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The Ecological and Social Effects of Open Ocean Mussel Farming

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THE ECOLOGICAL AND SOCIAL EFFECTS OF OPEN OCEAN MUSSEL FARMING

by

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At no time during the registration for the degree of Doctor of Philosophy has the author been registered for any other University award without prior agreement of the Doctoral College Quality Sub-Committee.

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Abstract

THE ECOLOGICAL AND SOCIAL EFFECTS OF OPEN OCEAN MUSSEL FARMING

Danielle Robyn Bridger

Mussel aquaculture installations located in inshore waters have been shown to have a wide range of impacts on the surrounding environment and marine organisms, while also presenting a problem to other marine users. However, there is some evidence that moving these installations further offshore into the open ocean could mitigate these impacts. This thesis aimed to develop and pilot a robust monitoring programme that could be used to inform future management of aquaculture installations. A further aim was to assess the effects of mussel headlines at an open ocean long-line mussel farm, currently under development in Lyme Bay, southwest UK, on benthic and pelagic ecosystems, and on local fishers.

Filter feeding mussels can affect the pelagic and benthic ecosystems through the addition of ropes and hard structure to the pelagic environment, the drop-off of mussels, mussel debris, and build up of biodeposits (faeces and psuedofaeces) on the seabed. However, there is a lack of knowledge on the effects of open ocean mussel farms compared to extensive research on coastal farms. There is also the need for a holistic monitoring system that accounts for the effects of the whole ecosystem as well as the perceptions of other marine users (Chapter 1).

The Lyme Bay mussel farm, which is located in an area of historic heavy fishing activity, has introduced ropes into the pelagic ecosystem, which are acting as fish aggregation devices and a habitat for epibiota. There were large aggregations of pelagic fishes around the mussel farm headlines, with a greater abundance around

ropes growing 1-year-old and 2-year-old mussels, which supported a greater species richness of epibiota, illustrating that the fishes may not just be attracted to the structure, but to the food source provided. Furthermore, the presence of mussel headlines did not lead to a detectable reduction in zooplankton abundance (Chapter 3), although this may be because of sampling techniques. The mussel headlines have led to a change in the epibenthic community. Taxa recorded in the epibenthos, including some commercial species, showed a trend for greater abundances beneath the headlines, compared to areas that were still being heavily fished. There was no change to the organic matter or mean particle size of the sediment beneath the headlines or associated infaunal communities, although there were indications that the mussel headlines may be causing a reduction in redox potential (Chapter 4). Perceptions from local fishers were mixed. Some had been displaced by the farm, and had negative views on its development, whereas others noticed an increase in their catch around the farm area and recognised the potential for the farm to have a positive effect on fisheries. There was no evidence that the farm had increased landings in the area so far, so any increases in catch would only be on an individual level (Chapter 5).

The monitoring programme used has successfully sampled taxa from both the benthic and pelagic ecosystems, however, a few modifications are provided, along with recommendations for future monitoring (Chapter 6). This thesis has highlighted the importance of taking a holistic approach to assessing the effects of open ocean mussel farming, while increasing the evidence base available to policy makers that could be used to help guide the initiative to move aquaculture installations offshore, supporting the Blue Growth agenda.

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General Introduction

To feed the world's growing population, and meet global fish consumption demands, the aquaculture industry continues to expand rapidly. In 2018, aquaculture production made up 46 % of global total production (82 million tonnes) (FAO, 2020), making up the shortfall left by stagnating capture fisheries that are unable to keep up with an ever-increasing demand for fish and seafood (Pauly et al., 1998; Jackson et al., 2001; Pauly et al., 2002). Mussel aquaculture has been steadily increasing globally to over 1.2 million tonnes produced in 2018 (FAO, 2020). However, production in the European Union (EU) has shown a decreasing trend in the last two decades; low profitability, diseases and lack of mussel seed have been suggested as causes (Avdelas et al., 2021).

The official European Blue Growth Strategy report recognises that the main growth in supplies of seafood, to provide enough food for a growing population, will have to come from sustainable aquaculture production. The EU directive on Marine Spatial Planning encourages investment in offshore activities and moving aquaculture developments further offshore to support sustainable growth in the aquaculture sector (European Commission, 2012). Offshore aquaculture is gaining acceptance (Froehlich et al., 2017; Thomas et al., 2019). However, compared to research on coastal installations, research on offshore farms is limited, with discrepancies on what constitutes "offshore" aquaculture (Froehlich et al., 2017). When the concept of offshore aquaculture is open to interpretation, this makes it difficult to compare the impacts of offshore and coastal developments on the surrounding environment. Holmer (2010) set out definitions of offshore farming, including being located over 3 km from the shore, in an exposed area with wave heights of up to 5 m. The faster currents that exist further offshore could help reduce impacts often found in coastal farms, such as pollution and area use conflicts. However, it is still difficult to compare coastal and offshore installations when different methods of assessment have been used (Froehlich et al., 2017).

Recently, molluscan aquaculture has been identified as one of the lowest impact production methods, compared to finfish and shrimp aquaculture, capture fishery and livestock production. Aquaculture of molluscs requires very little energy input, has the lowest greenhouse gas production per portion of protein, absorbs nutrients rather than contributing to eutrophication, and requires almost no fresh water and no antibiotics (Hilborn et al., 2018). Aside from being high in protein, they are known to provide ecosystem services that are beneficial to the environment (van der Schatte Olivier et al, 2018), increase habitat diversity as ecosystem engineers (Borthagaray and Carranza, 2007), and remove particulate matter from the water column through filter feeding (Lüskow and Riisgård, 2018).

Although mussel aquaculture, in particular offshore mussel farming, may present a reduced ecological footprint compared to other culture species, as they do not rely on feed pellets or additives for nutrition (Shumway et al., 2003; Hixson, 2014), they also have their own environmental consequences (Lacson et al., 2019). In areas of low dispersal capacity, mussel farms may cause organic enrichment and hypoxic sediment (Cranford et al., 2009; Grant et al., 2005), changing macrobenthic infaunal communities (Chamberlain et al., 2001; Newell, 2004). Moving farms offshore into areas of strong hydrodynamic forces may mitigate this somewhat (da Costa and Nalesso, 2006; Lacoste et al., 2009); offshore cultivation has been linked to an increase in macrofaunal diversity due to mussel drop-off increasing the heterogeneity of the benthic environment (McKindsey et al., 2011; Wilding and Nickell, 2013). However, offshore cultured bivalves may still affect the carrying capacity of the surrounding environment through competition with naturally occurring filter feeders (McKindsey, 2013).

Objectives of this Thesis

The objectives of this research were to identify the main gaps in knowledge of the effects of offshore mussel aquaculture and to develop a framework for an environmental and social monitoring programme for future mussel farms to adopt. This monitoring programme will be equipped to assess fully the whole ecosystem effect of installing a mussel farm in the open ocean, as well as the perceptions of the farm from other marine stakeholders.

In order to capture the main ecosystem components, four video and three physical sampling methods were employed at headlines within a new open ocean mussel farm under construction in Lyme Bay, south west UK. Further to this, a questionnaire was devised to explore the views of local fishers about the farm.

The following research questions were applied to this thesis:

- **Chapter 1** – What is the current knowledge on the effects of long-line mussel farming and where do the knowledge and data gaps lie when assessing the effects of open ocean mussel farms?
- **Chapter 2** – What are the site characteristics of the study mussel farm? What protocols do they use?
- **Chapter 3** – What methods can be used to assess how a mussel farm affects the pelagic ecosystem? What effects have the headlines at the study mussel farm had so far?

- **Chapter 4 –** What methods can be used to assess how a mussel farm affects the benthic ecosystem, including the epibenthic and infaunal organisms? What are the effects of the headlines at the study mussel farm so far on the habitat beneath the headlines and the associated epibenthic and infaunal organisms?
- **Chapter 5 –** How can the perceptions of local fishers be assessed? How is the study mussel farm perceived by local fishers so far and has it started to change their fishing practices?
- **Chapter 6 –** General discussion. Was the monitoring programme effective in surveying the benthic and pelagic ecosystems? Are any improvements to the programme needed?

It is intended that the evidence and learning from this research will provide novel information to support decision making for how ocean space is utilised, and for the sustainable development of aquaculture. Chapters 3, 4 and 5 are submitted as a series of papers, therefore relevant information may be shared between chapters.

Chapter 1: The Ecological and Social Effects of Long-line Mussel Farming: A Review.

The ecological and social effects of long-line mussel farming: A review.

Abstract:

With world fish consumption increasing, and capture fisheries unable to keep up with the demand, there has been an increase in aquaculture production. This has raised concerns about the impact of aquaculture on the surrounding environment. Mussel aquaculture has expanded in many countries, but its development has been limited due to the environmental impacts of farming in inshore water, along with decreasing coastal water space. Open ocean aquaculture installations could have the potential to overcome these issues. However, compared to research on coastal installations, research on open ocean farms is limited.

This review synthesises the existing literature on the effects of coastal and open ocean long-line mussel farming with the aim of identifying knowledge gaps on open ocean farms. It also explores human perception of mussel aquaculture and potential contribution to ecosystem services. The impacts of long-line mussel farming identified in this review include epibenthic and infaunal organisms, benthic habitat, plankton and pelagic fish that have been sampled by both extractive (e.g. grab sampling) and non-extractive (e.g. underwater cameras) techniques.

With the need for sustainable management of aquaculture, a holistic approach to monitoring is needed first to understand the effects of existing open ocean long-line mussel farms. This monitoring programme would support pre-development permissions and inform policy and management practices on a sustainable approach for the environment, while taking into account social perceptions and other marine users.

Keywords: aquaculture, ecology, mussel farming, open ocean, offshore, socio-ecology

1.1 Introduction

World fish consumption has increased from an average of 9.9 kg per capita in the 1960s to 20.5 kg per capita in 2018, with 179 million tonnes in total produced for human consumption (FAO, 2020). Capture fisheries have not been able to keep up with this increase in demand (Pauly et al., 1998; Jackson et al., 2001; Pauly et al., 2002; Pauly and Zenner, 2016; Rousseau et al., 2019), with production remaining relatively static since the 1980s (Figure 1.1). Aquaculture has helped make up the shortfall that capture fishery production can no longer provide. Aquaculture is defined by the United Nations Food and Agriculture Organisation (FAO) as "the farming of aquatic organisms including fish, molluscs, crustaceans and aquatic plants" (FAO, 2003). In 2018, total global production was 96.4 million tonnes from capture fisheries, and 82.1 million tonnes from aquaculture. Aquaculture is now contributing 46 % of total global production, compared to just 7 % in 1974, and has been instrumental in the growth of fish supply for human consumption (FAO, 2020).

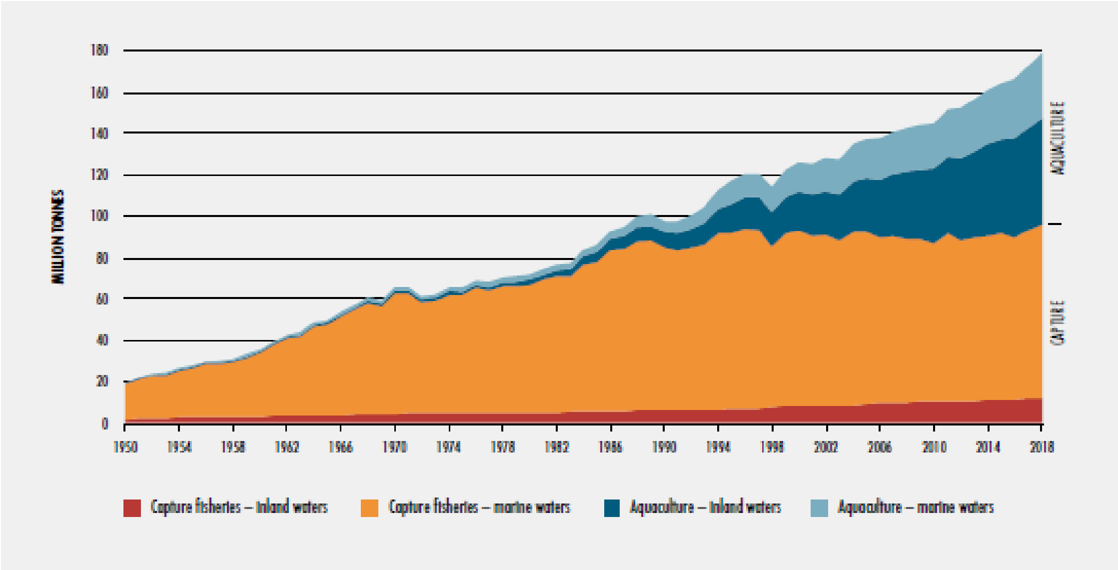


Figure 1.1: World capture fisheries and aquaculture production from 1950 to 2018 (Source: FAO, 2020).

The reported world total of 82.1 million tonnes of seafood from aquaculture production has an estimated value of USD 250.1 billion, with 54.3 million tonnes of finfish making up the highest proportion of this value (USD 139.7 billion), followed by 17.7 million tonnes of molluscs (USD 34.6 billion) (FAO, 2020). Table 1.1 shows the full breakdown of production of farmed aquatic organisms and their values. In 2018, China was by far the largest producers of farmed species, producing 58 % (47.6 million tonnes) of the world total. Europe produced only a small fraction of this amount (3.1 million tonnes), accounting for less than 4 % of the world total (FAO, 2020). Aquaculture accounted for 17 % of total fish production in Europe. Aquaculture employment has been growing slowly in Europe, while fisheries employment has been declining since 2010 (FAO, 2020).

Table 1.1: Farmed organisms harvested from global aquaculture for human consumption in 2020. Numbers taken from FAO (2020). 'Others' are frogs, reptiles and aquatic invertebrates.

Category	Number of species	Production (million tonnes)	Value (USD billion)
Finfish	369	54.3	139.7
Molluscs	109	17.7	34.6
Crustaceans	64	9.4	69.3
Others	16	0.9	6.5

Marine and coastal aquaculture (both inshore and offshore) contributes to about 37 % of total aquaculture; the rest comes from inland aquaculture. The vast majority (86 %) of finfish are farmed inland (FAO, 2020) in, for example, recirculation systems or ponds. The remaining 14 % are primarily raised in floating suspended cages anchored to the seabed (Appleford et al., 2012). In contrast, molluscs are almost entirely farmed in the marine and coastal environment (99 %; FAO, 2020), and shelled molluscs represented 56.2 % of the production of marine and coastal aquaculture (FAO, 2020). Bottom-dwelling molluscs, such as scallop and oyster, can be enclosed by mesh fences, grown in mesh trays on horizontal racks, or in the same manner as other bivalve molluscs, for example mussels, in suspended culture in/on nets, ropes etc. (Appleford et al., 2012). France and Italy are the greatest producers of molluscs in the marine and coastal environment in Europe, with 144.8 and 93.2 thousand tonnes produced in 2018, respectively (FAO, 2020).

1.2 Literature review methods

Due to the extensive amount of literature relating to mussel farming, this review concentrates on the effects on long-line farming, with examples from other methods given where relevant. Specifically, the effects on long-line farming on the pelagic, epibenthic and benthic systems, as well as human perception studies, were identified as the focus. This review gives an overview of the status of mussel farming, specifically within Europe and the UK, and then focuses on the impacts of long-line mussel aquaculture on the surrounding environment, as well as on other marine stakeholders. It discusses the survey methods used in the studies with the aim to identify gaps in the current knowledge of the effects of open ocean long-line mussel aquaculture.

Literature searches were conducted using Google Scholar and Web of Science using search terms such as “offshore mussel farming”, “offshore aquaculture”, “open ocean mussel farming”, “effects of mussel farming”, “socio-economic effects of mussel farming”, “benthic effects of mussel farming”, “effects of aquaculture” and any combination of these. More keywords used were “longline”, “long-line”, “benthic”, “pelagic”, “plankton” and any combination of these. Literature was then read and assessed on its relevance to this review.

Studies on raft, bouchot, polyculture and culture of mussels in lagoons and estuarine environments were not actively searched for and only included if complimenting studies on long-line mussel farms, as the focus of this review is identifying gaps in the knowledge of open ocean long-line mussel farms.

1.3 Mussel aquaculture

Global mussel aquaculture production has been increasing steadily, with the production of mussels reaching 2.1 million tonnes in 2018 (worth USD 4.5 billion). China produced almost half this volume (FAO, 2020). Large producers in Europe were Spain (283,800 tonnes), Italy (62,035 tonnes) and France (57,148), with the Netherlands, Greece, Germany and the UK also appearing in the 15 largest producers list in 2018 (FAO FishStatJ, 2021). Despite this, and Europe contributing about 20 % of total mussel production, European mussel aquaculture is declining. It decreased from 600,000 tonnes in the late 1990s, to 480,000 tonnes (worth USD 486 million) in 2016 (Avdelas et al., 2021).

The UK produced 14,800 tonnes of mussels in 2018 (FAO FishStatJ, 2021), with mussel farming dominating shellfish aquaculture in all four regions (Seafish, 2021). Within the UK, the most widely cultivated mollusc is the blue mussel *Mytilus edulis* (Linnaeus, 1758) (Laing and Spencer, 2006), a filter feeding bivalve. Mussels have a number of attributes that make them a successful species to cultivate. These include high fecundity, self-seeding larvae, rapid growth rate and, perhaps most importantly, their mechanism of byssal attachment which anchors the mussel to its substrate (Spencer, 2002). They are ecosystem engineers that form large biogenic reefs (Borthagaray and Carranza, 2007; Ysebaert et al., 2009), which provide important ecosystem services through providing habitat structure, filtering water and cycling nutrients.

Mussels can either be produced by bottom or off-bottom cultivation, accounting for around 15 % and 85 % of overall production, respectively. Bottom culture (Figure 1.2a) involves moving mussels from natural subtidal or intertidal beds to more sheltered areas where there will be an improved growth rate (Spencer, 2002). This method is used in Wales, Northern Ireland and Poole Harbour, with 6,136 tonnes of mussels produced this way in the UK in 2016 (Seafish, 2021). However, this method of culture is typically considered to attract heavy predation, especially by crabs and starfish (Dare, 1980; Dare, 1982), making it a less favoured option.

To combat the heavy predation by crabs and starfish in the marine environment, the majority of cultivated mussels are grown ‘off-bottom’, suspended above the seabed.

The UK produced 8,549 tonnes of off-bottom mussels in 2016 (Seafish, 2021). There are three principle methods of off-bottom culture: pole, raft and long-line (Nielsen and Carvalho, 2018). Pole culture (Figure 1.2b), also known as 'bouchot', involves growing mussels on wooden stakes driven into the ground in low intertidal zones so mussels can be harvested at low tide (McKindsey et al., 2011; Goulletquer, 2020). This method is primarily used in France (e.g. Grant et al., 2012; Toupoint et al., 2016; Aubin et al., 2018). Raft culture (Figure 1.2c) is the major cultivation method employed in Spain (Spencer, 2002): seed is attached to culture ropes suspended from moored, floating rafts (Figueiras et al., 2002). Long-line culture (Figure 1.2d) consists of a series of rope droppers suspended from an anchored headline, with buoys at regular intervals to keep the structure floating. More buoys are added as the mussels grow to keep the ropes from touching the sea floor (McKindsey et al., 2011). This is the most widespread technique as it supports the most substantial harvest with minimum infrastructure (Stevens et al., 2008; Nielsen and Carvalho, 2018).

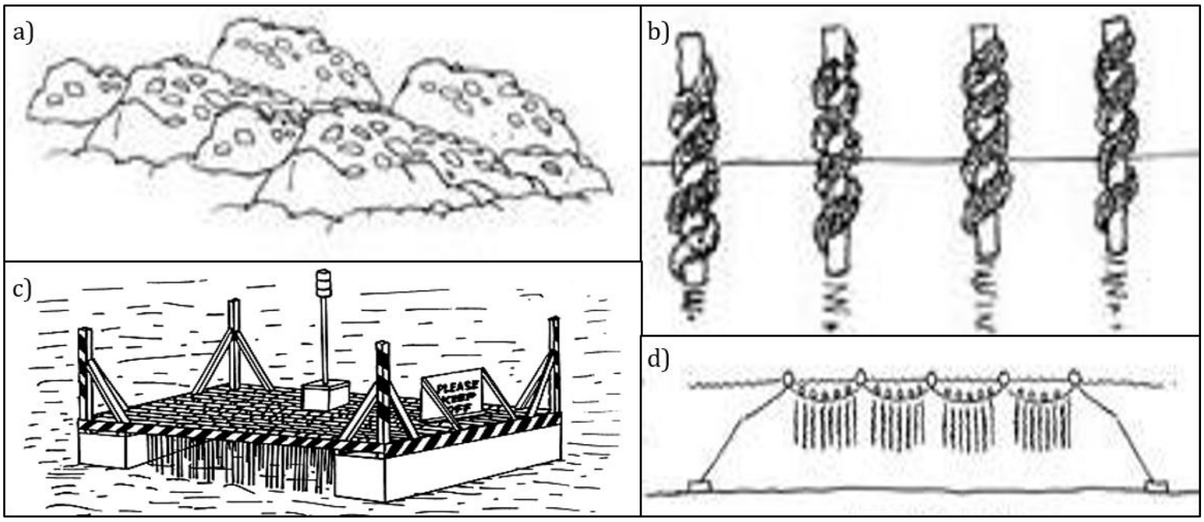


Figure 1.2: a) Bottom culture. Source: FAO (2004), b) Pole or 'bouchot' culture. Source: FAO (2004), c) Raft culture. Source: FAO (1990), and d). Long-line culture. Source: FAO (2004).

The trend toward an increase in production from this fast growing food industry sector has raised concerns about the impact of aquaculture on the surrounding environment (Black, 2001). This concern is born from experience of environmental impacts associated with sea-based finfish aquaculture systems, where farmed fish are often kept in dense populations in cages and have two main outputs of pollution: animal faeces and feed waste. Pollution accumulates under and around the fish cages and causes organic loading, negatively affecting the benthic community structure below (Kumar and Cripps, 2012). Concerns have also been raised about the effects of bivalve farming (McKindsey at al., 2001). Bivalve culture has fewer environmental impacts than finfish farming, due to there being no need to add additional food to the system, along with lower potential for acidification and lower greenhouse gas production per portion of protein (Hilborn et al., 2018). However, there is still an introduction of hard structures to the environment, which contributes to ocean sprawl (Firth et al., 2016; Heery et al., 2017), and biodeposits in the form of faeces and pseudo-faeces which settle on the seabed (Kumar and Cripps, 2012).

Research indicates that production of non-fed species can be more sustainable in terms of the environment and food security (FAO, 2016; Hilborn et al., 2018). Nevertheless, production growth has been faster for fed species rather than non-fed species, and finfish are worth more USD per tonne than molluscs (see Table 1.1). Bivalve molluscs are one of the most important non-fed species in aquaculture in terms of demand (FAO, 2016).

Mussel farms have varying effects on the surrounding environment. There are reports of negative impacts (Kaspar et al, 1985; Stenton-Dozey et al., 1999; Chamberlain et al., 2001; Hargrave et al., 2008, Cranford et al., 2009; Keeley, 2013), little or no ecological change (Crawford et al., 2003; Danovaro et al., 2004; Lasiak et al., 2006; McKindsey et al., 2012; Wilding and Nickell, 2013; Dimitriou et al., 2015), or even an increase in biodiversity and biomass of fish assemblages (Inglis and Gust, 2003; Clynick et al., 2008; D'Amours et al., 2008).

There has been a variety of terms used in the aquaculture literature to define the type of farm being studied (e.g. inshore, offshore, open ocean). To provide common terminology for general use, Holmer (2010) provided a set of guidelines to distinguish between farm types based on data from a working group addressing offshore aquaculture. The review defines three types of marine aquaculture: coastal, off-coast and offshore. Table 1.2 provides definitions of these three types based on physical and hydrodynamical settings. The term open ocean aquaculture is used when the farm is in an area which exhibits characteristics from both off-coast and offshore definitions (Holmer, 2010). From here on, the terms 'coastal', 'off-coast', 'offshore' and 'open ocean' will be used to define the type of aquaculture being addressed.

Table 1.2: Definitions of the three types of marine aquaculture. Table adapted from Holmer (2010).

