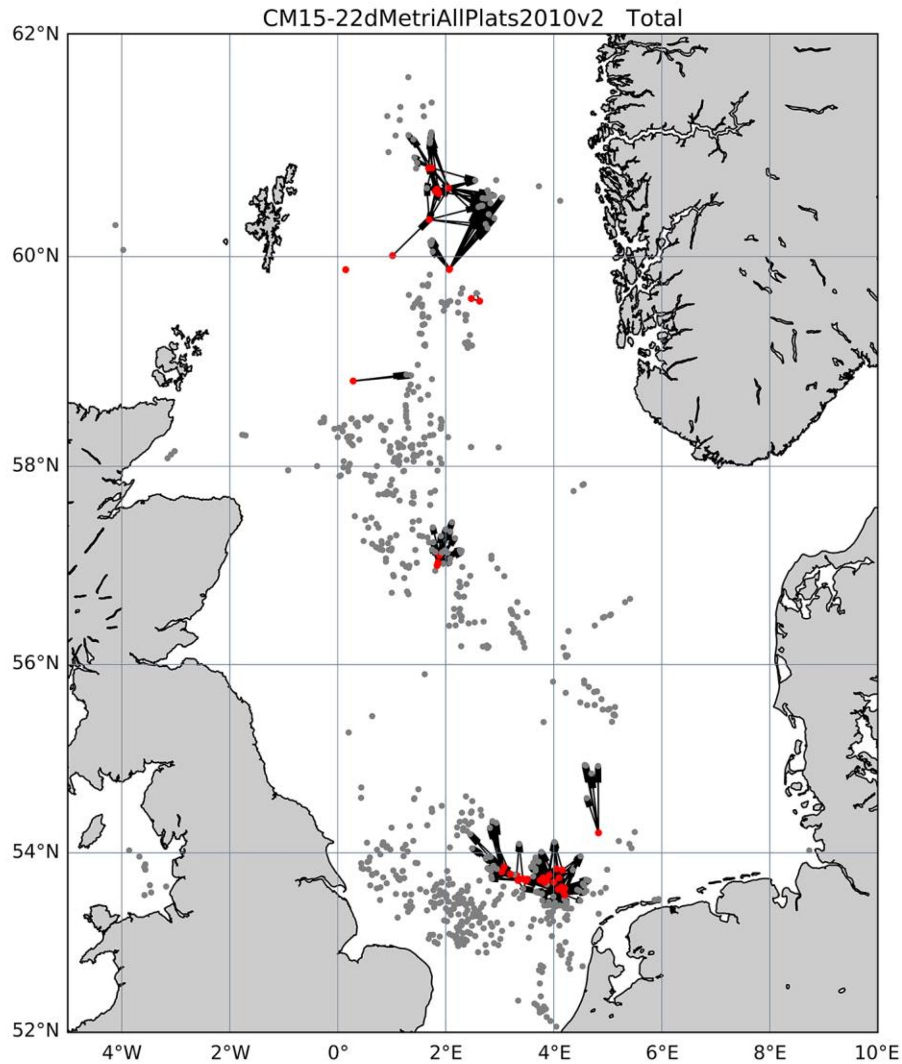
Total's network for the soft coral *Alcyonium digitatum*



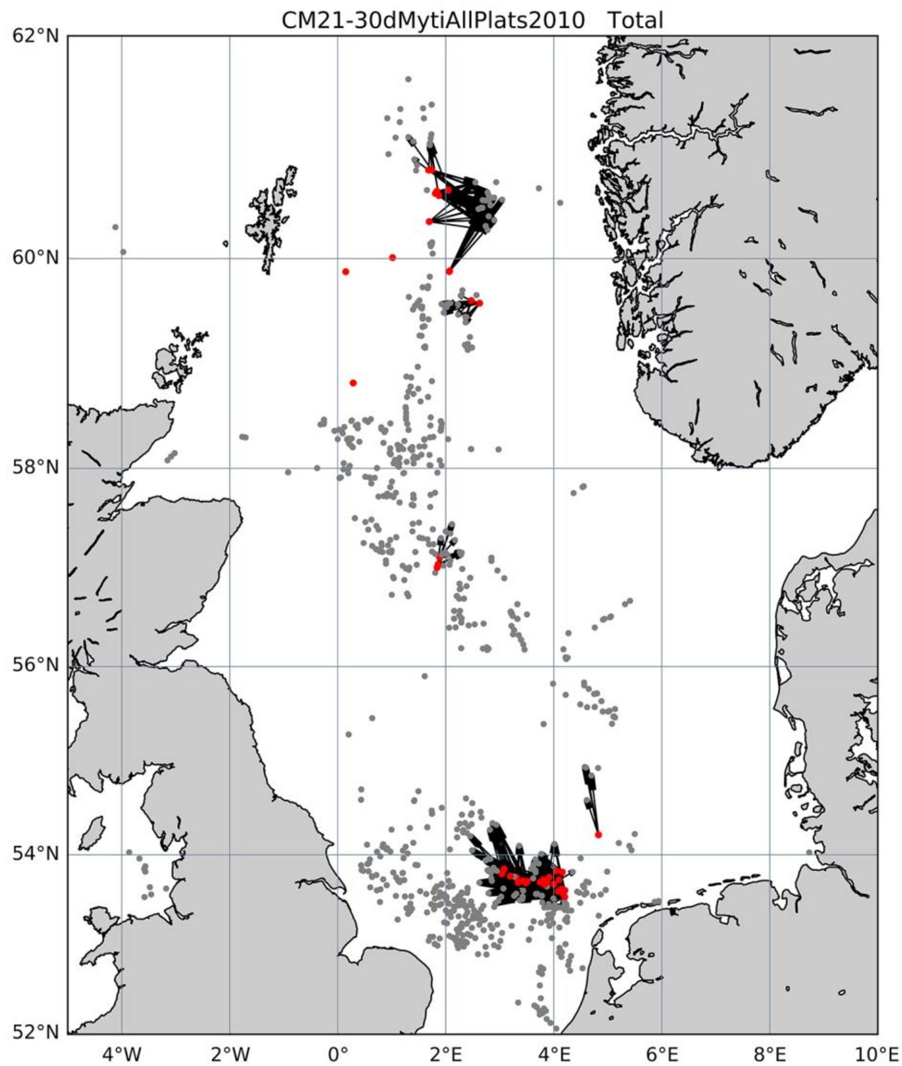
Total's network for the barnacle *Chirona hameri*



Total's network for the anemone *Metridium senile*



Total's network for the blue mussel *Mytilus edulis*



Total's network for the stony coral *Lophelia pertusa*