Type of aquaculture	Distance from shore	Water depth	Visual impact	Wave height	Exposure
Coastal	< 500m	< 10 m	Within sight of shore	< 1m	Sheltered
Off-coast	500 m to 3 km	10 to 50 m	Usually within sight	< 3 to 4 m	Somewhat sheltered
Offshore	> 3 km	> 50 m	Not visible from shore	Up to 5 m	Exposed

1.4 Current knowledge on the effect of long-line mussel farming on the benthic and epibenthic ecosystem

Studies of shellfish aquaculture impacts on the marine benthic environment and associated macrobenthic communities have provided a range of observations. There have been reports of little or no impact (e.g. Crawford et al., 2003; Lasiak et al., 2006), in contrast to conflicting significant positive (e.g. Inglis and Gust, 2003; D'Amours et al., 2008; Ysebaert et al., 2009) or negative (e.g. Chamberlain et al., 2001; Hargrave et al., 2008) ecological changes within farms.

Mussels are filter feeders; they pump water in through the gills where suspended material is trapped, passed by the cilia to the mouth and sorted into food and unwanted material. Unwanted material is mixed with mucus and expelled from the shell as pseudo-faeces (Swift, 1993). Food material passes through the mouth and down to the stomach where digestion takes place. Undigested particles are mixed with other unwanted matter and transferred to the lower intestine, compacted into ribbon-shaped faeces and disposed of with the outgoing flow of water (Spencer, 2002). Large amounts of biodeposits from coastal long-line mussel farms can increase benthic organic loading, changing the physical and chemical characteristics of the sediment beneath mussel farms (Kaspar et al., 1985; Nizzoli et al., 2006), therefore affecting benthic communities (Kaspar et al., 1985; Chamberlain et al., 2001). These are the negative effects most commonly reported by literature investigating the farming of mussels and other shellfish including raft (e.g. Stenton-Dozey et al., 1999) and bouchot (e.g. Grant et al., 2012) culture.

1.4.1 Effects on abiotic measures

Common methods of assessing the impact of mussel farming on the sediment beneath include particle size analysis, organic matter content and redox potential (Miron et al., 2005; Hargrave et al., 2008; Grant et al., 2012; Wilding, 2012). Some authors have found reduced oxygen conditions beneath long-line mussel farms, along with an increase in organic matter and finer sediment (Chamberlain et al., 2001; Hartstein and Rowden, 2004; Carlsson et al., 2012), especially in shallow coastal inlets with relatively low dispersal capacity (Lacson et al., 2019). Redox probes can be used to classify sediments as polluted in terms of organic enrichment (Wildish et al., 2001). For example, reduced conditions within long-line mussel farms in Canada (Hargrave et al., 2008), Italy (Nizzoli et al., 2006) and Sweden (Gibbs, 2007) have been recorded. However, not all studies agree with these findings; Crawford et al. (2003) found no significant differences in redox potential between long-line mussel farm and reference sites in Tasmania, Australia. Dimitriou et al. (2015) also concluded that the biodeposition of organic material did not change the ecological status of benthic communities below a long-line mussel farm in Maliakos Gulf in the western Aegean Sea.

The same discrepancies occur for particle size and organic matter content in sediment samples. Some studies report a greater proportion of silty sediment and higher organic matter (Kaspar et al., 1985; Christensen et al., 2003; Nizzoli et al., 2006; Hargrave et al., 2008) beneath long-line mussel farms, whereas others found no significant differences in either metric (Crawford et al., 2003; Miron et al., 2005; da Costa and Nalesso, 2006). This is most likely linked to the location of the mussel farm site, for example, whether the site is sheltered or exposed, in an area of weak or strong tidal flows.

This is demonstrated by Hartstein and Rowden (2004) and Hartstein and Stevens (2005). These studies compared long-line mussel farm sites of different hydrodynamic regimes in the Marlborough Sounds, New Zealand. Two sites were sheltered and one site was more exposed and close to strong tidal flows. Unsurprisingly, sediment beneath farms at the two sheltered sites had significantly greater organic matter content and carbon/nitrogen ratios than reference sites, but there was no significant difference at the exposed site (Hartstein and Stevens, 2005). Sediment particle size was also finer at the sheltered sites than the exposed site, coupled with significantly different macroinvertebrate assemblage compositions (Hartstein and Rowden, 2004). These studies illustrate the importance of location and flow characteristics when considering the effects a mussel farm will have on the benthos.

1.4.2 Effects on biotic measures

Negatively impacted sediment conditions are likely to affect the associated infaunal assemblage. Mirto et al. (2000) found a reduction in meiofaunal densities in response to reduced sediment at a long-line mussel farm located in the western Mediterranean Sea. Another common response of infauna to adverse environmental conditions is higher diversity of taxa but a lower abundance of organisms (da Costa and Nalesso, 2006). However, Ysebaert et al. (2009) found that species richness, diversity and abundance of infauna were significantly higher at mussel farm sites in the Oosterschelde, The Netherlands than at control sites.

Mobile benthic fauna, including fish and crustaceans, can also be affected by mussel aquaculture operations by the addition of physical structure to the benthos, and from the introduction of the mussels themselves (Callier et al., 2018). The mussels and associated epifauna may fall from mussel long-lines or other culture structures, build up on the seabed and represent an attractive food source for benthic predators (Inglis and Gust, 2003). Léonard (2004) estimated that an average of 30 g of 2-year-old mussels per metre drops per day at a long-line mussel farm in Canada.

More recently, diver video transects beneath a long-line mussel farm in New Zealand showed that living mussels and dead mussel shells covered up to 55 % of the seabed. Mean densities of the 11-armed starfish *Coscinasterias muricata* were up to 39 times greater beneath farm sites than in reference areas, and positively correlated with living mussel abundance on the seabed (Inglis and Gust, 2003). This supports observations by Dare (1982) of a natural phenomenon where large, dense aggregations of common starfish *Asterias rubens* invaded and decimated intertidal *M. edulis* beds in the Irish Sea. Wilding and Nickell (2013) also found that starfish were approximately ten times more abundant close to the mussel raft droppers compared to the reference site, although they could not positively associate this with the presence of shell-hash. Further, Ysebaert et al. (2009) used video tracks under a long-line mussel farm in the Oosterschelde to record the presence of epibenthic animals. They occasionally observed *A. rubens* and the common shore crab *Carcinus maenas*, along with regular sightings of the sea slug *Philine aperta* and netted dog whelk *Tritia reticulata* (as *Hinia reticulata*). These studies illustrate how long-line culture can introduce mussels to the seabed through drop-off, which can alter the local distribution of epibenthic species.

The introduction of long-line mussel farms have also been shown to increase the abundance of macrobenthic species under them. Both Archambault et al. (2008) and Clynick et al. (2008) found that winter flounder *Pseudopleuronectes americanus* and rock crab *Cancer irroratus* were present at long-line mussel farms in the Magdalen Islands, Canada. Further, Drouin et al. (2015) found that *P. americanus*, *C. irroratus*, *A. rubens*, and American lobster *Homarus americanus* were all at least three times more abundant at an area within a long-line mussel farm in Canada with 2-year-old mussels and more frequent mussel drop-off than other areas within or outside of the farm. They also showed the effect that addition of physical structure can have on mobile fauna, observing a strong association of *H. americanus* with mussel long-line structures, particularly anchor blocks. A further manipulative experiment showed that *H. americanus* were significantly attracted to the anchor blocks. Mussel farms therefore have the potential to provide food and refuge for larger, commercially important species. Anchor blocks have the potential to act as artificial reef structures, which are used around the world for various purposes including improving fishery production and rehabilitating habitats (Lee et al., 2018). However, instead of rehabilitating habitats they may artificially increase the benthic ecosystem beyond its natural complexity, which may lead to a change in ecosystem features. Therefore, anchor blocks may cause negative effects rather than the positive effects they were installed to generate. Species richness and fish abundance can be greater on natural reefs than artificial reefs (Carr and Hixon, 1997), although this is not always true (Folpp et al., 2013). Filter feeders like bryozoans and sponges can be more abundant on artificial reefs when they were designed to mimic natural reefs (Perkol-Finkel and Benayahu, 2007). The combination of mussel drop-off (biotic) and anchor blocks (abiotic) as reef structure on the seabed could therefore provide habitat for both mobile fishes and sessile filter feeders, or instead change the habitat features beyond what would be considered normal for the benthic ecosystem.

All of the above literature refers to coastal mussel culture operations, where most work on determining the impact of mussel farming on the benthos has been concentrated. Literature on the other types of aquaculture (off-coast, offshore, open ocean) are scarcer as offshore production remains limited compared to coastal aquaculture (Lacoste et al., 2018). Danovaro et al. (2004) investigated the impact of a large off-coast long-line mussel farm located 3 km off the coast in the Adriatic Sea and found that there was no effect on the meiofaunal abundance, taxon richness or community structure. Also in the Adriatic Sea, Fabi et al. (2009) assessed the impacts of a long-line mussel farm situated 2.5 km from the coast on benthic infauna communities. They found that any major dissimilarity between the communities inside and outside the farm was due to seasonal fluctuations rather than the mussel farm itself, which had very little impact on the infaunal community.

Lacoste et al. (2018) recognised the lack of studies on offshore mussel farms. Aiming to fill in some of the knowledge gaps in the literature, they provided baseline information on the benthic impact of an offshore long-line mussel farm about 4 km off the coast of Îles-de-la-Madeleine, eastern Canada. They concluded that the farm had a limited impact on organic enrichment from biodeposits and on macroinfaunal communities. They also observed that macrofauna (e.g. crabs and lobsters) were more abundant at the mussel farm compared to control sites, perhaps benefitting from the mussel prey falling off the lines.

1.4.3 Monitoring methods

The benthic effects of mussel farms have been primarily assessed using extractive grab sampling. This is an effective way of gaining detailed quantitative data on infauna abundance and species composition, particle size analysis and organic content analysis (Davies et al., 2001), and the sampling points are easily replicated through time-series monitoring (Eleftheriou and McIntyre, 2005). However, it can be fairly time consuming, both in gathering and identifying samples (Kingston and

Riddle, 1989), hard to get samples from directly beneath headlines due to mussel farm infrastructure, and there can be large variations in infauna communities over relatively small spatial scales (Underwood and Chapman, 2013). Large variations can be mitigated by increasing replication, although this is not always possible due to time and budget constraints.

The use of underwater cameras can complement or provide an alternative to assessing the benthic effects of mussel farm installations. Underwater camera methods include towed video (Sheehan et al., 2016), remotely operated vehicles (ROVs), diver-operated video (Mallet and Pelletier, 2014), and remote or baited remote underwater video (RUV/BRUV) (Cappo et al., 2004; Cappo et al., 2006). They can work around marine infrastructure, are cost and time effective, non-destructive and can provide data on benthic epifauna that would be missed by grab sampling. They are also able to monitor hard bottom substrates that grabs are unable to sample (Pohle and Thomas, 1997).

Towed cameras can be used to sample large areas of seabed (Sheehan et al., 2010; Sheehan et al., 2016), to record transects. However, this becomes difficult in areas of high tidal velocity, and ineffective in low visibility. Furthermore, there is still the time issue of analysing large segments of seabed, and human error in identifying species via a screen. Hydroids, sponges and bryozoans are very difficult to identify correctly through this method (Davies et al., 2001; Mallet and Pelletier, 2016). Baited video gives more information on mobile species that may be missed by towed video (Cappo et al., 2004). However, despite providing better statistical power than un-baited video and more able to detect temporal change, use of them alone shows a bias toward predatory and scavenging species (Stobart et al., 2015). Using ROVs instead of divers to film the seabed removes depth limitations as well as diver bias

(Stobart et al., 2015), and allows the same control over where the video sample are taken.

No single grab sampling or video camera method is perfect for assessing the effects of mussel farming on the seabed. Grabs are unable to sample benthic fishes and larger epifauna, and video methods are unable to provide detail on infauna or sediment characteristics. Therefore, neither method alone will give a true picture of the effects of a long-line mussel farm on the epibenthic and benthic ecosystem. A combination of extractive and non-extractive methods may be a more accurate way of assessing how aquaculture installations are interacting with the benthic and epibenthic ecosystem. Currently, there is no published literature that uses a combination of methods.

1.5 Current knowledge on the effect of long-line mussel farming on the pelagic ecosystem

Compared to benthic ecosystems, there is very little research on the effects of mussel farming on pelagic ecosystems. Most research focuses on the effect on water column chemistry and plankton communities (La Rosa et al., 2002; Cranford et al., 2008; Maar et al., 2008; Trottet et al., 2008; Froján et al., 2018), and indicates variable outcomes which is likely due to differences in site characteristics.

1.5.1 Effects on plankton

Due to their extensive filtration activity (Spencer, 2002), large numbers of bivalve filter feeders, like *M. edulis*, can lead to ecosystem changes as they remove large quantities of phytoplankton (Krone et al., 2013). La Rosa et al. (2002) compared phytoplankton biomass, in the form of chlorophyll-α data, at an intensive fish farm and a long-line mussel farm in the Gaeta Gulf, northwest Mediterranean Sea, to a control station and found no difference in phytoplankton biomass between the sites. Physico-chemical data showed higher dissolved organic carbon concentrations at the fish farm, but not the mussel farm. Although inorganic nitrogen concentrations were higher at the mussel farm, they still concluded that the mussel farm had less of a negative impact on the surrounding environment than the fish farm. Trottet et al. (2008) also found no significant reduction in phytoplankton concentrations at a mussel farm in the Magdalen Islands, Canada compared to a control station outside of the farm. Cranford et al. (2008), on the other hand, found that phytoplankton was depleted at long-line mussel farms in Norway and Canada, and picophytoplankton (0.2 to 2 μm) dominated, as they are too small to be retained by the mussels. Comeau et al. (2015) found that long-line cultivated mussels were leaving behind picophytoplankton and grazing down phytoplankton of higher size classes, e.g. nanophytoplankton (2 to 20 μm). Froján et al. (2018) confirmed this for raft culture and further concluded that mussel farming in Ría de Vigo, northwest Spain was exerting a top-down control over the plankton community by consuming only microphytoplankton (20 to 200 μm) and nanophytoplankton, thereby changing the community structure. The above studies refer to mussel farms placed in embayments and lagoons and so it is unknown whether these effects would extend to mussel farms placed in the open ocean. Mussels also consume zooplankton, the effect of which has been less extensively studied than that of phytoplankton (Robinson et al., 2002). Peharda et al. (2012) found that zooplankton were present in the stomach content of 97 % of long-line cultured *Mytilus galloprovincialis*: up to 200 organisms per individual. Further to this, mussel gut contents have been found to include copepods and bivalve larvae (Zeldis et al., 2004), with higher mean number of zooplankton ingested by mussels in spring and summer (Lehane and Davenport, 2006).

1.5.2 Effects on pelagic fishes and fisheries

The introduction of long-lines introduces complex 'hard' structures that would otherwise be absent in the pelagic environment (Callier et al., 2018). These 'floating' structures occurring in the open ocean are known to attract pelagic fish and act as fish aggregation devices (FADs; Kingsford, 1993). Many studies have found that wild fish are attracted to fish farms (e.g. Boyra et al., 2004; Dempster et al., 2004; Dempster et al., 2009). Suspended cultivation systems, including long-line mussel farms, provide a three-dimensional habitat for other organisms such as macroalgae, bryozoans and tunicates (Clavelle et al., 2019). This, in turn, provides a direct food source and refuge from predation, making them attractive to pelagic fishes (Carbines, 1993; Brooks, 2000). Observations on offshore long-line installations in New Zealand and France report how the introduction of mussels to the area was followed by an increase in fish densities and pelagic fish were more common near the farm compared to open water areas. They were observed feeding on mussels and swimming through the mussel headlines, concluding that the headlines could be acting as FADs (Gerlotto et al., 2001; Brehmer et al., 2003; Keeley et al., 2009).

Gerlotto et al. (2001) and Brehmer et al. (2003) developed hydroacoustic methods to sample fish around long-line mussel culture grounds along the coast of the French Mediterranean Sea, where the introduction of mussels to the area was followed by an increase in fish densities. Brehemer et al. (2003) detected 191 schools of fish, most of which were located close to the mussel long-lines. The same four dominant species were found in the schools: European pilchard *Sardina pilchardus*, European anchovy *Engraulis encrasicolus*, bogue *Boops boops* and Atlantic horse mackerel *Trachurus trachurus*. Very few schools were recorded in the access channel to the mussel farm area. Furthermore, outside of the mussel farm, fish were mainly distributed close to the bottom, but near the long-lines, they were detected in the whole water column. This led to the conclusion that schools of fish could be attracted to the structure area and so the mussel long-lines could have been acting as FADs. Peteiro et al. (2010) highlighted that black seabream in the Ría de Ares-Betanzos (Galacia, northwest Spain) were feeding heavily on *M. galloprovincialis* being cultivated on long-lines, as much as 60 % of the mussel seed on collector ropes. Therefore, the fish were attracted to the long-lines, which were acting as a food source. Mussel farms acting as FADs may not only be attracting fishes into the farm, but also displacing fishes from their preferred habitat. This may cause the total abundance in the areas to remain the same, but the distribution of fishes to change (Gibbs, 2004). Long-line mussel farms could provide food for pelagic fishes, as well as a refuge from predation and therefore reduce mortality, causing there to be a greater abundance of these fishes in the ecosystem than there would naturally be. This may irrevocably alter the pelagic ecosystem, which could prove to be a negative effect of mussel farming. What is also not clear is whether mussel farms are just acting as FADs and attracting fishes from natural habitat, or whether they are contributing to the production of fishes as well. The physical farm infrastructure (e.g. ropes and buoys) provide substrate for colonisation by bryozoans, tunicates and other molluscs (Willemsen, 2005). This forms the biological components of an artificial reef structure, which may attract fish (Costa-Pierce and Bridger, 2002). It is unclear, however, whether the fish are attracted to the structure itself or to the prey associated with the structure (Würsig and Gailey, 2002). This is worthy of further research to see whether mussel farms have the capacity to contribute to the production of fish species rather than just attracting them from the wider area.

Again, these studies on pelagic ecosystems are based on coastal farms; an extensive literature search at the start of this work uncovered no literature on the effects of open ocean mussel farming on pelagic ecosystems. However, a review illustrating the increase in biodiversity on and around mussel headlines (Sheehan et al., 2019), and a paper focussing on a system for monitoring and analysing pelagic fish around mussel farms (Sheehan et al., 2020) have since been published, based on work carried out by this PhD.

1.5.3 Monitoring methods

Due to the extensive filtration activity of mussels (Spencer, 2002), plankton sampling forms a very important part of monitoring the effects of a mussel farm. As well as being ecologically important to the oceans (Lowery et al., 2020), evidence suggests that plankton are sensitive indicators of changes, perhaps more than environmental variables themselves (Taylor et al., 2002). We know that mussels ingest zooplankton (Zeldis et al., 2004; Perharda et al., 2012) but do not know whether open ocean mussel farms reduce the abundance or diversity of local zooplankton communities. As the above studies have shown, comparisons between phytoplankton communities between mussel farms and control stations outside of the farm are an effective way to assess whether the farm is depleting plankton around the headlines. Zooplankton are typically collected by vertical net hauls from the sea floor to the surface (e.g. Gallienne et al, 2001; Eloire et al., 2010; Saunders et al., 2015). However, they are notoriously patchy and can be highly aggregated (Omori and Hamner, 1982) so more replication may be needed to understand their distribution.

Change in pelagic community structure can be assessed using a number of techniques including diver counts, remotely operated vehicle (ROV) video counts and destructive sampling via anaesthetic (Morrisey et al., 2006). In Morrisey et al. (2006), diver counts involved counting fish in the general farm environment and searching for fish living within rope droppers. However, the authors recognised the problem that the presence of divers would have on the behaviour of the fish and so carried out ROV counts as well to sample fish associated with the rope droppers and mussels. However, a ROV might have affected fish behaviour just the same as diver presence. The anaesthetic sampling recorded more fish than the other two methods but is obviously not an ideal sampling method. Demersal species, including triplefins and wrasse, were recorded during the three methods but only one pelagic species (jack mackerel *Trachurus novaezelandiae*) which suggests that these methods are ineffective for the sampling of pelagic fishes. Although this study showed that the farm was performing an attraction function for some demersal and pelagic fish species, a less disturbing method is needed to sample pelagic fishes effectively around long-line mussel farms.

Gerlotto et al. (2001) and Brehmer et al. (2003) developed hydroacoustic methods to sample fish around mussel culture grounds. This has the advantage of being able to be used in poor visibility areas while mapping large areas in a short period of time (Magorrian et al., 2009; Fraser et al., 2016). However, ground-truthing is normally required to provide information on fish community composition via camera footage or grab samples. Obviously, grab samples are not possible in the pelagic ecosystem, so the use of underwater cameras would also be needed to monitor pelagic fishes if hydroacoustic methods were used. Based on this, the use of a static underwater camera would be more desirable to monitor mobile pelagic fish in this environment (Griffin et al., 2016).

There is a need for a reliable underwater camera method to film and analyse pelagic fish. The past studies that sought to understand the interaction between mussel farming ropes and pelagic fish used ineffective methods. There also needs to be the introduction of a monitoring programme targeting the mussel ropes themselves to understand what epibiota settle and colonise the ropes alongside the mussels and how this could cause the farm to act as an FAD or an artificial reef.

1.6 Human perceptions of bivalve aquaculture and potential contribution to ecosystem services

1.6.1 Perception studies

There are social and cultural issues with the current expansion of aquaculture because of stagnant wild capture fisheries and rising demands for protein from seafood (Tidwell and Allen, 2001). Interviews carried out by D'Anna and Murray (2015) and Murray and D'Anna (2015) on Canadian residents, highlighted a negative response to the possible effects of aquaculture on the environment and on well-being. In particular, respondents felt that aquaculture is detrimental to the seabed, created debris and noise, and they were unsure about the effects on water quality. However, they also recognised the economic benefits of a growing aquaculture industry, including the creation of sustainable jobs and jobs for local residents (Murray and D'Anna, 2015).

Flaherty et al. (2018) carried out an extensive study on the perceptions of marine aquaculture. Overall, fewer respondents held negative impressions of shellfish farming (2 %) than salmon farming (23 %). This either supports the perception of shellfish farming as a 'green' industry (Gallardi, 2014) with less controversy than fish farming, or perhaps shows that people are less informed about shellfish farming. However, only 50 % of respondents felt that shellfish farming was currently sustainable, compared to 32 % for salmon farming. Fairbanks (2016) found that respondents were concerned about interactions of farms with protected species, as well as the spatial, environmental and aesthetic impacts. There was also the view that there would be clashes with fishers and other offshore stakeholders who may view aquaculture expansion into the open ocean as privatisation of space. However, respondents were optimistic about technical considerations, environmental conditions and market opportunities.

Respondents in a perception study by Thomas et al. (2018) perceived fish aquaculture as having more negative impacts than mollusc or plant aquaculture. Over half of respondents agreed that mollusc aquaculture could improve water quality. When asked about their general opinion, respondents generally were either indifferent and/or uninformed, or positive towards it. Respondents who either had a higher awareness of aquaculture, had a farm site near their home, or go out to sea by boat, were significantly more positive towards aquaculture than respondents who had a low level of awareness. This highlights the importance for stakeholders to raise awareness about aquaculture through increased education about impacts, job opportunities and on the potential ecosystem services generated by sustainable aquaculture (Thomas et al., 2018).

1.6.2 Ecosystem services

The farm is not being examined in this thesis in terms of ecosystem services. However, more attention has recently been placed on examining aquaculture as part of the wider ecosystem, not just the negative or positive local effects (Gentry et al., 2019). If managed correctly, mussel culture can provide environmental and social benefits that extend beyond production of food (van der Schatte Olivier et al., 2018; Alleway et al., 2019): ecosystem services.

Ecosystem services are the "benefits people obtain from ecosystems" (MEA, 2005). Services are categorised by the Millennium Ecosystem Assessment (MEA) into four different services:

1. Provisioning services
2. Regulating services
3. Supporting services
4. Cultural services

There is an increasing policy focus on assessing the economic value of such services (van der Schatte Olivier et al., 2018). The Common International Classification of Ecosystem Services (CICES) typology (European Environment Agency, 2012) is widely used in the EU to quantify the value of ecosystem services. It builds upon the MEA but is tailored towards accounting and was used by van der Schatte Olivier et al. (2018) to look at economic value of bivalve aquaculture. Alternatively, The Economics of Ecosystems and Biodiversity (TEEB, 2010) study (Ring et al., 2010) was recently used by Gentry et al. (2019) and Alleway et al. (2019) to provide an overview of the ecosystem services associated with marine aquaculture. The TEEB study is an international initiative to draw attention to the global economic benefits of biodiversity (Ring et al., 2010). It is also widely used, providing a clear, structured evaluation framework for assessing ecosystem services (Alleway et al., 2019; Gentry et al., 2019). Both CICES and TEEB have been used to research and present the subcategories for each service category that are relevant to bivalve aquaculture (Table 1.3).

Table 1.3: Ecosystem services provided by bivalve aquaculture. Table adapted from Gentry et al. (2019) and van der Schatte Olivier et al. (2018).

Service category	Ecosystem service
Provisioning	Food production Enhance wild fisheries
Regulating	Carbon sequestration Nutrient cycling Improve water clarity Biological accumulation Biochemical accumulation Coastal protection
Supporting	Provision of artificial habitat
Cultural	Livelihoods Education and research Tourism

Provisioning services

Provisioning services are the energy and material outputs that can be directly consumed or traded (Haines-Young and Potschin, 2012). Aside from the obvious provision of food, with farmed molluscs worth USD 34.6 billion (FAO, 2020), bivalve aquaculture also has the potential to enhance wild fisheries catches through the addition of hard structure through the farm area. FADs in the form of drifting, floating objects have long been used by fishers to catch fish more effectively (Girard et al., 2004).

Regulating services

Regulating services are those that modify biotic and abiotic parameters that affect the performance of people (Haines-Young and Potschin, 2012). Carbon sequestration is an important ecosystem service in the drive to mitigate climate change (van der Schatte Olivier et al., 2018). During shell production, bivalves use carbon in the water to form calcium carbonate, hence removing carbon from the ocean (Hickey, 2009).

Bivalves filter large volumes of water daily, cycling large amounts of organic material from the water column, including phytoplankton which use dissolved organic nitrogen for growth (Kellogg et al., 2013). When filtered from the water column, the nutrients are deposited on the seabed as faeces or pseudo-faeces (Newell et al., 2005). Nitrogen and phosphorus are used for shell and tissue growth and removed from the system during harvest (Carmichael et al., 2012). Gentry et al. (2019) estimated that 170 kg of nitrogen is removed per hectare on bivalve farms each year. Filter feeding can also improve water quality and clarity by removing suspended particles, or seston, from the water column (Grizzle et al., 2008). Seston is assimilated by bivalves, then sequestered and stored, making the waste no longer biologically available in the water column (Mebs, 1998). Schröder et al. (2014) found that effects of mussel culture on water clarity were significant and can extend beyond the boundary of the farm.

Bivalves can also biologically accumulate sewage related microbes within their tissues (Hassard et al., 2017) and bioremediate waste, involving the removal of waste from the environment via burial, storage and recycling (Beaumont et al., 2007). The types of waste that *M. edulis* can bioremediate include phytoplankton and organic matter (Riisgård et al., 2011), toxins produced by phytoplankton (Moroño et al., 2001) and microplastics (Thompson et al., 2004). Finally, large mussel farms can provide protection for the coastline. Plew et al. (2005) observed that floats and mussel rope droppers form a barrier to water flow, influencing waves and water circulation with the potential to protect the coastline from storms.

Supporting services

Supporting services are those that help maintain biodiversity in an ecosystem (Gentry et al., 2019). Bivalve farms provide an artificial habitat and feeding area for fish, invertebrates and birds (e.g. Brehemer et al., 2003; Roycroft et al., 2004; Archambault et al., 2008), with the ropes and the shells themselves providing a suitable substrate for organisms to adhere to (Shumway et al., 2003). Mussel drop-off from ropes form mussel beds which provide a food source for benthic predators (Archambault et al., 2008; Clynick et al., 2008; Drouin et al., 2015), and support suspension feeders (Mainwaring et al., 2014).

Cultural services

Cultural services are the cultural benefits created for people by the interaction with an ecosystem (Church et al., 2014). Aquaculture farms are important for local economic activity, with usually a significant number of people relying on the industry (van der Schatte Olivier et al., 2018). These income and employment benefits contribute to people's livelihood (Gentry et al., 2019).

Bivalves cultivated within farms may not only be used for food; they can also be used for education and research. *M. edulis* is frequently used for scientific experiments, as it is hardy, abundant, and can reach sexual maturity within one year (Ackefors and Haamer, 1987).

Aquaculture can contribute to the tourism of regions, which aids the economic stability of the region (Telfer and Wall, 1996). Regions can become known for local food produce that is sold at, for example, seafood festivals. This increases benefits to both local businesses and communities (van der Schatte Olivier et al., 2018).

1.7 Further research

This review has identified that individual studies have not taken an ecosystem approach and have instead assessed a single component of the ecosystem. Evidence from coastal farms suggests that there could be potential 'cross-ecosystem' impacts. For example, an increase in mussel shells on the seabed could be providing food and habitat for epibenthic species, but the local infauna could be responding in the opposite way, with reduction in species richness and abundance. In order to provide a holistic approach to evaluating the effect of open ocean long-line mussel farming on the surrounding environment, a combination of methods should be used (Gabriel et al., 2005), as one single method would not be representative of all biodiversity within an area (Costello et al., 2017). Refining current methods and combining these with new methods to monitor the seabed and water column within a mussel farm may help gain accurate information of the effects of the farm.

Offshore aquaculture is an emerging sector of the blue economy, identified as an area for growth (Novaglio et al., 2021). By 2030, aquaculture is expected to provide around 62 % of aquatic foods (World Bank, 2017) but most of the current production is in coastal waters or on land where space for expansion is limited. Required in the planning and licensing framework is a monitoring programme that can address how aquaculture farms affect existing ocean activities and environmental concern (Lester et al., 2018). The components of the aquaculture consenting framework in England comprise, but are not limited to:

- Planning permission from local authority
- Crown Estate seabed lease
- Several Order application from Defra
- Local authority food safety and hygiene permissions
- Navigational markers
- Marine Development license from the Marine Management Organisation (MMO), which requires consent from:

- Environmental Impact Assessment (from MMO)
- Fishery regulations and bylaws (from Inshore Fisheries and Conservation Authorities (IFCAs))
- Water quality and environment issues (from Environment Agency)
- Safety of navigation (from The Maritime and Coastguard Agency)

It is recognised that within the current planning frameworks that exist in ocean spaces that the emergence and development of new industry, if not managed correctly, could result in environmental impacts and socio-economic conflicts (Lester et al., 2018). Marine Spatial Planning and licensing are governance tools to enable consideration of environmental and socio-economic trade-offs. There is a need for a holistic ecosystem-based approach to planning the siting of offshore aquaculture as potential impacts cannot be summarised by a single metric (Lester et al., 2018).

Providing a framework for assessing ecosystem impacts of aquaculture developments is essential for ensuring sustainable farming practices and comparing results between farms, helping towards both sustainable development and economic growth goals. Further to this, this understanding of whether situating future aquaculture installations in the open ocean mitigates some of the existing issues to the surrounding environment is paramount. Providing a universal framework that can be adopted by new or existing open ocean mussel farms to assess impact can allow comparison between sites. This will help pin down the aspects of open ocean farm sites that allow the most sustainable production of protein. This will help guide policy makers in the siting of new mussel farm developments in the drive to move aquaculture installations in to the open ocean as part of the Blue Growth Strategy (European Commission, 2012).

Chapter 2: The Lyme Bay Mussel Farm

2.1 The Lyme Bay Mussel Farm

The establishment of the UK's first large scale open ocean long-line mussel farm is being developed by Offshore Shellfish Ltd., founded by John and Nikki Holmyard. The most popular cultivation method in the UK and Ireland is long-line culture, which consists of headlines anchored to the seabed, with a series of rope droppers suspended in the water column (McKindsey et al., 2011). The farm will be the largest of its type in European waters, using a specially designed technology of suspended ropes to cultivate the blue mussel *Mytilus edulis* over three sites between 4 and 10 km offshore in Lyme Bay, south Devon. When fully developed, these three sites will cover a total area of 15.4 km^2 and are expected to produce up to 10,000 tonnes of mussels per year.

Using the definitions set out by Holmer (2010), the Lyme Bay mussel farm is classified as an open ocean mussel farm as it exhibits characteristics from both off-coast and offshore definitions. The farm is located over 3 km from the shore, exposed and not visible from the shore. However, the water depth is ca. 25 - 30 m, less than the 50 m required to be offshore.

Special Mark buoys were deployed to delineate the site boundaries and identify the area to local fishers and other sea users. The farm consists of a series of 150 m long headlines moored to the seabed with a pair of screw anchors. At Site 1 and 2, there will be five columns of 61 headlines. 10 m long rope droppers are hung from the headlines, with buoys placed at regular intervals to keep the structures floating (Figure 2.1). The number and spacing of rope droppers is commercially sensitive information not given out by the mussel farmers.

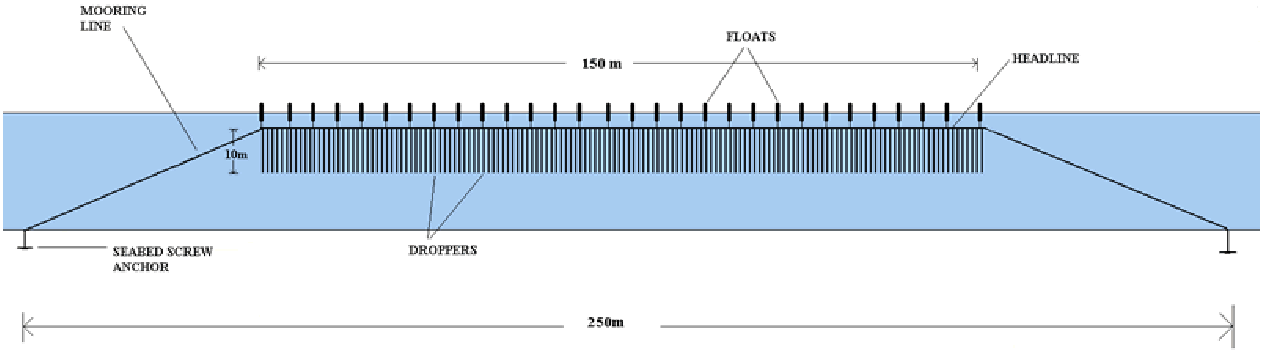


Figure 2.1: Sectional view of a headline, showing rope droppers, floats to keep the structure floating, mooring lines and seabed screw anchors.

To assess potential ecological impacts of this development, trial stations were designated within two of the mussel farm sites, each measuring 100 m x 650 m. The first is in the southeast corner of Site 1 (Trial Station 1: average depth = 28 m), and the second is in the northwest corner of Site 2 (Trial Station 2: average depth = 23 m) (Figure 2.2). Within each trial station, there are two plots (50 m apart) where headlines have been deployed (shown in blue) and two replicate control plots located 500 m to the west and east of the farm (shown in red). Distance of control plots was based on existing literature that used this distance (da Costa and Nalesso, 2006; Callier et al., 2008; Drouin et al., 2015) or even less (e.g. Lasiak et al., 2006 (250 m); Fabi et al., 2009 (300 m)). The mussel farm surveyed by Fabi et al. (2009) is also in the open ocean, 2.5 km offshore the Western Adriatic coast. Although environmental conditions, current speeds and direction are not the same as the Lyme Bay mussel farm, using control plots that are 500 m away is expected to ensure that they are not compromised by any effects from the farm.

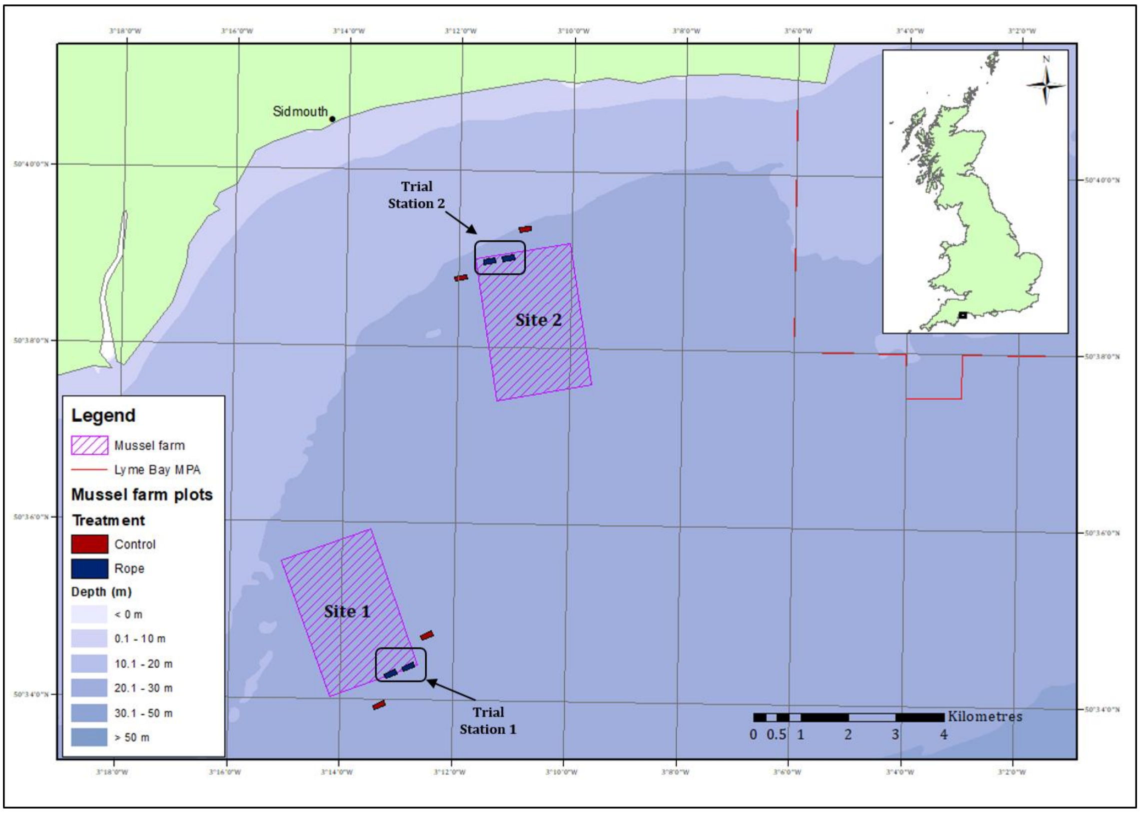


Figure 2.2: Map showing the trial stations within Site 1 and Site 2 of the Lyme Bay mussel farm.

In a preliminary study investigating the oceanography of the area, carried out by Hosegood et al. (2014) current and water properties were sampled throughout four semidiurnal tidal cycles during late summer (August 2013) and late winter (March 2014). The timing of the surveys was intended to capture conditions between neap and spring tides, and between thermally stratified and vertically well-mixed conditions. The survey comprised vessel mounted acoustic Doppler current profiler (ADCP) measurements of the current regime, and towed conductivity-temperature-depth (CTD) measurements. Surveys were a total of 12 hours and repeated transects were completed every hour between the two trial station areas.

The survey found that currents rotate clockwise throughout the tidal cycle and reach a maximum speed of 0.56 m/s^{-1} at high water + 5 hours during spring tide. The currents were strongest during the ebb tide. Currents are directed to the east on the flood (mean direction of 56°N) for approximately 3 hours and then to the west (mean direction of 242°N) on the ebb tide for approximately 3 hours.

Tidal excursions at the surface during spring tides follow an elliptical path and exceed 4 km but are less than 2 km at neap tides. Near the seabed, tidal excursions become rectilinear and smaller by a factor of two.

Water properties in this area exhibit stratification throughout both seasons. During summer months, stratification appears to evolve on a diurnal timescale in response to insolation, whereas during winter months an unexpected degree of stratification was observed due to freshwater input. This freshwater most likely originates from the Exe estuary and is sent eastwards by the tide (Hosegood et al., 2014).

2.2 Headline development

Within each trial station, there are two plots where headlines have been deployed. The number of headlines within these plots have varied between the two sites over the sampling years (Figure 2.3). In Year 0, no headlines were installed at either Trial Station. In Year 1, there were two headlines deployed in Plot 1 at Trial Station 1, and one headline deployed in Plot 2 at Trial Station 2. In Year 2, the number of headlines remained the same at Trial Station 1, but at Trial Station 2, there were two headlines in each Plot, the maximum number for the rest of the study. In Year 3, a new headline was introduced in Plot 2 at Trial Station 1, the maximum number for the rest of the study.

At Trial Station 2, the deployed headlines were exclusively used as spat ropes. However, at Trial Station 1, use changed from spat ropes to re-seeded ropes early on. This was because spat were settling more successfully at Trial Station 2. Trial Station 1 was then used to grow mussels to harvest.

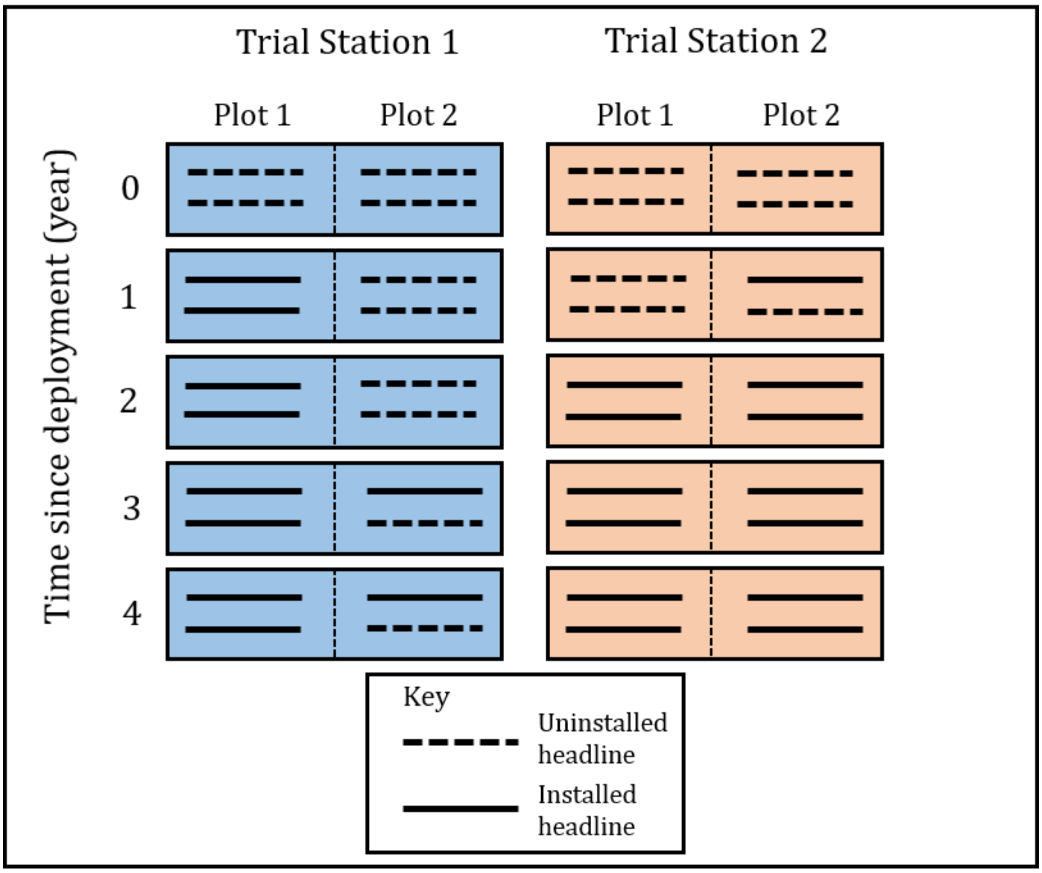


Figure 2.3: Visual representation of headline development at each Trial Station throughout the study.

Throughout the rest of the farm, headline deployment was ongoing, although not near the locations of the Trial Stations. This is detailed in Figure 2.4. The dashed grey lines show the locations in which headlines will eventually be deployed and the varying shades of blue lines show the headlines that were deployed throughout the study and in what year. In all cases, no headlines have been deployed within 400 m from the Trial Stations.

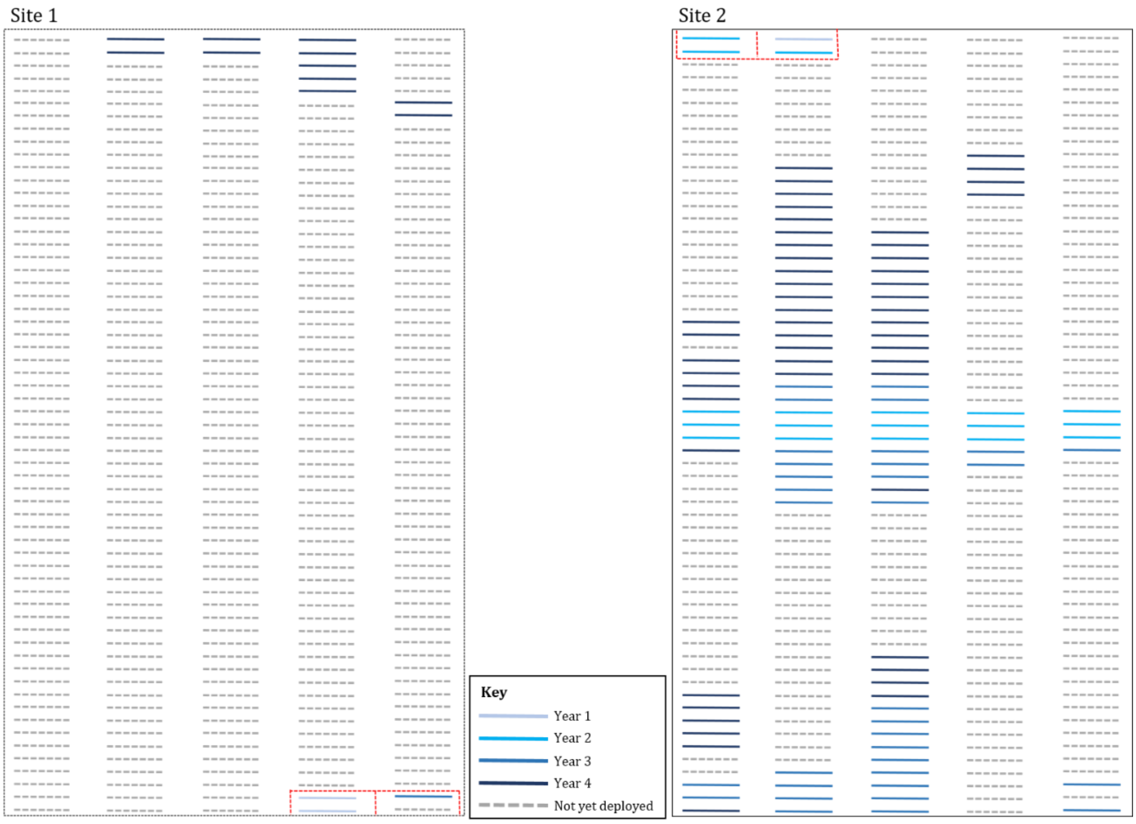


Figure 2.4: Headline development throughout the rest of the farm during the years of the study.

The headline development throughout the survey, along with production can be seen in Table 2.1.

Table 2.1: Headline development throughout the survey.

	Projected no. of headlines	
Year	Site 1	Site 2
2013	Baseline surveys	
2014	2	1
2015	2	18
2016	3	51
2017	14	102

2.3 Farm protocols

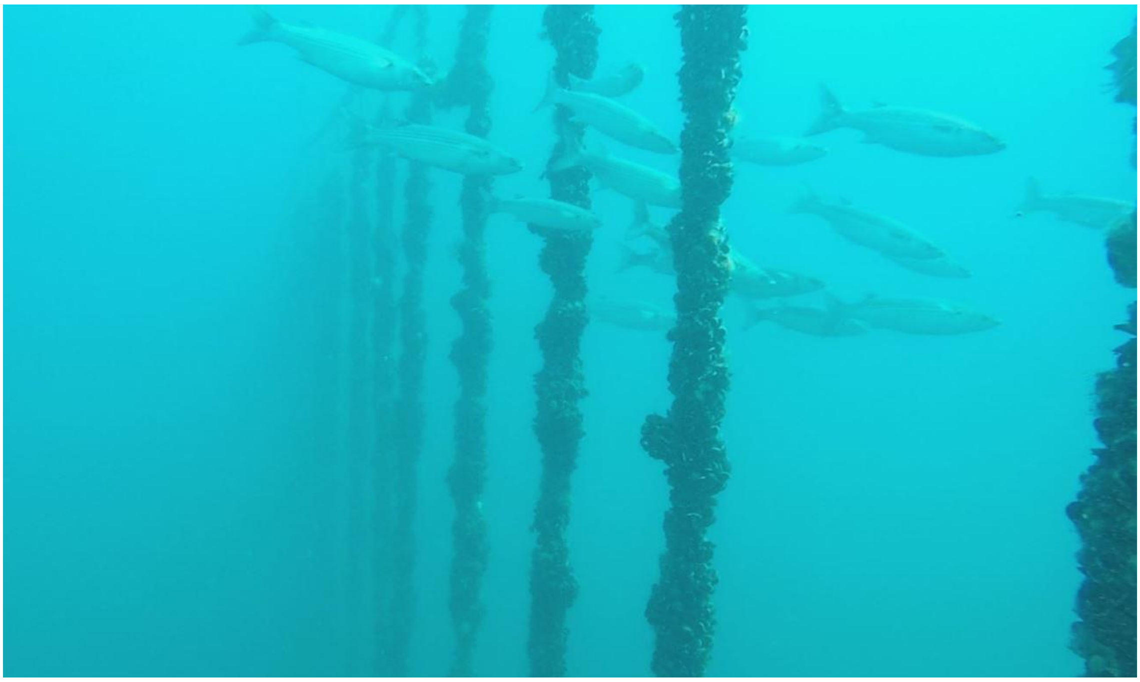
The farm self-seeds on to 'fuzzy' polyethylene spat collecting ropes. These ropes are put out sea in and around the Trial Station at Site 2 in April each year, with spat visible on the rope from June. After six months, the mussel spat are removed from the spat ropes, and reseeded onto new ropes to ensure they have enough space to grow. When the mussels are reseeded after six months, they are moved to other areas of the farm. After around 18-24 months, the mussels are harvested. The spat collecting ropes are then replaced in April the following year for the next years spat to settle on.

Figure 2.5: Customised reseeding equipment on board mussel farming boat 'Holly Mai'.

Figure 2.6: Six-month-old mussels in the process of being re-seeded onto new ropes.

Figure 2.7: Mussels ready for harvesting.

Chapter 3: Effects of open ocean mussel farming on the pelagic ecosystem.



Target Journal: Aquaculture Environment Interactions

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DB led the design of the experimental procedure, experimental set up and sampling locations, with ES and MA. DB led the data collection with assistance from ES, MC and University of Plymouth technical staff. DB analysed the data and drafted the Chapter. ES, MA and SR reviewed and commented on the Chapter.

Effects of open ocean mussel farming on the pelagic ecosystem.

Abstract:

Mussel farms add a great deal of hard structure (e.g. headlines and rope droppers) into the pelagic environment, where structure would largely be absent. Floating hard structures in the open ocean are known to attract fish in the same way as fish aggregation devices (FADs), and cultivated mussels can deplete zooplankton groups, filtering large volumes of water each day. The aim of this Chapter is to develop and pilot a monitoring programme for the pelagic ecosystem, which can be used when testing the effects of an open ocean mussel farm. In addition, the mussels and associated epibiota on rope droppers were surveyed along with pelagic fishes and zooplankton to test the hypothesis that, over time, the addition of hard structure in the pelagic environment changes the surrounding fish and zooplankton communities relative to control areas.

Pelagic fishes were more abundant in the mussel farm compared to the control areas, with large number of Atlantic horse mackerel *Trachurus trachurus* recorded within the farm (possible FAD effect). These fish were also more abundant around ropes with older mussels on them, which supported a greater species richness of epibiota. There was also evidence that commercial brown crab *Cancer pagurus* is using the mussel ropes as a nursery area. Zooplankton communities were not significantly different within the farm compared to control areas, possibly because of a deeper mixing layer and greater integration in open ocean aquaculture sites. These findings suggest that the addition of structure in the pelagic environment has changed the surrounding fish communities. There were no detectable effects on zooplankton communities, although this may have been because of the sampling techniques used in the survey.

Keywords: aquaculture, mussel farming, offshore, open ocean, pelagic fish, zooplankton

3.1 Introduction

In 2018, aquaculture production made up 46 % of global total production (82 million tonnes) (FAO, 2020), making up the shortfall left by stagnating capture fisheries that are unable to keep up with an ever-increasing demand for fish and seafood (Pauly et al., 1998; Jackson et al., 2001; Pauly et al., 2002). The highest proportion of this production comes from finfish (54.2 million tonnes), followed by molluscs (17.5 million tonnes), and crustaceans (9.4 million tonnes) (FAO, 2020). Recently, molluscs have been identified as a low impact animal food source when compared to other sources of animal protein, for example beef, whitefish and shrimps. Mollusc aquaculture requires very little energy input, no antibiotics and almost no freshwater, and has the lowest greenhouse gas production per portion of protein (Hilborn et al., 2018).

Within the UK, the most widely cultivated mollusc is the blue mussel *Mytilus edulis*. In 2014, Scotland and Wales produced around 8,000 tonnes of *M. edulis* (Seafish, 2016). One of the main culture techniques in the European Union (EU) is long-line culture (Avdelas et al., 2021), which consists of headlines anchored to the seabed, with a series of rope droppers suspended in the water column (McKindsey et al., 2011). This method was developed to resist storm and wave effects, which are common conditions in the UK (FAO, 2004). As well as adding hard structure to the seabed (e.g. anchor blocks and mussel drop-off), the rope droppers and anchor lines add physical structure to the water column, where such structure would largely be absent (Callier et al., 2018). Through this physical structure, mussel farming introduces a different habitat to the water column in the form of the mussels themselves, which provide substrata for other sessile organisms, known as epibiota (Gutiérrez et al., 2003). Epibiota growing on farmed mussels is known as biofouling, which can have major impacts on the cultured organisms and the farming structures, with common fouling organisms including barnacles, ascidians, sponges and tubeworms (Dürr and Watson, 2010).

Floating structures in the open ocean are known to attract fish, therefore acting as fish aggregation devices (FADs; Kingsford, 1993); wild fish are attracted to fish farms for this reason (Boyra et al., 2004; Dempster et al., 2004; Dempster et al., 2009). Suspended cultivation systems, including long-line mussel farms, are attractive to pelagic fishes due to the three-dimensional habitat and food source provided (Carbines, 1993; Brooks, 2000). Schools of pelagic fishes occur around mussel farms, distributed close to the long-lines themselves (Brehemer et al., 2003), and can feed heavily on mussel long-lines (Peteiro et al., 2010).

The area on which the farm is being developed has historically been heavily fished by bottom towed fishing gear (Sheehan et al., 2013). However, Olsen's (1883) Piscatorial Atlas shows fisher's accounts that suggest mussels and oysters were prevalent around the UK including Lyme Bay. Mussels held in suspended culture provide a key ecosystem service in the form of water filtration as they sequester large quantities of nutrients and phytoplankton from the water column (Cranford et al., 2008; Krone et al., 2013; Froján et al., 2018). In addition to filtering plankton, mussels also ingest zooplankton (Robinson et al., 2002) and can locally deplete zooplankton groups by 26 to 77 % (Maar et al., 2008). At an intensive rope culture area in Clova Bay, an enclosed site in New Zealand, mussel gut contents contained whole copepods, numerous copepod parts, and bivalve larvae (Zeldis et al., 2004).

Cultivated mussels may therefore play a role in regulating plankton at a local level. However, it is uncertain how zooplankton communities will be affected within an open ocean mussel farm in an area that is likely to support greater zooplankton biodiversity and biomass than coastal areas because of a deeper mixing layer and greater depth of integration of chlorophyll (Gasol et al., 1997).

The primary aim of this Chapter is to develop and pilot a time-series monitoring programme that can be used when testing for changes in the pelagic ecosystem between areas within an open ocean long-line mussel farm, and control locations. In this Chapter, the pelagic ecosystem is defined as the water column from above the benthos up to the surface.

A method to survey the plankton community will be trialled. In addition, remote video methods will be used to assess whether the addition of hard structure in the water column changes the surrounding pelagic fish community over time. Over time, as the number of headlines in the farm increases, a decrease in plankton abundance and an increase in pelagic fish abundance is expected, due to the demand for food from mussels and the foraging opportunities provided by the mussels and associated epibiota. A further aim was to investigate whether there is an interaction between the age of cultivated mussels with the number of epibiota species and the abundance of pelagic fishes. As mussels age, an increase in both epibiota diversity and abundance of pelagic fishes would be expected due to the amount of cover provided for epibiota settlement. Trial stations where spat was collected and initially grown on ropes were annually monitored since deployment to assess the change over time of pelagic fish and zooplankton populations relative to control areas. Secondly, one cohort of mussel spat were monitored throughout their cycle (spat, 1 year-old and 2 year-old) before they were harvested. For each mussel age group, the mussel biomass, associated rope epifauna and attraction to pelagic fishes were monitored.

The following hypotheses were tested:

1. Over time, the mussel farm changes the surrounding fish and zooplankton communities (abundance, number of taxa, assemblage composition) relative to control areas.
2. Older and larger mussels support increasingly biodiverse communities (abundance, number of taxa, assemblage composition) and greater abundances of pelagic fishes and other commercially valuable species e.g. brown crab.

3.2 Methods

3.2.1 Time-Series Monitoring

3.2.1.1 Survey design and sampling equipment

To assess change in the pelagic ecosystem at the mussel farm relative to the surrounding environment, pelagic fishes and zooplankton were sampled at both Trial Stations and at comparable controls. Trial Stations were designated by Offshore Shellfish Ltd. in agreement with Natural England to assess potential ecological impacts of the farm. Each Trial Station was subdivided into two adjacent 'Rope' Plots. Corresponding Control Plots for each Site were located 500 m to the southwest and 500 m to the northeast of the Rope Plots (Figure 3.1). Distance of control plots was based on existing literature (da Costa and Nalesso, 2006; Callier et al., 2008; Drouin et al., 2015). A preliminary oceanography study found that currents in the area rotate clockwise throughout the tidal cycle and reach a maximum speed of 0.56 m/s^{-1} at high water + 5 hours during spring tide. Currents are directed to the east on the flood (mean direction of 56°N) for approximately 3 hours and then to the west (mean direction of 242°N) on the ebb tide for approximately 3 hours (Hosegood et al., 2014).

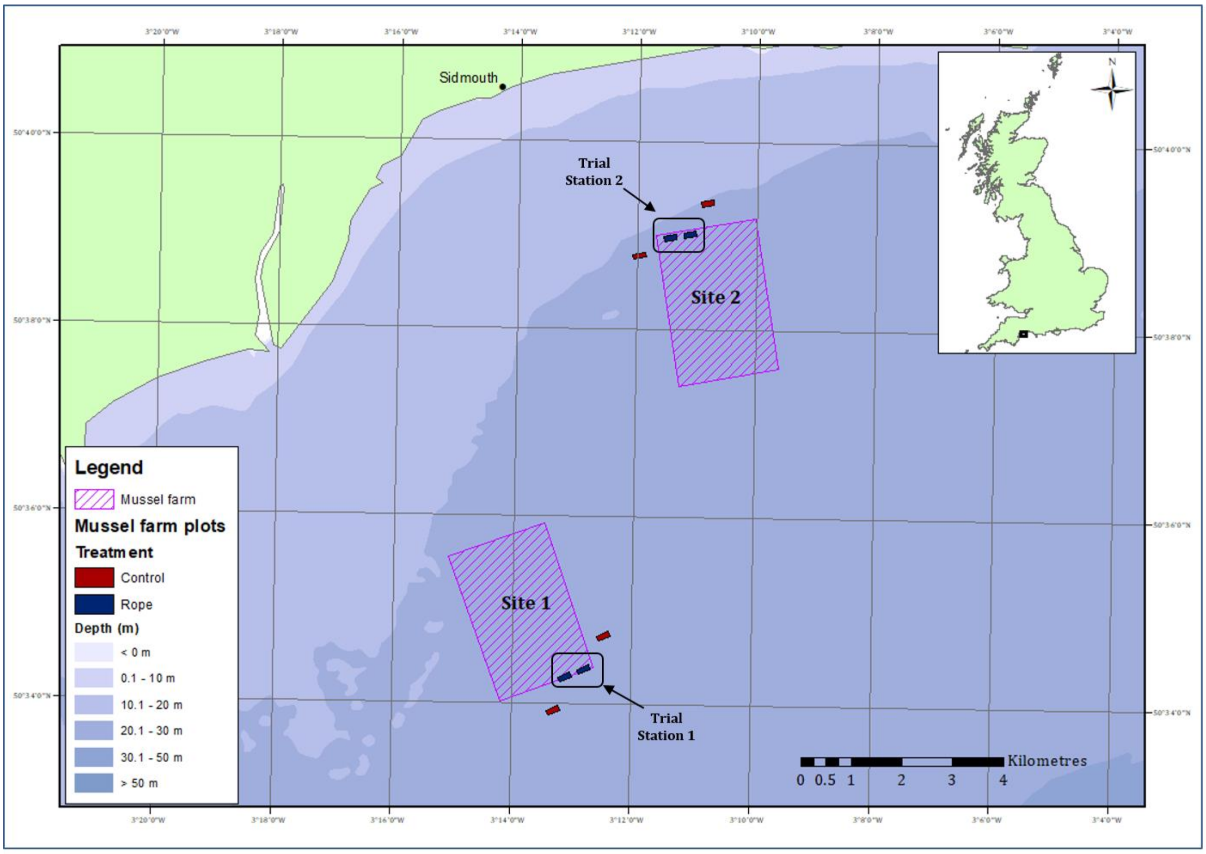


Figure 3.1: Locations of Rope Plots at Trial Stations 1 and 2, and corresponding Control Plots used to assess the pelagic ecosystem at the Lyme Bay mussel farm.

Temporal change was considered within two Treatments (Rope, Control) over four years, from 2014 (one year after headlines were first installed), to 2017 (four years after deployment). Throughout the survey, spat collecting ropes were put out sea in and around Trial Station 2 in April each year. After six months, the mussel spat are removed from the spat ropes, and reseeded onto new ropes. These ropes are distributed throughout the farm, including the Trial Station 1. The mussels are then generally harvested after around 18-24 months. Therefore, the headlines at Trial

Station 2 house spat mussels throughout the survey, and the headlines at Trial Station 1 house mussels of different ages.

Within each Treatment, at each Trial Station Plot and corresponding Control Plots, three non-baited video films were collected (Figure 3.2). However, in 2016 (Year 3) the headlines at Trial Station 1 were harvested for mussel spat and rope droppers were removed before sampling occurred. Sampling occurred in August each year in daylight hours (9 am to 5 pm) during neap tidal cycles.

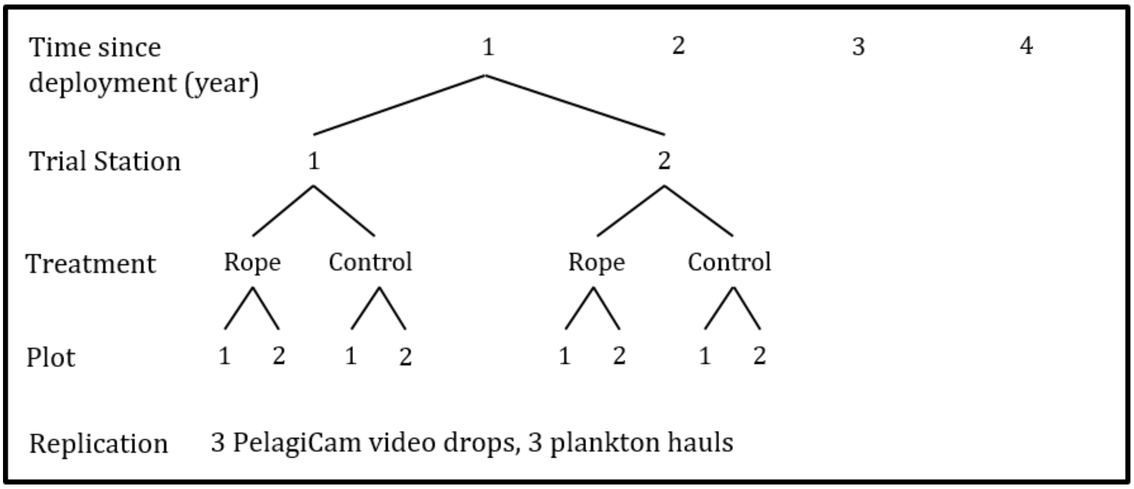


Figure 3.2: Time series monitoring survey regime.

Pelagic fishes were sampled using custom-made PelagiCam units (Sheehan et al., 2020), which were designed and built to be suspended in the water column alongside the mussel farm rope droppers (Figure 3.3). The units comprised an anodised stainless steel circular plate (400 m diameter) equipped with three GoPro cameras (Hero 4 Silver) encased in dive housing, fixed at 120° from each other. The GoPro cameras were set up as the following: 720p video resolution, 30 frames per second, ultra wide field of view (screen resolution 1280x720, 16:9). These settings were chosen as a compromise between video resolution and the ability to obtain as much footage as possible on the 32 GB microSD cards. Each camera was secured to the plate with GoPro mounts, and paired with a dive torch (Underwater Kinetics

Aqualite eLED Pro Dive Light) which was bolted on to the plate. This was to allow a 360° view to ensure the mussel rope droppers were always in view by at least one of the GoPro cameras.

A stainless steel cage was welded onto the plate to protect the cameras and torches from abrasive contact with the mussel rope droppers. A hollow pole (425 mm length, 30 mm diameter) was positioned through the centre of the plate so that 24 mm polysteel rope could be passed through it and run up to a surface buoy. To align with the prevailing current, each PelagiCam had a vane (200 mm length, 185 mm width) welded to the bottom of the plate and the hollow pole. Secured directly under the rig was 6 kg of dive weight to stabilise the system.

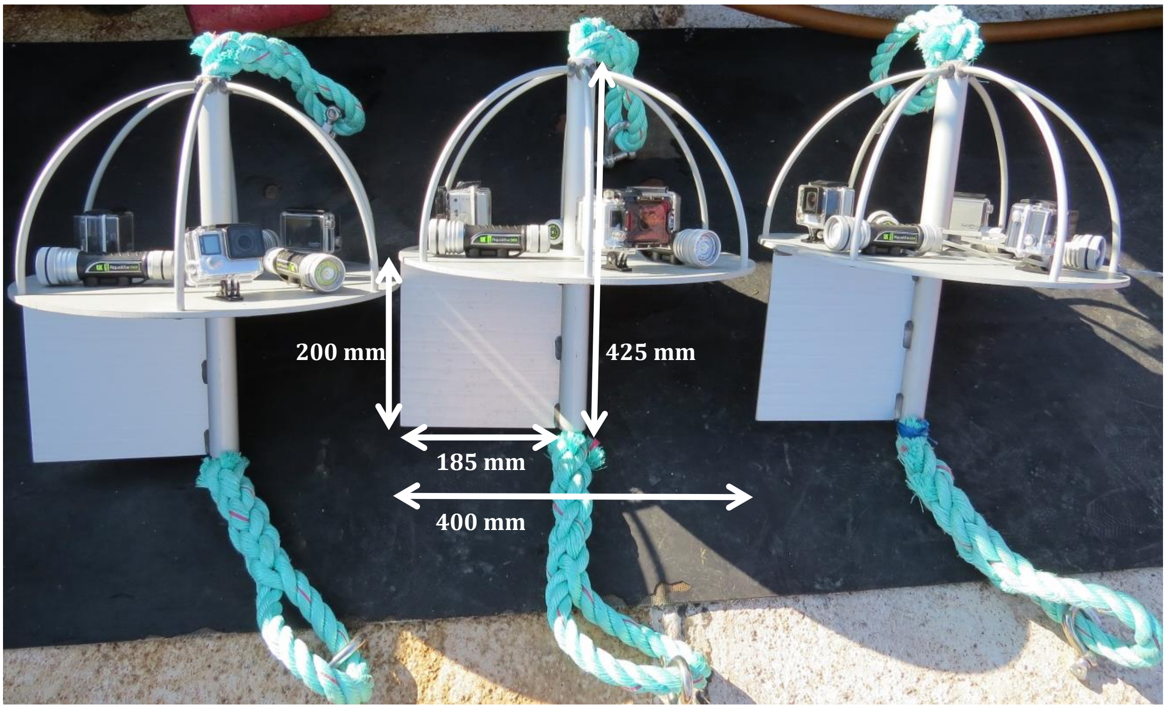


Figure 3.3: Custom-made PelagiCam units, showing GoPro cameras and dive torches, and measurements of vane and hollow pole.

In the Control treatment, the PelagiCam units were secured to a depth of 6 m where they were moored with a 30 kg drop weight (Figure 3.4a). In the Rope treatment, the units were initially moored adjacent to the headlines. This method was improved in Year 2 by clipping the PelagiCam units directly onto the mussel headline buoys with 11 mm stainless steel carbine hooks, so that they hung at a depth of 6 m, approximately half way down the rope dropper (Figure 3.4b). This change in method avoided the PelagiCam units becoming tangled amongst the rope droppers and did not affect the resulting footage. This allowed a view of as much of the rope dropper as possible, so fishes could be counted from a greater depth range. Three PelagiCam units were deployed at haphazardly selected points along a single headline within each Trial Station Plot. One was deployed at each end of the headline and one in the middle. The exact point along the headline where the units were placed were based on where the skipper could safely approach the headline depending on currents and sea state. The units were deployed for 70 minutes to obtain 60 minutes of footage, with a five minute settling period and five minutes of contingency time.

The units were left un-baited, as baited cameras are biased towards predatory and scavenging species (Harvey et al., 2007), and types of bait influence abundance (Rees et al., 2015). Furthermore, the research question is focused on the function of the mussel farm as a fish aggregation device (FAD), and so using bait to attract the fish is not appropriate.

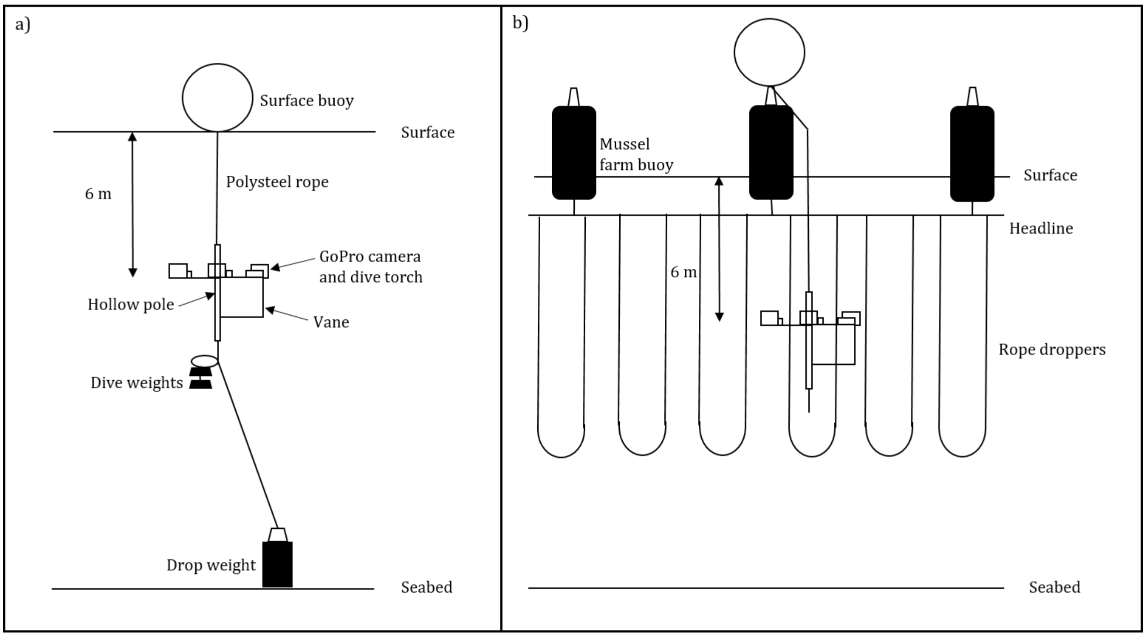


Figure 3.4: Diagrammatic representation of PelagiCam deployment in a) the Control treatment, and b) the Rope treatment.

A plankton net with a 250 μm mesh size, 250 mm frame diameter and 550 mm long bag (manufactured by NHBS) was used to collect zooplankton samples. Zooplankton were sampled from just above the seabed to the water surface in one vertical net haul. The sample was emptied into a pot and fixed with 10 % borax-buffered formalin. To understand whether the filter-feeding activity of mussels and any filter-feeding epibiota affects the zooplankton community, zooplankton were surveyed over four years, from 2014 (Year 1) to 2017 (Year 4). Within each Treatment at each Trial Station Plot and corresponding Control Plots, three plankton samples were collected (Figure 3.2). Sampling was carried out in September in 2014 (sea surface temperature (SST) = 16.7 °C) and 2015 (SST = 16.3 °C), and early October in 2016 (SST = 16.3°C) and 2017 (SST = 16.1 °C) in daylight hours (10 am to 5 pm) during neap tidal cycles.

3.2.1.2 Data extraction

For the Rope treatment, the video footage from the GoPro on the PelagiCam units that spent the most amount of time facing the mussel rope droppers was used. For the Control treatment, the video footage with the best visibility was used. Pelagic fishes were identified from the video and the maximum number of individuals in the field of view were recorded in 1-min segments. This established the maximum number of each species present within a minute during each 60-min video (maxN: Priede et al., 1994; Cappo et al., 2003), which minimised the risk of counting the same individual several times (Willis et al., 2000). The 1-min long segments were averaged to give relative abundance (mean maxN min^{-1}). MaxN is used in the vast majority of studies (e.g. Ellis and DeMartini, 1995; Willis and Babcock, 2000; Cappo et al., 2003; Bicknell et al., 2019) and is considered to be a conservative measure of abundance (Bicknell et al., 2019) as there may be individuals that do not enter the field of view (Whitmarsh et al., 2016). Prior to zooplankton identification, samples were sieved through a 250 μm mesh and placed into pentachlorophenol (PCP) solution. The sample was homogenised and split into two subsamples using measuring cylinders. The first subsample, containing three quarters of the sample, was used to count decapod and bivalve larvae. The second subsample, containing one quarter of sample, was used to identify and count all zooplankton present. The subsamples were placed into a Bogrov chamber with 1 cm wide serpentine pathway (40 ml sample volume) for systematic analysis. Subsampled zooplankton abundances were multiplied by four to give a representation of the whole sample. Abundance was then converted into cells l^{-1}. Four key phyla were pre-selected from the assemblage: decapods, bivalves, copepods and chaetognaths. Although unable to identify all decapod larvae to species level, this group was included as a key group as it may include commercial brown crab *Cancer pagurus* larvae. Bivalves were included as, although too small to identify taxa, the group may be made up of the cultured species (*Mytilus edulis*) as well as commercially important king scallop *Pecten maximus*, which supports a large fishery in Lyme Bay (Rees et al., 2016). Marine copepods are the most abundant metazoans on Earth and are important links in marine food webs, serving as prey for ichthyoplankton (fish eggs and larvae) and pelagic carnivores (Turner, 2004). Chaetognaths are an important pelagic predator group in the plankton community, most commonly feeding on copepods (Feigenbaum and Maris, 1984). Samples were analysed at The Marine Biological Association of the UK under the direction of plankton analysts from the Continuous Plankton Recorder (CPR) Survey.

3.2.1.3 Data analyses

Permutational multivariate analysis of variance (PERMANOVA) has been used throughout the thesis. As it was originally designed for ecological studies, it can manage a large number of abundance counts for a large number of species (Anderson, 2017). There are no explicit assumptions on the distribution of variables (Anderson, 2005) and so it can deal with non-normal and zero-inflated data (Anderson, 2017). PERMANOVA only assumes that the samples are exchangeable under a true null hypothesis and that exchangeable objects (samples) are independent (Anderson et al., 2008). All samples in this thesis are independent. PERMANOVA is generally more powerful than other tests (e.g. ANOSIM and the Mantel test) in detecting changes in community structure (Anderson and Walsh, 2013).

PERMANOVA+, (Anderson, 2001) in the PRIMER v7 software package (Clarke et al., 2014) was used to conduct multivariate and univariate analyses. Prior to analysis, shade plots were used to inform the selection of the most appropriate data transformation method.

Temporal change of pelagic fishes was analysed using three factors to assess change in the Abundance of *Trachurus trachurus*: Time since deployment (year) (fixed: 1, 2, 3, 4), Trial Station (random: Trial Station 1, Trial Station 2) and Treatment (fixed, nested within Trial Station: Rope, Control). As there were no specific hypotheses regarding differences between headlines within Plots, Plots were pooled within Treatment. Statistically significant interactions ($P < 0.05$) between Year and Treatment (nested within Trial Station) were further interpreted using pairwise tests. The resemblance matrix was constructed using Euclidean distance indices (Anderson, 2001; Anderson, 2017).

Zooplankton analysis comprised three factors: Year (fixed: 1, 2, 3, 4), Trial Station (random: Trial Station 1, Trial Station 2) and Treatment (fixed, nested within Trial Station: Rope, Control). Data were square root transformed. Univariate resemblance matrices (Species richness, Total abundance, Abundance of key groups) were constructed using Euclidean distance indices (Anderson, 2017), and the multivariate resemblance matrix (Assemblage composition) was constructed using Bray-Curtis similarity indices (Anderson, 2017). Multivariate patterns were visualised using a non-metric multidimensional scaling (nMDS) ordination plot. The centroids of each Year x Trial Station x Treatment points were visualised to reduce the number of points on the plot (Terlizzi et al., 2005). SIMPER (similarity percentages) was used to examine the taxa driving the nMDS (Clarke and Warwick, 2001).

3.2.2 FAD effect

3.2.2.1 Survey design and sampling equipment

To assess the effect of the ageing mussels on the pelagic fishes, three Treatments were used: 'M_0' (rope droppers housing spat mussels), 'M_1' (rope droppers housing 1-year-old mussels) and 'M_2' (rope droppers housing 2-year-old mussels) (Figure 3.5). Different ropes were sampled for pelagic fishes (Figure 3.5a) and rope epibiota (Figure 3.5b). Within each Treatment, three non-baited PelgiCam video units were deployed along three single headlines. Positioning of units along the headline was carried out in the same way as in the time-series monitoring. These were sampled once within the same week in August 2017.

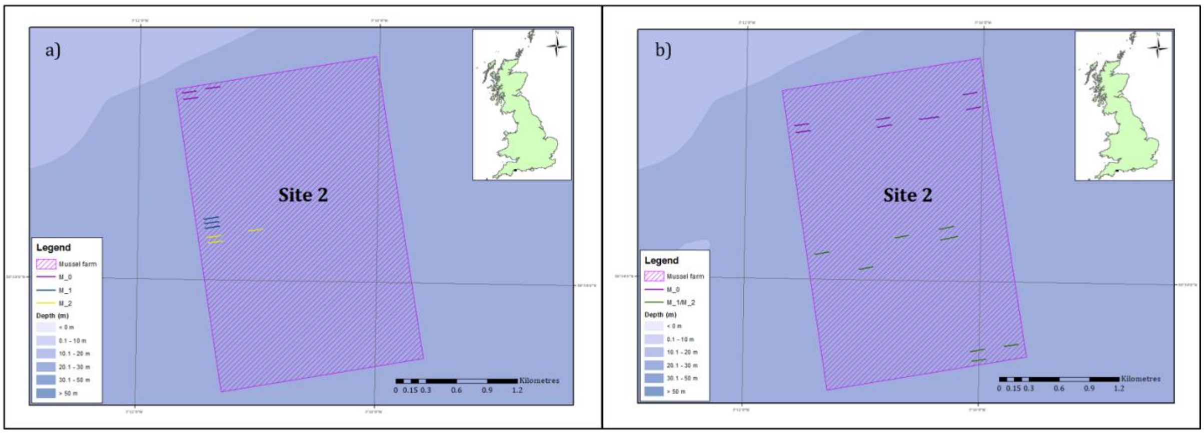


Figure 3.5: Sampling locations of M_0, M_1 and M_2 treatments for a) pelagic fishes and b) rope assemblage surveys.

Mussel biomass and species richness of epibiota were sampled from 30 cm sections of rope. The headline was pulled up and a rope was picked along the headline. The mussels and epibiota were pulled off a 30 cm section of rope, 1-2 m from the top of the rope dropper, which is at 5-6 m depth in the water column, corresponding with the depth of the PelagiCam footage. The section was then washed by hand in a bucket of seawater for 30 seconds, turned over and then washed for another 30 seconds. The sample was sieved through a 0.5 mm Endecott sieve, placed in a bag and fixed with 10 % borax-buffered formalin. Six headlines were sampled with rope droppers housing spat mussels (M_0) and 1-year-old mussels (M_1). However, only four headlines with rope droppers housing 2-year-old mussels (M_2) were available for sampling. The headlines housing each age of mussels were sampled once in May 2016 (M_0), May 2017 (M_1) and June 2018 (M_2).

The commercial brown crab *Cancer pagurus* were sampled from all the rope droppers from a full headline in December 2018 (M_0), December 2018 (M_1) and February 2019 (M_2). The number of brown crab on all headlines in each treatment were counted and their carapace measured (Figure 3.6). The total length of rope droppers harvested for each headline was recorded to allow a density of crabs per metre of rope to be calculated. Permission to remove *C. pagurus* under the minimum conservation reference size for scientific purposes was granted under Devon and Severn Inshore Fisheries and Conservation Authority (D&S IFCA) Byelaw 2 (Supplementary material, Section A: Figure 1). All crabs collected were returned to the sea alive.

Figure 3.6: a) Crabs collected during survey, and b) measuring the crab's carapace.

3.2.2.2 Data extraction

Video footage from the PelagiCam units was analysed in the same way as in the time-series monitoring survey.

Prior to rope assemblage epibiota identification, samples were sieved through a 0.5 mm Endecott sieve under a fume hood and the whole sample was weighed. The sample was then placed in a white tray and pulled apart. Mussels were placed into a separate tray and epibiota were placed in labelled glass vials filled with 70 % Industrial Denatured Alcohol (IDA).

The mussels were then sieved, separating mussels into two size categories: < 2 cm and > 2 cm. The length, height and width of all mussels > 2 cm were measured and the total weight of all mussels in each size category were recorded. Epibiota were identified to the lowest taxonomic level possible using taxonomic keys (Hayward and Ryland, 1995; Hayward and Ryland, 2017) with a Leica EZ4 microscope.

3.2.2.3 Data analyses

PERMANOVA+, (Anderson, 2001; Clarke et al., 2014) in the PRIMER v7 software package was used to conduct analyses. Prior to analysis, shade plots were used to inform the selection of the most appropriate data transformation method. One factor was used to analyse univariate measures Abundance of *Trachurus trachurus*, Abundance of *Chelon labrosus*, Mussel biomass, Species richness of rope epibiota and Carapace width of *Cancer pagurus*: Treatment (fixed: M_0, M_1, M_2). Date were square root transformed and resemblance matrices were constructed using Euclidean distance indices (Anderson, 2017). Statistically significant results were based on a P value of <0.05.

3.3 Results

3.3.1 Time Series Monitoring

3.3.1.1 Pelagic fish

Three pelagic fish species were identified in this survey: Atlantic horse mackerel *Trachurus trachurus*, grey thick-lipped mullet *Chelon labrosus* and garfish *Belone belone*. However, only *T. trachurus* were identified frequently enough for statistical analysis. 26 grey thick-lipped mullet were recorded in the Rope treatment in Year 4 at Trial Station 2, and one individual garfish was recorded in the Control treatment in Year 2 at Trial Station 2.

There was a significant interaction between Time since deployment and Treatment on the abundance of *T. trachurus* (Ti x Tr (TS): P = 0.0001; Supplementary material, Section A: Table 1a). *T. trachurus* were only observed in the Rope treatment at either Trial Station (Figure 3.7). There was a significantly greater abundance in the Rope treatment in Trial Station 2 in Year 1, both Trial Stations in Year 2, and Trial Station 1 in Year 4 (Supplementary material, Section A: Table 1b). Abundance was greatest in Year 2 and Year 1 at Trial Station 1 and Trial Station 2, respectively (Figure 3.7).

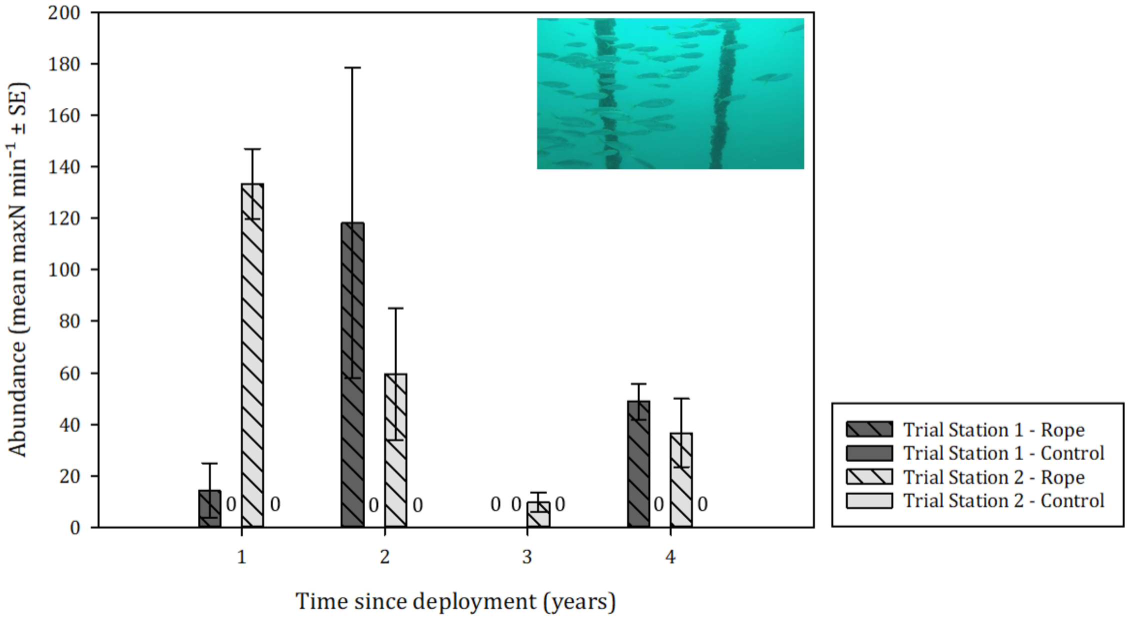


Figure 3.7: Abundance of *Trachurus trachurus* (mean maxN min^{-1} ± SE) within Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 1-4). '0' shows where no fish were recorded.

3.3.1.2 <u>Zooplankton</u>

Zooplankton species richness and total abundance showed no significant difference between Treatments over Time (Ti x Tr(TS): both $P > 0.05$; Supplementary material, Section A: Tables 2 and 3).

Species richness remained similar between Treatments in all Years at both Trial Stations (Figure 3.8a). At Trial Station 1, total abundance was greater in the Control treatment throughout the survey, with the greatest difference between Treatments in Year 2 (Rope = 2.25 ± 0.25 cells l^{-1}, Control = 3.73 ± 0.36 cells l^{-1}; Figure 3.8b). At Trial Station 2, total abundance of zooplankton became more similar between Treatments with Time since deployment. In Year 1, total abundance was greater in the Control than the Rope treatment (Rope = 1.89 ± 0.44 cells l^{-1}, Control = 2.27 ±

0.59 cells l^{-1}; Figure 3.8b). Abundance then became more similar between Treatments through to Year 4 (Rope = 0.49 ± 0.04 cells l^{-1}, Control = 0.48 ± 0.06 cells l^{-1}; Figure 3.8b). There is a significant decrease in abundance of zooplankton over time (P = 0.02; Supplementary material, Section A: Table 3). However, this decrease is seen in both Treatments.

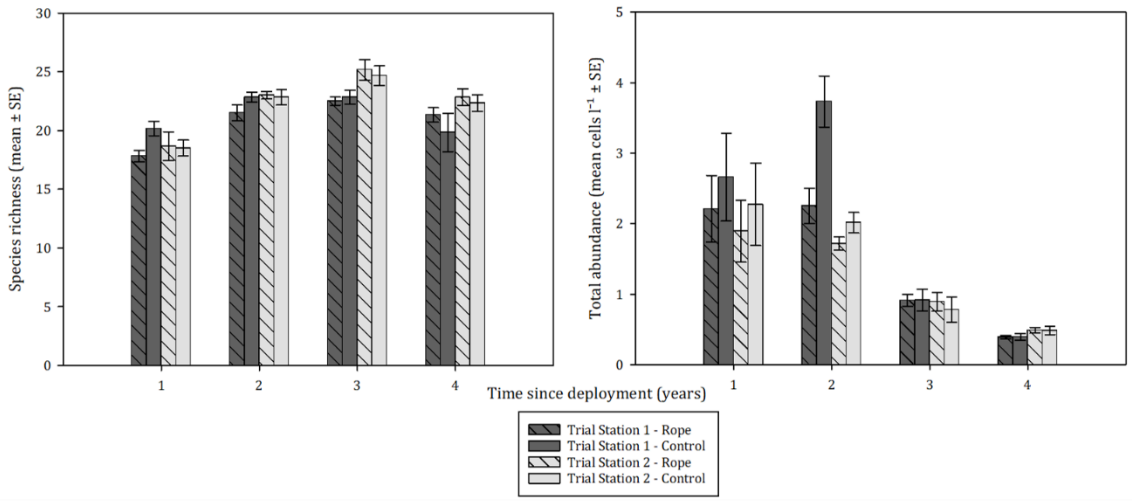


Figure 3.8: Zooplankton a) Species richness (mean ± SE), and b) Total abundance (mean cells l^{-1} ± SE) within Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 1-4).

There was a statistically significant Time since deployment x Treatment effect on the assemblage composition of zooplankton (Ti x Tr(TS): P = 0.0002; Supplementary material, Section A: Table 4a). Pairwise tests showed that at Trial Station 1, assemblage composition was significantly different between Treatments from Year 2 (all P < 0.05; Supplementary material, Section A: Table 4b). This effect is visually represented in the nMDS (Figure 3.9) which shows greater distance between Treatments in these years. SIMPER analysis shows that in Year 2, Ophiuroidea contributed to over 20 % of the dissimilarity between Treatments and were almost two times more abundant in the Control treatment. In Years 3 and 4, *Paracalanus* spp. contributed most to the dissimilarity between Treatments and we more abundant in the Rope treatment and the Control treatment, respectively (Table 3.1).

At Trial Station 2, assemblage composition was only significantly different between Treatments in Year 2 (P = 0.009; Supplementary material, Section A: Table 4b). However, the nMDS (Figure 3.9) shows a greater distance between Treatments in Year 3 than any other year. This is reflected in the SIMPER results, which showed an average dissimilarity of 21.16 % in Year 2, and 28.16 % in Year 3 (Table 3.1). In Year 3, the three taxa contributing the most to the dissimilarity between Treatments were all copepods: *Corycaeus* spp., *Paracalanus* spp. and *Centropages* spp. (Table 3.1).

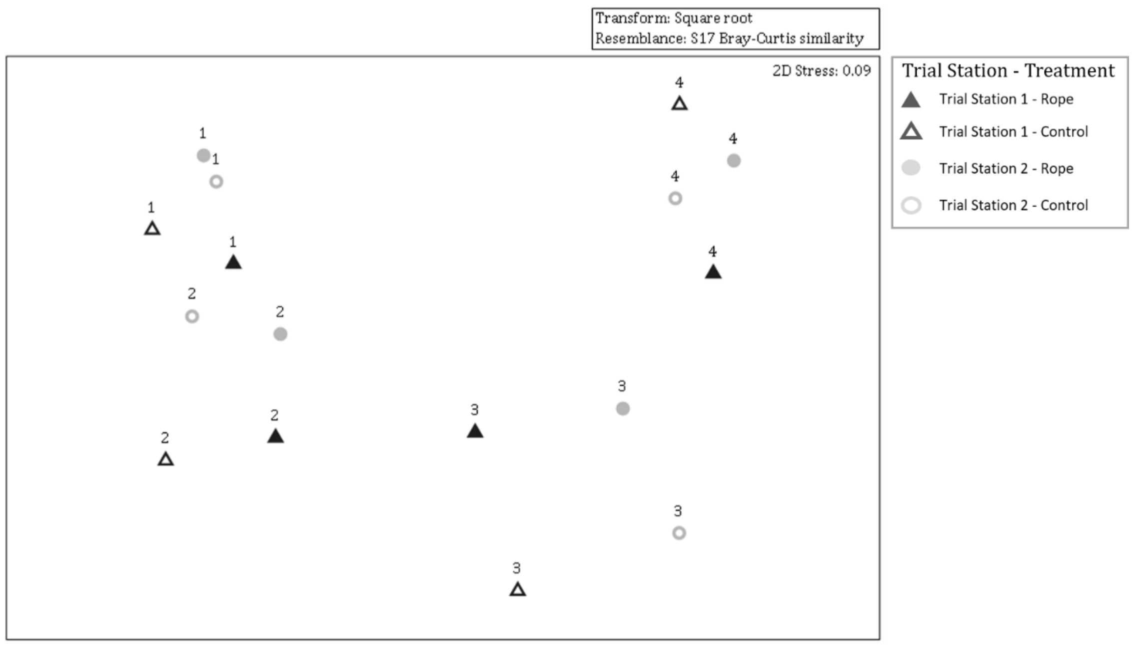


Figure 3.9: nMDS ordination plot illustrating difference in assemblage composition of zooplankton within Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 1-4).

Table 3.1 SIMPER analysis in groups outlined by PERMANOVA showing the top five organisms which most contributed to the observed differences between Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 1-4).

Taxon	Av. Abun.	Av. Abun.	Av. Diss.	Diss./SD	Contrib. %	Cum. %
Trial Station 1						
Year 1 Av. Diss.: 23.58	**Rope**	**Control**				
Temora longicornis	0.85	0.97	3.65	1.07	15.49	15.49
Paracalanus spp.	0.65	0.62	2.84	1.35	12.03	27.51
Corycaeus spp.	0.59	0.66	2.21	1.17	9.36	36.87
Mytilus edulis	0.35	0.45	1.68	1.01	7.12	43.99
Centropages spp.	0.27	0.29	1.14	1.26	4.84	48.83
Year 2 Av. Diss.: 19.57	**Rope**	**Control**				
Ophiuroidea	0.65	1.18	4.66	1.73	23.83	23.83
Temora longicornis	0.61	0.76	1.66	1.11	8.48	32.31
Corycaeus spp.	0.47	0.61	1.30	1.42	6.62	38.93
Evadne	0.23	0.16	1.11	1.32	5.65	44.59
Podon spp.	0.13	0.23	0.93	1.99	4.75	49.33
Year 3 Av. Diss.: 21.42	**Rope**	**Control**				
Paracalanus spp.	0.38	0.17	3.09	1.94	14.42	14.42
Temora longicornis	0.44	0.42	1.74	1.35	8.12	22.54
Acartia clausii	0.19	0.08	1.52	1.90	7.08	29.62
Chaetognatha	0.19	0.28	1.40	1.38	6.56	36.18
Corycaeus spp.	0.41	0.45	1.33	1.24	6.23	42.40
Year 4 Av. Diss.: 26.44	**Rope**	**Control**				
Paracalanus spp.	0.28	0.37	2.53	1.58	9.57	9.57
Corycaeus spp.	0.36	0.31	2.18	1.03	8.23	17.8
Acartia clausii	0.14	0.19	1.29	1.66	4.86	22.66
Cirrepedia	0.14	011	1.25	1.30	4.72	27.38
Calanus spp.	0.08	0.04	1.18	1.52	4.47	31.85
Trial Station 2						
Year 1 Av. Diss.: 25.63	**Rope**	**Control**				
Temora longicornis	0.55	0.62	3.72	1.62	14.52	14.52
Paracalanus spp.	0.87	0.92	3.10	1.42	12.10	26.62
Cirrepedia	0.36	0.33	1.88	1.32	7.35	33.97
Podon spp.	0.43	0.38	1.74	1.42	6.80	40.77
Corycaeus spp.	0.28	0.32	1.66	1.26	6.47	47.24
Year 2 Av. Diss.: 21.16	**Rope**	**Control**				
Paracalanus spp.	0.53	0.77	2.51	1.75	11.85	11.85
Corycaeus spp.	0.58	0.39	2.42	1.15	11.45	23.31
Evadne	0.27	0.13	1.48	2.97	7.00	30.31
Temora longicornis	0.63	0.70	1.34	1.14	6.32	36.63

Acartia clausii	0.26	0.38	1.19	1.58	5.64	42.27
Year 3 Av. Diss.: 28.16	**Rope**	**Control**				
Corycaeus spp.	0.47	0.58	3.77	1.29	13.40	13.4
Paracalanus spp.	0.33	0.14	2.97	1.93	10.53	23.93
Centropages spp.	0.14	0.05	1.86	0.57	6.61	30.54
Chaetognatha	0.22	0.23	1.61	1.52	5.70	36.24
Siphonophorae	0.32	0.29	1.55	1.21	5.50	41.74
Year 4 Av. Diss.: 20.00	**Rope**	**Control**				
Evadne	0.37	0.27	2.24	1.24	11.22	11.22
Podon spp.	0.23	0.19	1.51	2.01	7.54	18.76
Paracalanus spp.	0.30	0.35	1.31	1.40	6.55	25.31
Corycaeus spp.	0.27	0.30	1.17	1.40	5.86	31.17
Appendicularia	0.08	0.08	0.99	1.29	4.94	36.11

There was no significant interaction between Time since deployment and Treatment on abundance of decapods, bivalves, copepods or chaetognaths (Ti x Tr(TS): all P > 0.05: Supplementary material, Section A: Table 5). At both Trial Stations, abundance of decapods was greater in the Control than the Rope treatment from Year 1 to Year 3, but slightly greater in the Rope treatment 4 years after headline deployment (Figure 3.10a). The abundance of bivalves was greater in the Control treatment than the Rope treatment in Years 1 and 2, and then very low in both Treatments in Years 3 and 4, at both Trial Stations (Figure 3.10b). Copepod abundance also followed the same pattern at both Trial Stations; abundance was greater in the Control treatment in Years 1 and 2, and greater in the Rope treatment in Years 3 and 4 (Figure 3.10c). The abundance of chaetognaths was more variable. At Trial Station 1, chaetognath abundance was greater in the Rope treatment at the start and end of the survey, but considerably greater in the Control treatment in Years 2 and 3. At Trial Station 2, abundance was greater in the Control than the Rope Treatment in all Years except Year 2 (Figure 3.10d).

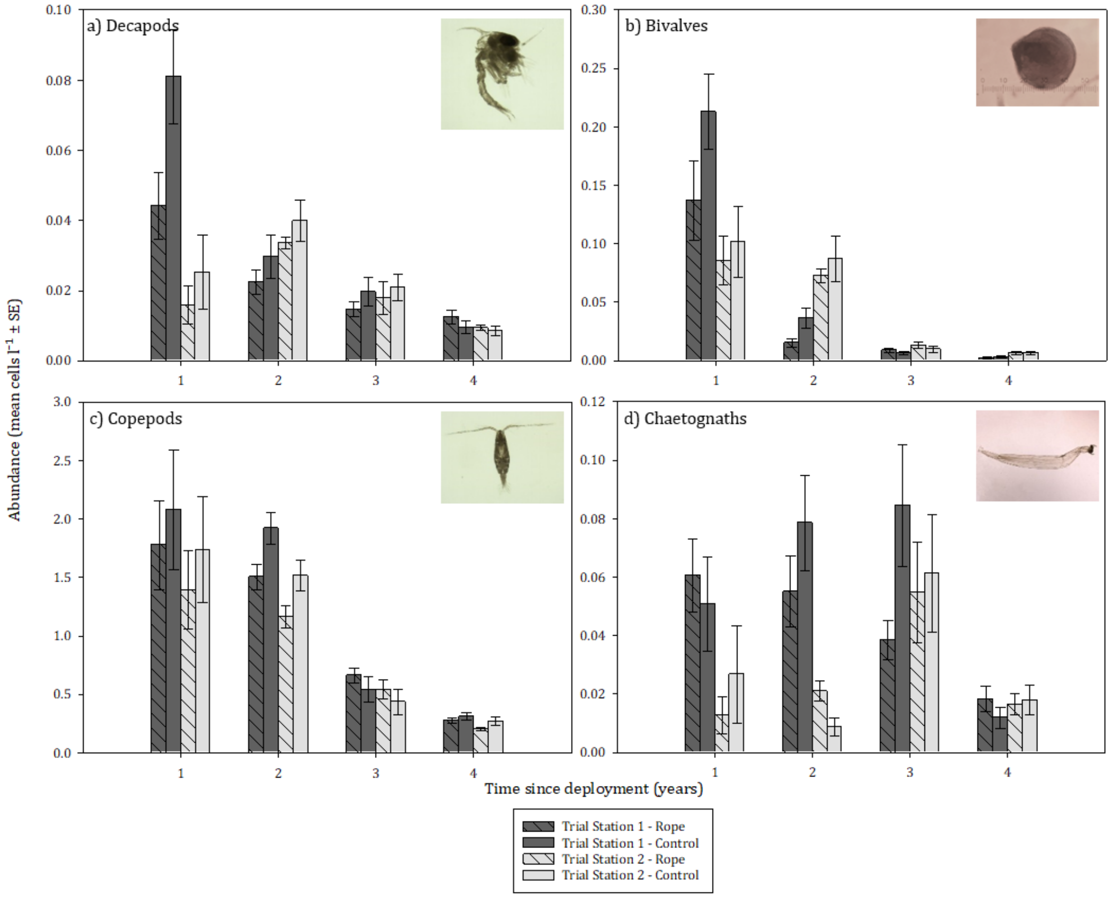


Figure 3.10: Abundance (mean per haul ± SE) of a) Decapods, b) Bivalves, c) Copepods, and d) Chaetognaths within Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 1-4).

3.3.2 FAD effect

3.3.2.1 Pelagic fishes

Atlantic horse mackerel *T. trachurus* and grey thick-lipped mullet *C. labrosus* were identified in this survey and both included in statistical analyses.

There was a significant Treatment effect on the abundance of *T. trachurus* (P = 0.0001; Supplementary material, Section A: Table 6a). Pairwise tests showed that there was a significantly greater abundance of *T. trachurus* in the M_1 treatment (439.17 ± 104.73 maxN min^{-1}; Figure 3.11a) and M_2 treatment (805 ± 278.02 maxN min^{-1}; Figure 3.11a) than the M_0 treatment (29.42 ± 8.52 maxN min^{-1}; Figure 3.11a) (both P = 0.0001; Supplementary material, Section B: Table 1b). Abundance was not significantly different between the M_1 and M_2 treatments ($P > 0.05$; Supplementary material, Section A: Table 6b), although there was an almost two-fold increase in abundance between treatments (Figure 3.11a).

There was no significant effect of Treatment on the abundance of *C. labrosus* ($P > 0.05$; Supplementary material, Section A: Table 7). Abundance was marginally greater in the M_1 treatment than the M_0 and M_2 treatments (M_0 = 2.25 ± 1.26 maxN min^{-1}, M_1 = 3.00 ± 2.24 maxN min^{-1}, M_2 = 0.50 ± 0.34 maxN min^{-1}; Figure 3.11b).

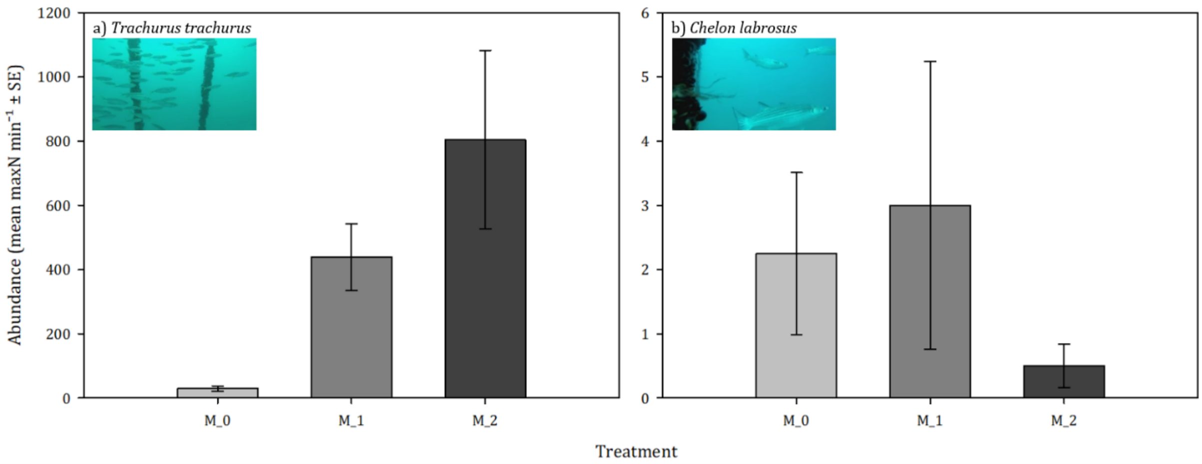


Figure 3.11: Abundance (mean maxN min^{-1} ± SE) of a) *Trachurus trachurus* and b) *Chelon labrosus* in the M_0, M_1 and M_2 treatments.

3.3.2.2 Rope assemblage

There were 21 taxa identified in the rope assemblage: these can be seen in Table 3.2, which also gives an indication of when each taxa colonised the ropes.

Table 3.2: Rope assemblage taxa on spat mussels (M_0), 1-year-old mussels (M_1) and 2-year-old mussels (M_2).

			Treatment		
Phylum	Taxa	Common name	M_0	M_1	M_2
Arthropoda	*Jassa marmorata*	Tube-building amphipod	✓	✓	✓
Annelida	Phyllodocidae	Polychaete worm		✓	
Arthropoda	*Pisidia longicornis*	Long-clawed porcelain crab		✓	
Mollusca	Anomiidae	Saltwater clam		✓	
Mollusca	*Aequipecten opercularis*	Queen scallop		✓	
Mollusca	*Facelina bostoniensis*	Nudibranch		✓	
Mollusca	*Hiatella arctica*	Wrinkled rock borer		✓	
Mollusca	*Ostrea edulis*	Native oyster		✓	
Bryozoa	*Cellepora pumicosa*	Bryozoan		✓	
Platyhelminthes	*Leptoplana tremellaris*	Flatworm		✓	
Annelida	*Harmothoe imbricata*	Polychaete worm		✓	✓
Arthropoda	*Pilumnus hirtellus*	Hairy crab		✓	✓
Echinodermata	*Psammechinus miliaris*	Green sea urchin		✓	✓
Cnidaria	*Corynactis viridis*	Jewel anemone			✓
Cnidaria	*Sagartia elegans*	Elegant anemone			✓
Annelida	Terebellidae	Polychaete worm			✓
Arthropoda	Caprellidae	Skeleton shrimp			✓
Chordata	*Ascidiella scabra*	Sea squirt			✓
Chordata	*Ciona intestinalis*	Sea squirt			✓
Chordata	*Molgula manhattensis*	Sea grapes			✓
Chordata	*Molva molva*	Common ling			✓

There was a significant Treatment effect on the species richness of epibiota ($P = 0.004$; Supplementary material, Section A: Table 8a). Species richness was significantly greater in the M_2 treatment than the M_0 treatment ($P = 0.004$; Supplementary material, Section A: Table 8b), with over six times greater the number of epibiota found on the ropes (M_0 = 1.00 ± 0.00, M_2 = 6.50 ± 0.96; Figure 3.12a). Species richness was greater in the M_1 treatment than the M_0 treatment and greater in the M_2 treatment than the M_1 treatment (Figure 3.12a), but not significantly greater (both $P > 0.05$; Supplementary material, Section A: Table 8b).

There was a significant Treatment effect on the biomass of mussels ($P = 0.0002$; Supplementary material, Section A: Table 9a). Pairwise tests showed that mussel biomass was significantly greater on ropes in the M_1 (2320.32 ± 287.36 g; Figure 3.12b) and M_2 treatments (1772.76 ± 81.88 g; Figure 3.12a) than the M_0 treatment (543.10 ± 78.88 g; Figure 3.12b) (both P < 0.05; Supplementary material, Section A: Table 9b). Mussel biomass was not significantly different between Treatments M_1 and M_2 (P > 0.05; Supplementary material, Section A: Table 9b).

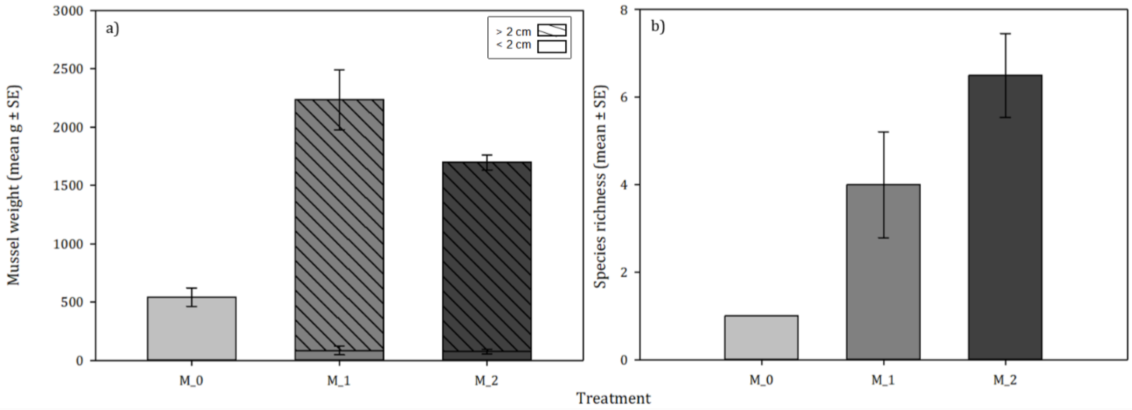


Figure 3.12: a) Biomass of > 2 cm and < 2 cm mussels (mean g ± SE), and b) Species richness (mean ± SE) of epibiota in the M_0, M_1 and M_2 treatments.

Abundance of *Cancer pagurus* was greatest in the M_1 treatment (0.27 m^{-2}; Figure 3.13a) compared to the M_0 (0.16 m^{-2}; Figure 3.13a) and M_2 treatments (0.13 m^{-2}; Figure 3.13a). There was a significant Treatment effect on the carapace width of *C. pagurus* individuals (P = 0.0001; Supplementary material, Section A: Table 10a). Carapace width was significantly greater in the M_2 (36.66 ± 1.08 mm; Figure 3.13b) treatment that the M_0 treatment (28.55 ± 0.69 mm; Figure 3.13b) and M_1 treatment (24.84 ± 0.63 mm; Figure 3.13b) (both P = 0.0001 Supplementary material, Section A: Table 10b).

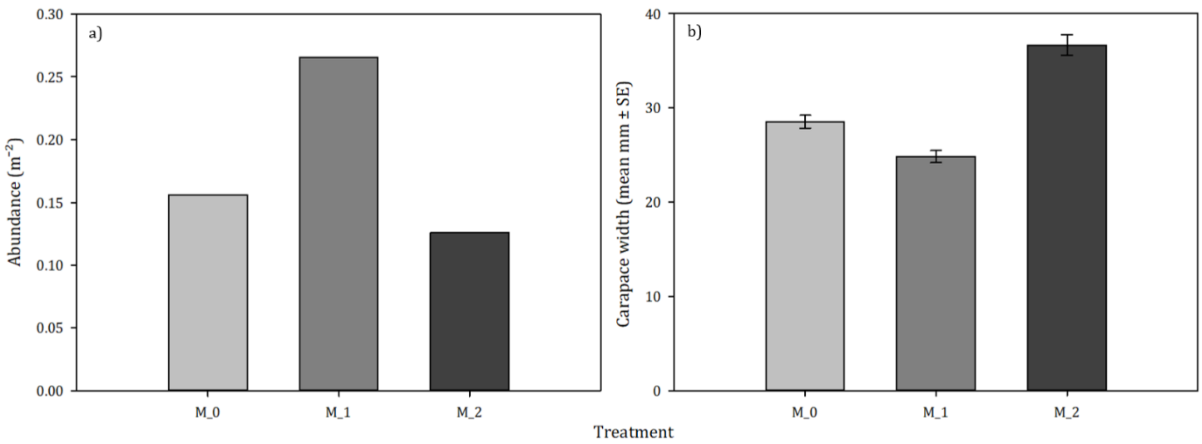


Figure 3.13: a) Abundance of *Cancer pagurus* (m^{-2}), and b) Carapace width of *Cancer pagurus* (mean mm ± SE) in the M_0, M_1 and M_2 treatments.

3.4 Discussion

The primary aim of this study was to develop and pilot a time-series monitoring programme that can be used when testing for changes in the pelagic ecosystem (pelagic fishes and zooplankton) between areas within an open ocean long-line mussel farm, and control locations. A further aim was to investigate whether there is an interaction between the age of cultivated mussels with the number of epibiota species and the abundance of pelagic fishes.

Pelagic fishes were monitored using custom-made PelagiCam units. During time-series monitoring, Atlantic horse mackerel *Trachurus trachurus* were recorded exclusively around the mussel farm headlines, indicating that the mussel rope droppers appear to be acting as a fish aggregation device (FAD). Abundance was generally lower in years 3 and 4 after headline deployment. This could be a due to a dilution effect as from 2015 (year 2 after headline deployment at the Trial Stations) many more headlines were installed within the mussel farm, especially at Site 2, and so fish may have been aggregated in other areas throughout the farm rather just round the original headlines in the two trial stations. The continued addition of headlines which are each acting as FADs might result in diminishing abundance of pelagic fishes in specific locations as the relative benefit of each headline to pelagic fishes is diluted (Davies et al., 2014).

The PelagiCam units equipped with GoPro cameras were an effective method of filming the mussel rope droppers. The units were successfully deployed on each occasion and the adapted method of clipping the units on to the headlines further eased the deployment process for both the skipper and the deployment team. The units are small and lightweight, making them easy to transport and deploy. The non-disruptive nature of the units avoided the bias that has been reported in Morrisey et al. (2006) where remotely operated vehicles (ROV) and SCUBA divers disturbed fish behaviour and led to low counts of pelagic fishes. Leaving the cameras unbaited ensured that the fishes recorded were attracted to the mussel headlines, and not to the PelagiCam units. The video resolution used on the GoPro cameras gave extremely clear footage, while also allowing the same SD cards to be used for two consecutive video drops, helping to decrease the turnaround time on the boat between drops and human error with making sure the waterproof GoPro housing are sealed properly. This did happen on a couple of occasions and led to the loss of the cameras.

Zooplankton abundance remained similar between treatments throughout the survey and did not appear to be depleted by the filter feeding activity of the mussels and epibiota in the farm compared to the control areas. Although, there was a general decline in abundance of zooplankton from 2015 onwards. This could be linked to the 2013/2014 winter storms that hit the southwest coast (Masselink et al., 2016). Shifts in zooplankton abundance are often linked to environmental variables (Hays et al., 2005; Mackas et al., 2012) and tends to be higher during and after storm events (Cruz-Rosado et al., 2020), as primary production increases. The zooplankton community responds to this increase in food both functionally and numerically. This could explain why, after a particularly stormy winter, abundance of zooplankton was higher in 2014 (Year 1) relative to 2016 (Year 3) and 2017 (Year 4). However, it is unclear whether this would still be influencing zooplankton abundance in 2015 (Year 2), when abundance was still high. After a storm event, female copepod egg production increases and ciliates become more abundant (Nielsen and Kiørboe, 1991). This effect could be being seen in the copepods recorded in this study, with a greater abundance in 2014 (Year 1) and 2015 (Year 2), then a sharp decline in 2016 (Year 3). There was also a peak in abundance of chaetognaths in Year 3, which could explain the sharp decline in abundance of the other indicator taxa, as chaetognaths are an important pelagic predator group in the plankton community, most commonly feeding on copepods (Feigenbaum and Maris, 1984). It is, however, also possible that that control locations are not beyond the influence of the farm. This perhaps is unlikely as in 2014, when the survey started, there were only three headlines deployed throughout the whole farm area and these were only housing spat mussels. It would be unexpected for zooplankton at control sites, located 500 m away, to be under the influence of these headlines. If zooplankton abundance is so far unaffected by the mussel headlines, this could be due to the open ocean nature of the farm, which may support more zooplankton because of a deeper mixing layer and greater integration (Gasol et al., 1997).

However, there was a shift in the assemblage composition of zooplankton in years 2 and 3 after headline deployment at Trial Station 1, mainly due to differences in the abundance of the most frequent copepods: *Temora longicornis*, *Acartia clausii*, *Corycaeus* spp. and *Paracalanus* spp. By 4 years after headline deployment, there was no longer a significant difference in zooplankton assemblage composition between treatments. It is unclear what the cause of this could be, but there may be a link with the prey selection of chaetognaths, which were abundant in these years. It may also be due to different aged mussels growing on the ropes, and therefore filtering varying volumes of water. At Trial Station 2, the ropes are always housing spat mussels so variations in the volume of water filtered would be less pronounced.

The piloted method to survey the zooplankton community was not effective in fully understanding the influence of the existing mussel headlines. In 2013, when baseline monitoring was carried out, the effect of the farm on plankton was overlooked. If there had been baseline monitoring, it would have been clearer whether the control plots were compromised, or whether zooplankton abundance declined at the two treatments due to another factor. Future farm developers should carry out baseline monitoring of plankton to avoid this. Further to this, samples taken along a gradient from within to farm area to control plots would be beneficial to be able to conclude the distance at which plankton communities are not under the influence of the farm.

In the survey investigating whether pelagic fishes are more abundant around rope droppers housing older mussels, grey thick-lipped mullet *Chelon labrosus* were recorded within the farm, and some were recorded eating directly off the mussel ropes. Mullet typically eat algae and invertebrates, both of which grow on the ropes as epibiota. Mussel farm workers have also anecdotally recorded bass *Dicentrarchus labrax* in the farm and, more recently, Atlantic bluefin tuna *Thunnus thynnus* preying on the large schools of *T. trachurus*. Fishes *D. labrax*, *C. labrosus* and *T. trachurus* are all commercially caught in Lyme Bay. As the farm develops and more headlines are installed, greater abundance of these species could aggregate within the farm, with the potential to spillover into adjacent fishing ground and enhance local fisheries.

The abundance of *T. trachurus* increased as the age of the mussels growing on the rope increased, indicating that they are more attracted to the ropes with older mussels. This may be due to the food provision that these mussels provide. As mussels grow and reach adulthood, they provide a greater surface area for colonisation and, in symmetry with the abundance of *T. trachurus*, as the age of the mussels growing on the ropes increased, species richness of epibiota increased. Overall, 22 taxa from eight phyla were identified. The most abundant species was *Jassa marmorata*, a tube-building amphipod that is a frequent fouling organism on aquaculture and offshore wind farm installations (Fernandez-Gonzalez and Sanchez-Jerez, 2011; Bouma and Lengkeek, 2012; De Mesel et al., 2015). *T. trachurus* mainly feed on crustaceans, cephalopods and teleosts (Jardis et al., 2004; Šantić et al., 2005). Four species of crustaceans were found on the mussel ropes, including skeleton shrimp, which could be a food choice for *T. trachurus*, as Jardis et al. (2004) noted the presence of deep-water rose shrimp in fish stomach contents. It is possible that when the mussel farm is fully functional, the distribution of pelagic fishes, including *T. trachurus,* could change. It is unclear, so far, whether this will be a positive or negative impact, especially for local fishers.

The commercial brown crab *Cancer pagurus* was also found living on the mussel ropes and were most abundant on those ropes housing 1-year-old mussels, and abundance on ropes with 2-year-old mussels more than halved. This decrease in abundance on ropes housing 2-year-old mussels could be because the mussels are too big to be optimally foraged. *C. pagurus* actively select *Mytilus edulis* as prey and show evidence of size-selective predation (Mascaró and Seed, 2001). In Mascaró and

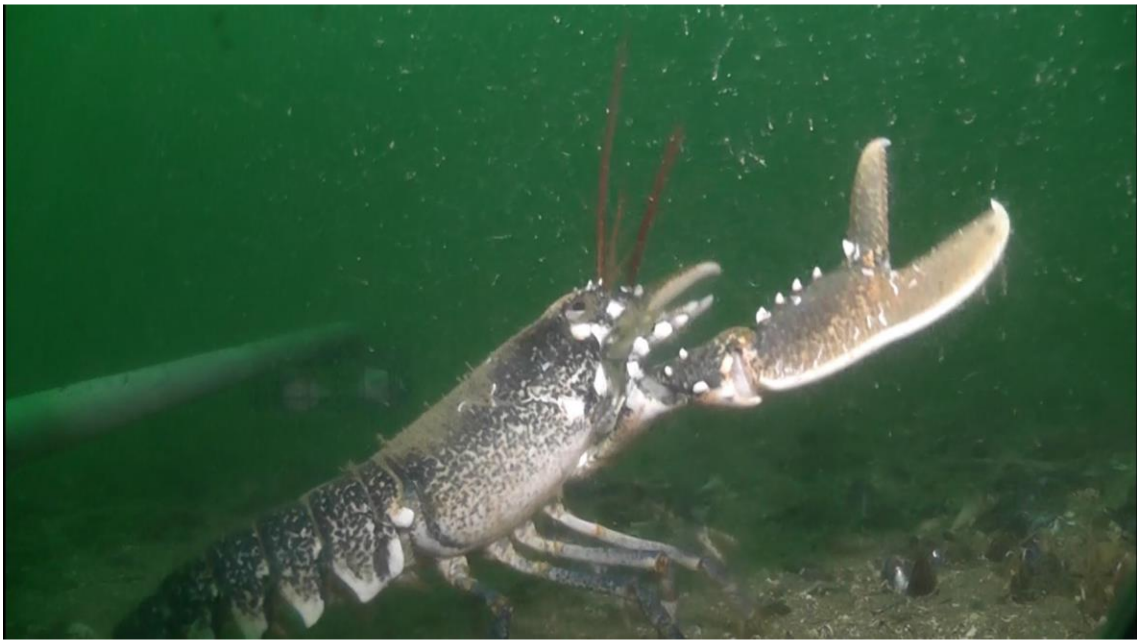
Seed (2001), small crabs (20-30 mm) selected for 4-12 mm long mussels, and small-medium crabs (30-40 mm) selected for slightly bigger 5-15 mm long mussels. In the present study, the average carapace width of crabs living on ropes housing 1-year-old and 2-year-old mussels were 24.84 mm and 36.66 mm, respectively. Therefore, they would be classed as small and small-medium crabs. However, 2-year-old mussels at the Lyme Bay mussel farm are at marketable size (> 40 mm) and so would most likely be too large to be foraged by small-medium crabs. Therefore, if the crabs could no longer optimally forage the mussels on the ropes, they may drop onto the seabed to feed. Furthermore, there were five other mollusc species present on the 1-year-old mussels, which were not on the 2-year-old mussels that could have also been contributing to the diet of *C. pagurus*, including clam, scallop and oyster.

From this survey, it is apparent that the mussel farm could be contributing to the production of the pelagic ecosystem, not just attracting fish from the wider area. The physical farm infrastructure has provided a substrate for colonisation by a variety of epibiota, which forms the biological components of an artificial reef structure. The older and larger the mussels become, greater numbers of epibiota taxa are able to colonise, coupled with a greater abundance of pelagic fish recorded around the ropes. As the farm grows and more headlines are deployed, it would be interesting to further monitor this effect and deploy PelagiCam units around the edge of the farm boundary to see whether there is any spillover into adjacent fisheries, or whether the fish are exclusive to the mussel farm and therefore unlikely to be caught and contribute to local fisheries.

3.5 Conclusion

The use of the PelagiCam units have enabled the successful monitoring of the mussel headlines within the trial stations and, along with a rope assemblage monitoring programme, have shown that the mussel headlines are attracting fishes and providing a surface area for the settlement and colonisation of epibiota which could contribute to the production of the area. Pelagic fishes are more heavily aggregated around headlines with older mussels growing on them, perhaps due to them hosting a greater species richness of epibiota and therefore a greater variety and biomass of food sources. This survey showed the importance of time-series monitoring due to different epibiota communities developing on the rope droppers over time. The effects on zooplankton are less clear and a modified sampling design would be needed to understand the influence of the farm once more headlines have been introduced and the farm is fully functioning. It is important for the monitoring of pelagic fishes to continue as the number of headlines, and therefore mussels, within the farm increases, to determine how the addition of structure and filter-feeding organisms to the pelagic system affects existing pelagic organisms in a fully functioning mussel farm.

Chapter 4: Effects of open ocean mussel farming on the benthic ecosystem.



Target Journal: Journal of Applied Ecology

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DB led the design of the experimental procedure, experimental set up and sampling locations with ES, MA and LH. DB led the data collection with assistance from ES, LH, AC and University of Plymouth technical staff. DB analysed the data and drafted the Chapter. ES, MA and SR reviewed and commented on the Chapter.

Effects of open ocean mussel farming on the benthic ecosystem.

Abstract:

Mussel farms can have a detrimental effect on benthic habitat and infaunal organisms beneath headlines due to the build-up of biodeposits (faeces and psuedofaeces) on the seabed. Added complexity to the seabed in the form of anchor blocks and mussel drop-off can cause a greater abundance of epibenthic fauna within mussel farms compared to control areas. No one study takes a whole ecosystem approach to monitoring the benthic habitat and so the aim of this Chapter is to develop and pilot a time-series monitoring programme for the benthic ecosystem, including epibenthic organisms and infauna, which can be used when testing the effects of an open ocean long-line mussel farm.

The effects of the Lyme Bay mussel farm on the benthic habitat and assemblages underneath the mussel headlines were monitored over five years, from before trial headlines were installed, through to four years after the headlines became fully functional. Benthic habitat, along with epifauna and infauna responses were measured using an array of video survey methods (towed underwater video, remotely operated video, baited remote underwater video) and grab samples at two Trial Stations and comparable control locations set up to test the impact of the farm.

Early observations at the Lyme Bay mussel farm show that there are the beginnings of change in the benthic habitat beneath the farm, which led to significant changes in the abundance and assemblage composition of epifauna, but not infauna, over time. The three video methods used were more successful than the grab sampling at monitoring change associated with the mussel farm. Each video method was useful and recorded species that were not picked up in the other two methods, illustrating

the need for more than one method to capture interactions between the mussel farm and the epibenthic assemblage. Although the Shipek grab was deemed the most appropriate grab at the start of the survey, it may not have performed as well as a different method, perhaps, and so may have given inconclusive results on the effects of the mussel headlines on infauna and sediment characteristics.

Keywords: aquaculture, epibenthic organisms, infauna, mussel farming, offshore, open ocean, organic content, particle size analysis

4.1 Introduction

The main capture fishing method in the UK is demersal trawling, involving catching fish and shellfish that live on or just above the seabed (Hatcher and Read, 2001). This results in the physical disturbance of benthic habitats which impacts benthic species abundance, richness and community structure (Jones, 1992; Hiddink et al., 2018). Biogenic reefs have historically been degraded by mobile fishing gear. In particular, estuarine oyster reefs (Kirby, 2004; Airoldi and Beck, 2007; Roberts, 2007) have been degraded through fishery disturbance and pollution, which leads to increased bottom-water hypoxia and harmful algal blooms (Lenihan et al., 2001). The horse mussel *Modiolus modiolus* also forms highly complex biogenic reefs, where degradation leads to a decline in epifauna biodiversity, including tunicates, sponges and hydroids (Fariñas et al., 2018). As capture fishery production remains static (FAO, 2020), ocean space available for aquaculture is estimated to be larger than is needed to feed the world (Clavelle et al., 2019). Therefore, aquaculture will play a key role in food production as demand for protein increases.

To feed the world's growing population, and meet global fish consumption demands, aquaculture continues to expand rapidly. In 2018, total global production of aquaculture reached 82 million tonnes (FAO, 2020), increasing from 80 million tonnes in 2016 (FAO 2018), and compared to 97 million tonnes from capture fisheries (FAO, 2020). Bivalves (e.g. mussels and oysters) are some of the most important non-fed aquaculture species (FAO, 2020). Within the UK, the most widely cultivated bivalve is the blue mussel *Mytilus edulis* (Seafish, 2016). Recently, molluscs have been identified as one of the lowest impact animal source foods. Aquaculture of molluscs requires very little energy input, has the lowest greenhouse gas production per portion of protein, and requires almost no fresh water and no antibiotics (Hilborn et al., 2018). However, the rapid increase in production from the aquaculture industry has raised concerns about the impact of aquaculture on the surrounding environment (McKindsey et al., 2011), as 37 % of aquaculture production comes from the marine and coastal environment, with finfish and molluscs (predominately bivalves) contributing the greatest production (FAO, 2020). Bivalve culture produces biodeposits (faeces and psuedofaeces) which can settle on the seabed if not dispersed (Kumar and Cripps, 2012), changing the chemical and physical characteristics of the seabed, and reducing associated infauna abundance and diversity (Kaspar et al., 1985; Grant et al., 2012).

Studies describing the effect of inshore mussel farm activities on the epibenthic communities below them are inconsistent. Two long-line farms that had very similar conditions (located in lagoons of 5-7 m depth, covering an area of approximately 2.5 km^2, with a 2-year grow-out cycle and mussel lines hanging ~2 m from the seabed) had different reactions with epibenthic assemblages. One study found no consistent differences in mussel farms compared to surrounding sandy sites (Clynick et al.,

2008) and the other found that epibenthic fauna (including starfish *Asterias* spp. and rock crab *Cancer irroratus*) were significantly more abundant at mussel farms than at control sites (Drouin et al., 2015). This illustrates how individual mussel farms are and that even farms with very similar conditions can interact differently with local assemblages. However, only one of these studies provided information on production, so if this differs significantly between the two farms this might explain the difference in epibenthic assemblages. Furthermore, this may be explained if the farm with the greater abundance of epibenthic fauna used different seeding and harvesting methods that caused a great accumulation of mussel debris on the seabed. This accumulation, especially in soft-bottom habitats, could result in an increase in epibenthic species richness and density, as the mussels provide suitable substrata for sessile epifauna that would not normally be able to survive in that environment (Buschbaum, 2000). This increase in habitat complexity is one of the ways in which mussels act as ecosystem engineers (Gutiérrez et al., 2003).

A number of studies have considered the effects of suspended long-line mussel farming on the benthic ecosystem (Kaspar et al., 1995; Chamberlain et al., 2001; da Costa and Nalesso, 2006; Lasiak et al., 2006; Nizzoli et al., 2006) with results ranging from significant impact (e.g. Nizzoli et al., 2006) to minimal effects (e.g. Lasiak et al., 2006). The most common negative impacts of mussel farms are a greater proportion of silty sediment (Kaspar et al., 1985; Chamberlain et al., 2001), and a higher organic content due to the build-up of biodeposits (Christensen et al., 2003; Hargrave et al., 2008). This in turn leads to reduced infaunal diversity (Chamberlain et al., 2001) and abundance (da Costa and Nalesso, 2006), or a shift in community structure from suspension feeders to deposit feeders (Stenton-Dozey et al., 1999).

Moving mussel farms into the open ocean may help mitigate some of the negative consequences associated with coastal farms. Open ocean farms are more exposed, occur at greater depths, and subject to stronger ocean currents, ocean swells and greater wave heights, which helps disperse waste products (Holmer, 2010). Furthermore, open ocean aquaculture also appears to have a high capacity for nutrient assimilation and less conflict for space (Holmer, 2010; Froehlich et al., 2017). Offshore aquaculture is increasingly accepted as a mechanism to meet the growing demand for seafood (Froehlich et al., 2017), with the official European Blue Growth Strategy report recognising the possibility of moving aquaculture developments further offshore to support sustainable growth in the aquaculture sector (European Commission, 2012). However, research on offshore mussel farms remains scarcer and there appears to be no universal framework for how effects are assessed. Existing research has shown there is little or no effect on sediment organic content (Danovaro et al., 2004; Lacoste et al., 2018), sedimentation rates (Lacoste et al., 2018) or infaunal abundance and community structure (Danovaro et al., 2004; Fabi et al., 2009; Lacoste et al., 2018). This highlights the necessity for more extensive research into suitable locations for sustainable marine aquaculture expansion (Gentry et al., 2017). The south coast of England (Dorset, Devon and Cornwall) is partially exposed with varying degrees of wave exposure (Masselink et al., 2016) and could have potential for offshore aquaculture expansion. However, lack of data is limiting its expansion.

The primary aim of this Chapter is to develop and pilot a time-series monitoring programme that can be used when testing for changes in the benthic ecosystem between areas within an open ocean mussel farm, and control locations. The farm is situated between 4 and 10 km offshore Lyme Bay, southwest UK and is located over areas of soft sediment that have been subject to fishing activity disturbance over a long period of time (Offshore Shellfish Ltd., 2010). It is located near to a 206 km^2 Marine Protected Area (MPA), which has been monitored since 2008. The control sites monitored to the west of the MPA are in close proximity to the Lyme Bay mussel farm (Sheehan et al., 2013), providing further evidence that the area on which the farm is being developed has historically been heavily fished by bottom towed fishing gear.

A further aim was to determine whether the Lyme Bay mussel farm has had an impact on the benthic ecosystem over time so far, including the benthic habitat and the associated epibenthic and infaunal communities. The epibenthic assemblage is defined here as any organism recorded on or near the seabed, and the infaunal community is that which is found within the seabed. The following response variables for the benthic habitat within the farm and in control areas were compared: % cover of mussels (live and dead), Organic matter, Mean particle size and Redox potential. To assess the effect of the farm on epibenthic and infaunal assemblages, Species richness (number of taxa), Abundance (number of individuals) and Assemblage composition were compared beneath mussel headlines and in control areas. Further to this, abundance of pre-selected key taxa were compared: European lobster *Homarus gammarus* (commercial species), brown crab *Cancer pagurus* (commercial species) schooling fish (inc. Atlantic horse mackerel *Trachurus trachurus* and whiting *Merlangius merlangus*: commercial species), common whelk *Buccinum undatum* (commercial species), common starfish *Asterias rubens* (predator), and polychaetes and amphipods (for analysis on environmental quality). Additionally, patterns between the infauna (biotic) and benthic habitat (environmental) data were investigated.

Grab samples and underwater cameras were used to assess change in the benthic ecosystem at the mussel farm relative to the surrounding environment. Grab samples are an effective way to obtain detailed quantitative data on sediment characteristics and the infauna community. Underwater cameras were used to provide data on the epibenthic fauna that would be missed by grab sampling.

The following hypotheses were tested:

1. Over time, the mussel farm changes the benthic habitat (% cover of mussel, organic content, mean particle size, redox potential) relative to controls.
2. Over time, the mussel farm changes the epibenthic and infaunal assemblages (species richness, abundance, assemblage composition) and abundance of key taxa relative to controls.
3. There is a relationship between % mussel cover and the abundance of key taxa: schooling fish, *B. undatum* and *A. rubens*. As % mussel cover increases, taxa abundance increases.
4. There is a relationship between changes to the benthic habitat and associated infauna.

4.2 Methods

4.2.1 Survey design

To assess change in the benthic ecosystem at the mussel farm relative to the surrounding environment, underwater video arrays were deployed, and grab samples were taken at both Trial Stations and at comparable controls. Each Trial Station was subdivided into two adjacent 'Rope' Plots. Corresponding Control Plots for each Site were located 500 m to the southwest and 500 m to the northeast of the Rope Plots (Figure 4.1). All Plots were sampled the summer before any infrastructure was deployed in 2013 (Year 0), and continued annually until 2017: four years after deployment.

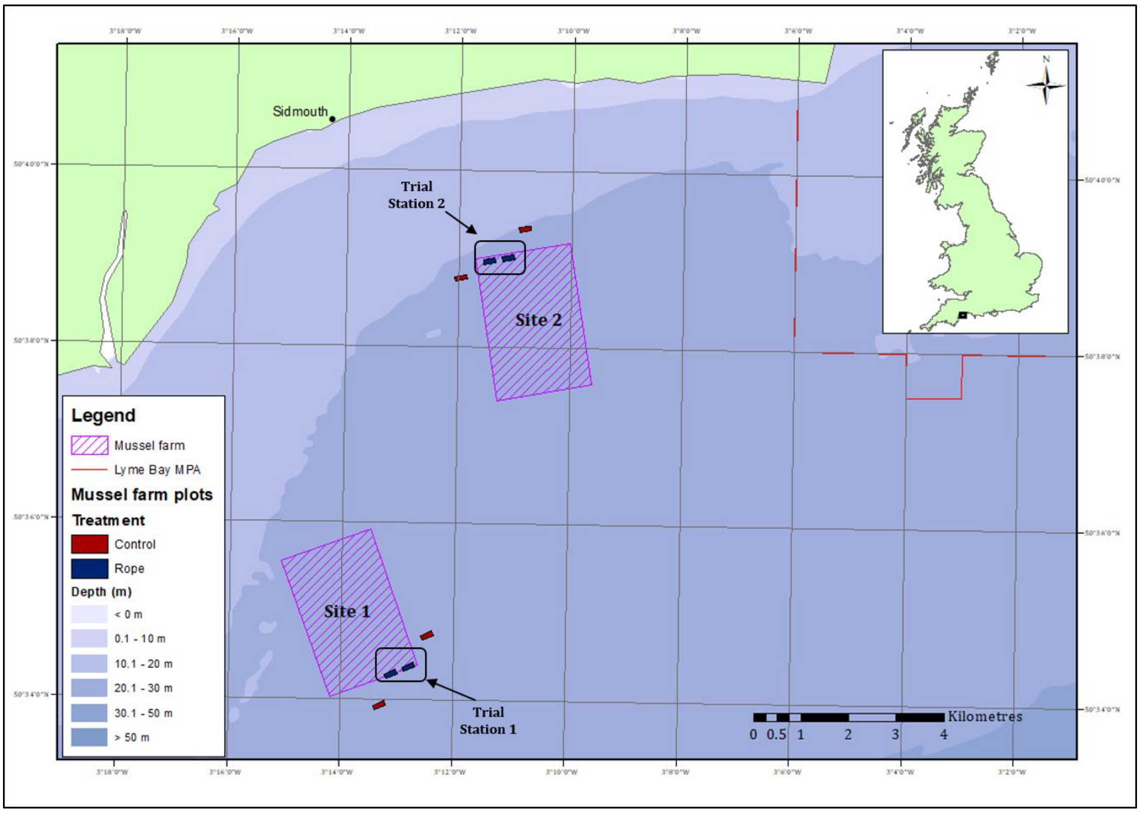

Figure 4.1: Locations of Rope Plots at Trial Stations 1 and 2, and corresponding Control Plots used to assess the benthic ecosystem at the Lyme Bay mussel farm. Lyme Bay MPA outlined in red.

To determine if the introduction of mussel ropes leads to a change in benthic communities over time, three remote video survey methods and grab samples were used to survey epibenthic and infaunal organisms over five years, from 2013-2017, monitored annually during the summer months. Within these sampling periods, sea surface temperatures ranged from 16.4 – 17.6 °C at ~ 2 m depth, using a handheld CTD sensor. Sessile and sedentary epifauna (those that are stationary or crawl slowly over the seabed) were recorded using a towed underwater video system (TUVS; Sheehan et al., 2013) and a remotely operated vehicle (ROV; Kim et al., 2021). To obtain a better representation of mobile species (those that tend to spend a large portion of the time moving), baited remote underwater video (BRUV; Rees et al.,

2021) was used to attract demersal fish in the area to the camera. Infauna were sampled using a Shipek grab (Desrosiers et al., 2019).

Within each of the Control Plots, three TUVS video transects of the seabed were collected. From Year 0, within each of the Rope Plots, three TUVS video transects were collected where the mussel farm headlines were to be deployed. In Year 1, after headlines had been deployed, an extra two video transects were collected directly underneath the headlines in each Plot using the ROV. Three sets of three replicate BRUV recordings were collected within each Plot in each Treatment (Figure 4.2). Four grabs were collected within each Plot at each Trial Station. However, a problem with the formalin production meant that the 2017 infauna samples perished. See Figure 4.2 for diagram explaining survey regime.

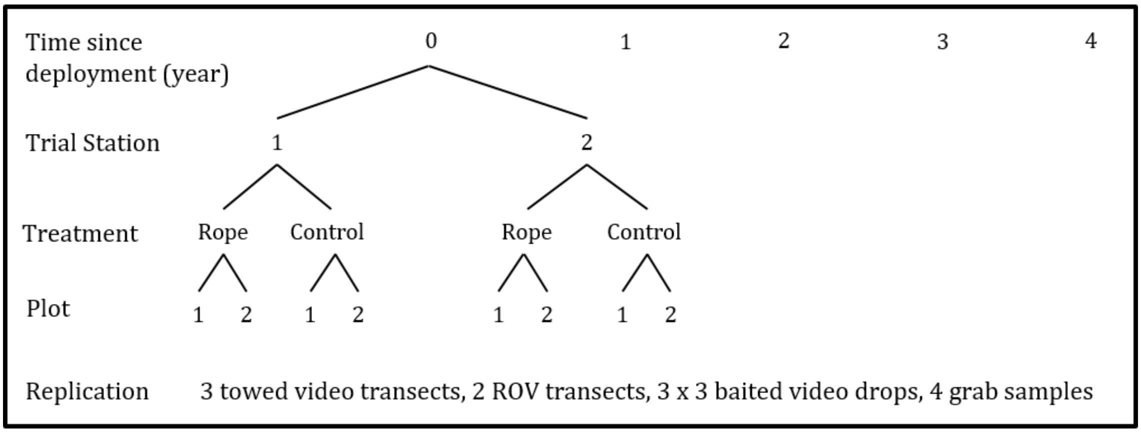

Figure 4.2: Survey regime for the collection of benthic data.

4.2.2 Sampling equipment

4.2.2.1 <u>Sessile and sedentary epifauna</u>

A floating towed underwater video system (TUVS), or "flying array", was used to collect video transect data from the benthos adjacent to the mussel farm headlines in the Rope Plots, and from all the Control Plots.

The TUVS (Figure 4.3a) is a relatively non-destructive, and cost and time-effective method for filming the seabed. The neutrally buoyant aluminium sled floats above the seabed, with height controlled by a length of chain (3.15 m length, 12 mm width, 10 kg). A drop weight (20 kg) was attached to a tow rope to stabilise the system. The video system held within the frame comprised a HD video camera (Surveyor-HD-J12 colour zoom titanium camera, 6000 m depth rated, 720p) positioned at an acute angle to the seabed, three LED lights (Bowtech Products limited, LED-1600-13, 1600 Lumen underwater LED) and a CTD (mini CTD profiler: Valeport Ltd). The system was controlled by a surface control unit. Two green 532 nm lasers (Beam of light technologies, Inc: Scuba-1 Underwater dive laser) were mounted either side of the camera, pointing forward at 30 cm apart to allow field of view calibration during video analysis. See Sheehan et al. (2010) and Sheehan et al. (2016) for detailed information on how the TUVS is configured and operated.

A remotely operated vehicle (ROV) was used to collect benthic video transects from underneath the ropes where the TUVS cannot reach. The ROV used was a VideoRay Pro 4 (37.5 cm length, 29 cm width, 22 cm height, 6.1 kg weight; Figure 4.3b). It comprised two LED lights (3600 lumens) and three thrusters (two horizontal, one vertical) which allow it to travel up to 4.2 knots. It is controlled on the surface by a USB hand controller linked to a 15-inch display. The camera has a 180° vertical field of view. However, the video quality was not suitable for video analysis so an external high definition GoPro (Hero4 Silver) camera was attached to the base of the ROV. The GoPro camera was set up as the following: 1080p video resolution, 60 frames per second, ultra wide field of view (screen resolution 1920x1080, 16:9). Two green 532 nm lasers (Beam of light technologies, Inc: Scuba-1 Underwater dive laser) were mounted either side of the GoPro, pointing forward at 18 cm apart to allow field of view calibration during video analysis.

At each Plot, the TUVS was used to collect three ~ 200 m transects and towed consistently at ~ 0.5 knots. An additional two ~ 100 m transects were recorded under each headline using the ROV. All transects were independent of each other.

4.2.2.2 Mobile epifauna

Baited remote underwater video (BRUV) units were used to record mobile epifauna. The BRUVs were constructed from aluminium composite (Greenaway Marine Ltd.), weighted with 2 x 15 kg blocks, with a Seapro Subsea Video Camera Module wing mounted in the centre of each frame (Figure 4.3c). Each module was equipped with a HD video camera (Panasonic HDC-SD60) and a Seapro Wideangle 50 watt diffused LED light, which were operated externally by a control lever. The cameras auto focused through a Wideangle Seapro Optolite Port lens, which provided a wider field of view from its concave inner surface and flat front. For each BRUV, a bait box (wire mesh; 130 mm length, 130 mm width, 2 mm height) was secured 1 m in front of the camera-housing lens on an aluminium pole. Prior to each deployment, the bait box was replenished with 100 g of fresh Atlantic mackerel *Scomber scombrus* cut into pieces ~ 1 inch thick. A surface marker buoy was attached to each BRUV.

At each Plot, three sets of three BRUVs were deployed ~ 30 m apart for 40 minutes. This allowed for 30 minutes of filming, with a five-minute 'settling' period when the unit had reached the seabed, and five minutes of contingency time. 30 minutes of video captures on average 75% or more of the species richness and abundance that would have been seen in 60 minutes of footage (Bicknell et al., 2019), and so was chosen in interest of time and cost-effectiveness, and to limit the spread of the bait plume.

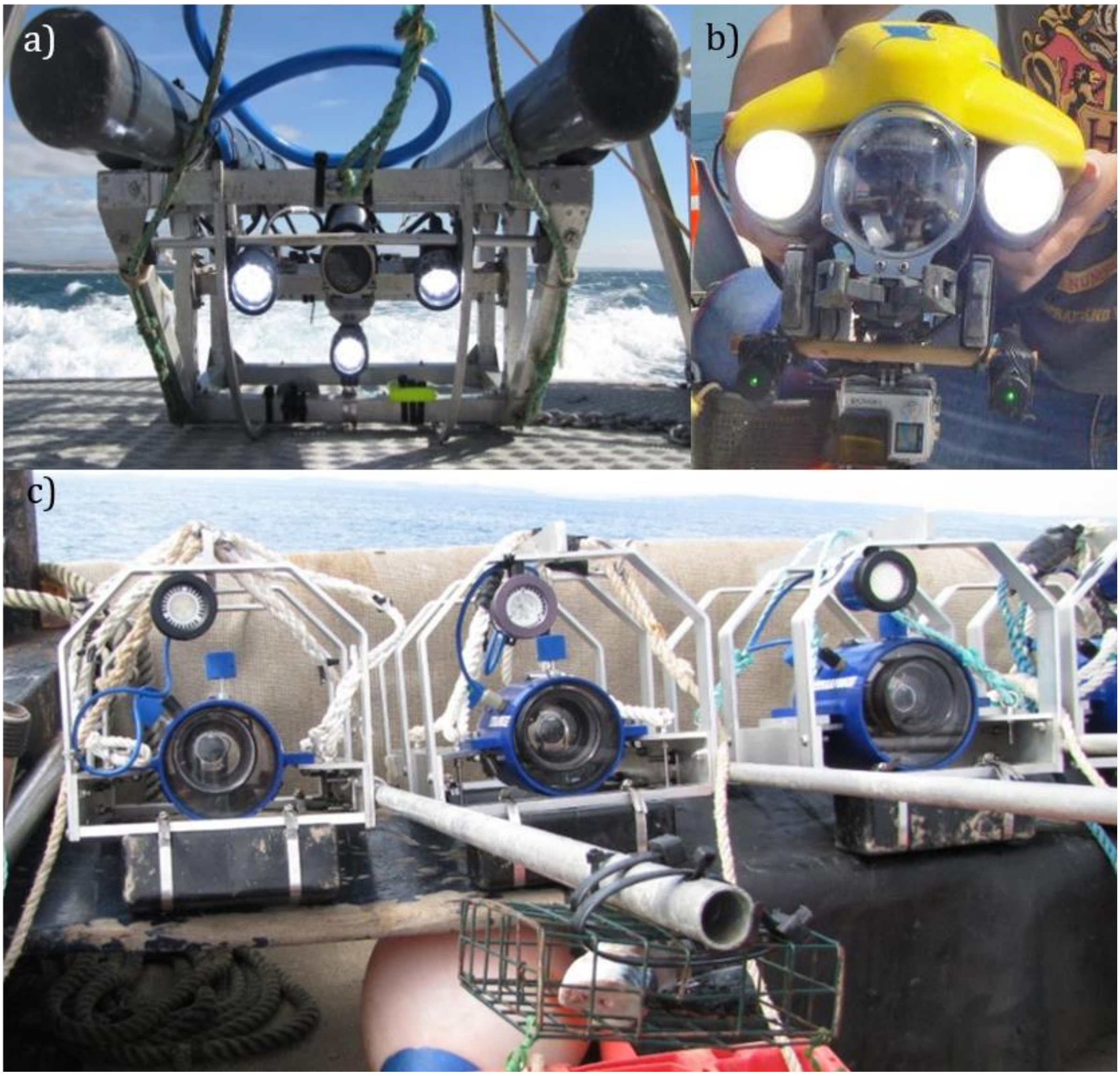

Figure 4.3: Images of video equipment used for data collection a) the TUVS showing HD video camera, three LED lights and two lasers, b) the ROV with mounted GoPro camera, two LED lights and two lasers, and c) BRUV units showing the camera module, LED light and 1 m aluminium pole with bait box attached.

4.2.2.3 <u>Sediment and infauna</u>

As the recent history of the sediment is being studied, a grab sampler is more appropriate than a corer. A smaller grab sampler was chosen to minimise the impact on the seabed, which is emphasised in the best practices of the research group. The smaller grabs that were available for use were a Shipek grab, which samples 0.04 m^2 of the seabed, or a Van Veen grab, which samples 0.025 m^2. The Shipek grab was chosen as it samples a slightly greater area and, as the exact characteristics of the seabed were unknown before the study, more appropriate for sampling seabed that may contain larger stones (Kirby et al., 2018). The Shipek grab has been frequently used to survey sediment characteristics and macroinvertebrate communities (Rempel et al., 2000; Smith et al., 2001; Shakouri and Auõunsson, 2006; Desrosiers et al., 2019).

The Shipek grab is a weighted bottom sampler, which was deployed by a winch from the back of the boat. Prior to deployment, the grab is set using a cocking wrench to wind the torsion springs and pull the half cylinder scoop in (Figure 4.4a). When the grab reaches the seabed, inertia releases a catch and the springs turn the scoop rapidly by 180° to cut a clean sample out of the seabed (Figure 4.4b).

Figure 4.4: a) Shipek grab being prepared for deployment, and b) undisturbed unwashed seabed sample.

4.2.3 Video data extraction

Analysis of the video transects from the TUVS and the ROV was conducted in two stages, based on previous work by Sheehan et al. (2010). Large, infrequent epibenthic fauna were counted by watching the video at normal speed and recording each organism that passed through the 'gate' formed by the two laser dots.

The laser dots were 30 cm apart so, for each 200 m tow, approximately 60 m^2 was covered. The raw count data was then converted into density (individuals m^{-2}).

Smaller, more frequent organisms were counted from still images obtained from frame grabs. Frame grabs were extracted at five-second intervals and overlaid with a digital quadrat (3Dive Cybertronix frame extractor software). Frame grabs were discarded if they were not in focus, obscured, overlapped the previous frame (to avoid replicate counts), or if the laser dots were not within the acceptable margins of the digital quadrat (Figure 4.5a). Of the selected suitable frames, 30 were randomly selected for analysis, following work by Stevens et al. (2014) which showed that sampling 30 frames from a 200 m transect gave equivalent results to sampling all frames. A minimum of 15 frames were selected from the shorter 100 m ROV transects. Randomly selecting 30 and 15 frames from the TUVS and ROV footage, respectively, means around 30 % of the useable frames are analysed for each method. Organism counts were converted to individuals m^{-2}.

Occurrence of mussel shells and clumps were recorded from the frame grabs using methods as described in Sheehan et al. (2015). The frame overlay splits the image into 25 squares (in a 5 x 5 formation) (Figure 4.5a). To quantify the amount of mussel matter on the seabed in each frame, % occurrence was calculated. This was determined by scoring the number of the 25 squares within the frame overlay that contain live or dead mussel shells or clumps (Figure 4.5b). As long as there was some mussel matter within the square then it was included in the calculation. The score was then converted into % occurrence (4 % per square). For example, if 10 of the 25 squares contained live or dead mussel shells or clumps, and each square equates to 4 %, then the frame would be given a % occurrence of 40 %. The term % cover will be used when referring to this method.

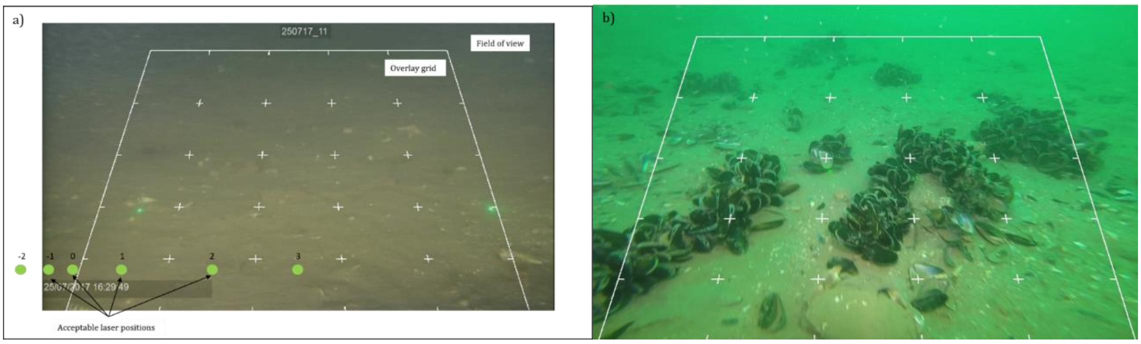

Figure 4.5: a) Example of a frame grab showing overlay grid and acceptable laser positions, and b) Frame grab showing mussel shells and clumps contributing to % cover of mussels.

Quantitative data were extracted from BRUV samples by viewing the video at normal speed counting the number of each mobile species in the field of view at 1-min intervals. This established the maximum number of each species present within one minute during each 30-min video (maxN min^{-1}) (Willis et al., 2000). MaxN is used in the vast majority of studies (Ellis and DeMartini, 1995; Cappo et al., 2003; Willis and Babcock, 2000; Bicknell et al., 2019). In this case, it represents the maximum number of a particular species seen within one minute of video footage. It considered to be a useful and conservative method to assess the relative abundance of species as there may be individuals around the BRUV that are not counted as they do not enter the field of view (Whitmarsh et al., 2016).

Taxa were split into two classifications: sessile and sedentary, and mobile. Sessile and sedentary taxa (recorded from TUVS and ROV) were those that live attached to substrate or partly buried within sediment, or able to move but do not typically travel very far within a day as adults e.g. crawlers. The mobile taxa (recorded from BRUV) were those that tend to spend a large portion of the time moving e.g. swimmers. All benthic organisms were identified to the lowest taxonomic level possible. Taxonomically similar species, which could not be confidently distinguished, were grouped. For example, Hydroids (excepting *Nemertesia* *antennina* and *Nemertesia ramosa*) and Gobies were broadly grouped, and *Inachus* spp., *Macropodia* spp. and *Liocarcinus* spp. were identified to genus level.

4.2.4 Grab data extraction

Redox potential readings were taken from the intact grab sample immediately after the sample was taken to detect levels of dissolved oxygen (Wildish et al., 1999). A redox probe and Ag/AgCl reference electrode connected to a SevenGo pro meter was used to record a millivolt (mV) reading at 1 cm intervals through the sample. Redox potential measurements of < 0 mV are classified as polluted in relation to organic enrichment (Wildish et al., 2001). 100 ml of each sample was then taken for sediment analyses and frozen. This was selected from the middle the sample, from the top through to the bottom. The rest of the sample was placed in a bag and fixed with 10 % borax-buffered formalin for infauna identification.

Sediment samples were thawed prior to processing and subsamples was taken for organic matter and particle size analysis (PSA). 1 teaspoon of the sample was used for organic matter analysis. Subsamples were placed in pre-weighed crucibles and oven-dried at 60 °C for 24 h. The dry weight was recorded and samples were then combusted in a muffle furnace set at 450 °C for 4 h to determine the ash-free dry weight, and therefore calculate percentage organic matter through loss on ignition.

The rest of the 100 ml sample was used for PSA. Laser diffraction and dry sieving were used to measure particle size distribution (PSD). Particles < 1 mm were measured using low angle laser diffraction with a Malvern Mastersizer 2000 laser particle sizer (software version 5.6). To prepare the samples, half a teaspoon was filtered through a small 1 mm sieve and funnelled into a sample tube using distilled water and the tube was filled with water to the top. This was repeated 5 times for each sample. Between samples, the equipment was rinsed to ensure no cross contamination of sediment. The tubes were put into metal racks, and placed into the sample area of the laser Malvern laser particle sizer. Two sets of lenses were employed: a 1000 mm lens for particles in the size range 4-2000 μm, and a 45 mm lens for particles in the size range 0.1-80 μm. The average of five runs measured from the 1000 mm lens data was blended with one reading from the 45 mm lens. To obtain the dry weight of larger fractions, > 1 mm and < 1 mm sediment was split into two beakers and oven-dried at 60 °C until fully dried. The dry weight of sediment < 1 mm was recorded. Sediment fractions > 1 mm were dried and sieved through Wentworth sieves in half phi (ϕ) intervals to obtain the dry weight of each grain size parameter. Laser diffraction data and sieve data were merged together to produce a full PSD at half ϕ intervals. This procedure is in line with NMBAQC's Best Practice Guidance for PSA (Mason, 2016).

Prior to infauna identification, samples were sieved through a 0.5 mm Endecott sieve under a fume hood with a sediment trap. For ease and accuracy of picking out all the infaunal organisms, the samples were then sieved through 2 mm and 1 mm Endecott sieves and infauna were picked from these size intervals. Organisms were systematically picked out of white trays then placed into labelled glass vials filled with 70 % Industrial Denatured Alcohol (IDA). All biological material that would have been alive at the time of sample collection were picked from the sample. Organisms were identified to at least family level, where possible, using taxonomic keys (Hayward and Ryland, 1995; Hayward and Ryland, 2017) with a Leica EZ4 microscope. Family level was used for as this taxonomic resolution provides enough information on overall changes in the whole community, which reduces analysis time (Sanchez-Jerez et al., 2018). Identification of infauna to family level is considered adequate for assessing ecological impacts (Gray et al., 1990; Chapman, 1998; Oliveira et al., 2020). Colonial organisms (hydroids and bryozoans) were given a value of '1' if they were present. Empty shells, empty worm tubes and cast skins from crustaceans were not counted. This procedure is in line with NMBAQC's Processing Requirements Protocol for marine invertebrate samples (Worsfold and Hall, 2010).

4.2.5 Data analyses

Permutational Multivariate Analysis of Variance (PERMANOVA+, (Anderson, 2001; Clarke et al., 2014) in the PRIMER v7 software package) was used to conduct multivariate and univariate analyses. Full justification has been provided in Chapter 3, page 72. Prior to analysis, shade plots were used to inform the appropriate species data transformation, if required. A draftsman plot was used to decide the appropriate data transformation of benthic habitat data, which shows skewness in the distribution over samples and highlights outliers (Clarke and Gorley, 2015). A constant value of 150 was added to Redox potential measurements to make all values positive and able to be transformed (McDonald, 2014).

Each analysis comprised three factors: Time since deployment (year) (fixed: 0, 1, 2, 3, 4), Trial Station (random: Trial Station 1, Trial Station 2) and Treatment (fixed, nested within Trial Station: Rope, Control). A fourth factor was used for Redox potential analysis: Depth (fixed: 1 cm, 2 cm, 3 cm, 4 cm, 5 cm, 6 cm). Unfortunately, the infauna samples in the fourth year were not adequately preserved and were therefore excluded from the analysis. As there were no specific hypotheses regarding differences between headlines within or between Plots, Plots were pooled within Treatment. Statistically significant interactions ($P < 0.05$) between Year and Treatment (nested within Trial Station) were further interpreted using pairwise tests. Each term in the analysis was tested using 9999 random permutations under the same permutation method (permutation of residuals under a reduced model) (Anderson et al., 2008).

Univariate data (% cover of mussels, Organic matter, Mean particle size, Redox potential, Species richness, Total abundance, Abundance of key benthic taxa) were square root transformed and resemblance matrices were constructed using Euclidean distance indices (Anderson, 2001; Anderson, 2017), with a dummy variable of +1 added to % cover of mussels and Abundance of *B. undatum*. This gives similarity to two samples with a value of zero (Clarke et al., 2006). To test for a relationship between the abundance of *M. edulis* and the abundance of schooling fish, *B. undatum* and *A. rubens*, regression analysis was carried out in Minitab 18.

Multivariate data (Assemblage composition) were square root transformed to increase the relative contribution of rare species (Clarke and Green, 1988) and down-weigh the importance of highly abundant species (Watson et al., 2005). Resemblance matrices were constructed using Bray-Curtis similarity indices. Multivariate patterns were visualised using non-metric multidimensional scaling (nMDS) ordination plots. As there were too many points to view in one ordination, the centroids of each Year x Trial Station x Treatment were visualised (Terlizzi et al., 2005). SIMPER (similarity percentages) was used to examine the taxa driving the nMDS (Clarke and Warwick, 2001).

BPOFA (Benthic Polychaete Opportunistic Families Amphipods) was used to detect changes in environmental quality of the benthos (Dauvin et al., 2016):

$$\text{BPOFA} = \log10 \left[\frac{f_{pof}}{f_a + 1} + 1 \right]$$

where f_{pof} is the frequency of opportunistic polychaetes families divided by the overall abundance in the sample, and f_a is the frequency of amphipods divided by the overall abundance in the sample. Thresholds for BPOFA were used to present the Ecological Quality Status (EcoQs) of each Treatment at each Trial Station over Time since deployment. These thresholds are shown below in Table 4.1. Using an abundance ratio between Polychaeta and Amphipoda is effective in identifying major changes in the benthic environment as most polychaetes are classified as tolerant or opportunistic to pollution, while amphipods are considered as sensitive. BPOFA represents a simple effective benthic indicator for assessing the ecological status of marine environments (Dauvin et al., 2016).

Table 4.1: Thresholds for establishing Ecological Quality Status by BO2A score. Table adapted from Dauvin et al. (2016).

Ecological Quality Status	BPOFA score
High-Good	0.031
Good-Moderate	0.126
Moderate-Bad	0.187
Poor-Bad	0.237

The BEST (Bio-Env) procedure was used to examine patterns between the biotic (infauna) and environmental (benthic habitat) data (Clarke and Gorley, 2015). Analysis was carried out on square root transformed data.

4.3 Results

4.3.1 Benthic habitat

There was a significant interaction between Time since deployment and Treatment on the % cover of mussels (Ti x Tr(TS): P = 0.0001; Supplementary material, Section

B: Table 1a). In every Year, there was 0 % mussel cover in the Control treatment at each Trial Station (Figure 4.6).

At Trial Station 1, there was a sharp increase in the % cover of mussels from Year 1 (1.00 ± 0.75 %) to Year 2 (18.80 ± 6.36 %) and is consistent from 2 to 4 years after headline deployment (Figure 4.6). This is reflected in the pairwise results; % cover of mussels in Years 0 and 1 is significantly lower than every other year, but from Year 2 there is no significant difference over time (Supplementary material, Section B: Table 1c). At Trial Station 2, there was a gradual increase from Year 0 (0 %) to Year 1 (12.51 ± 6.82 %) to Year 2 (23.14 ± 6.11 %) and then stayed consistent. Once the headlines has been deployed, there was no significant difference in % cover of mussels between Years (Supplementary material, Section B: Table 1c). After 4 years of headline deployment, % cover of mussel was ~ 25 % at each Trial Station (Trial Station 1 = 25.42 ± 7.95 %, Trial Station 2 = 24.52 ± 9.95 %; Figure 4.6).

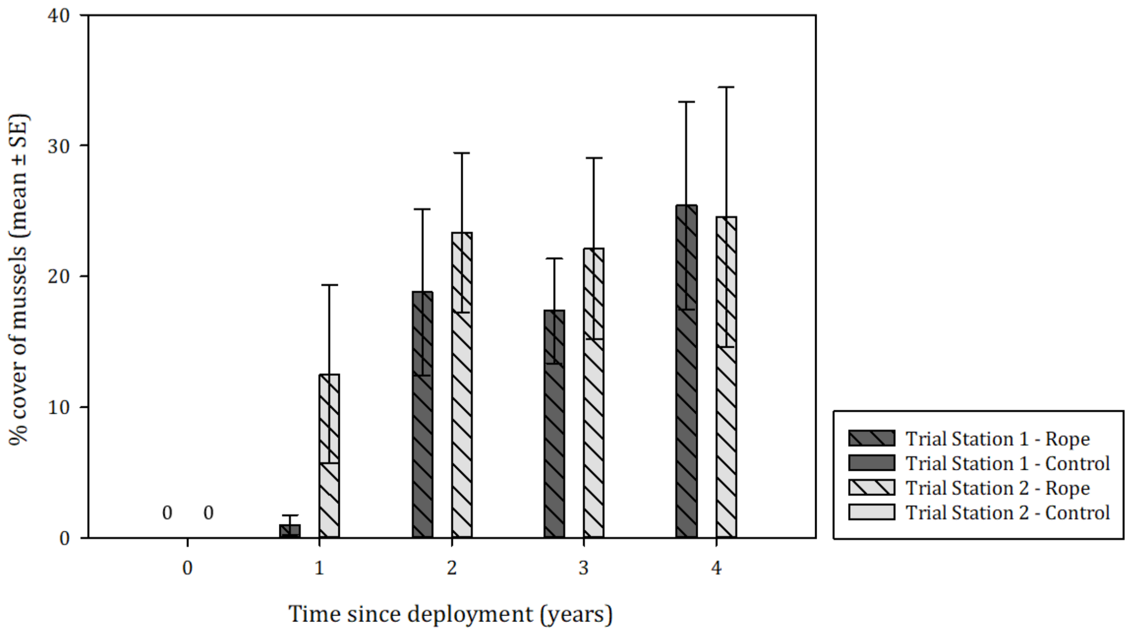

Figure 4.6: % cover of mussels (mean ± SE) within Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 0-4). Mussels were not observed in the Control treatment at either Trial Station. '0' shows where none were recorded.

There was no significant interaction between Time since deployment and Treatment on percentage organic matter (% OM) ($P > 0.05$; Supplementary material, Section B: Table 2). % OM at Trial Station 1 became more similar between Treatments over time and there was a marginal increase in % OM in the Rope treatment once the ropes had been deployed, and peaked in Year 2 (Year 0 = 1.52 ± 0.07 %, Year 2 = 2.02 ± 0.10 %; Figure 4.7a). At Trial Station 2, % OM slightly increased in the Rope treatment after headlines had been deployed and also peaked in Year 2 (Year 0 = 2.61 ± 0.17 %, Year 2 = 3.21 ± 0.45 %; Figure 4.7a).

There was no significant interaction between Time since deployment and Treatment on mean particle size (MPS) ($P > 0.05$; Supplementary material, Section B: Table 3). MPS was very similar between Treatments at both Trial Stations in Year 0. In Year 1, when the first mussel lines were deployed, MPS in the Rope treatment peaked (382.68 ± 59.98 μm; Figure 4.7b). MPS in the Rope treatment then decreased in Year 2 and again in Year 4, coming back down to below baseline levels (Year 0 = 217.13 ± 46.99 μm, Year 4 = 185.58 ± 33.83 μm; Figure 4.7b). At Trial Station 2, MPS remained similar between Treatments and stable across all years (Figure 4.7b).

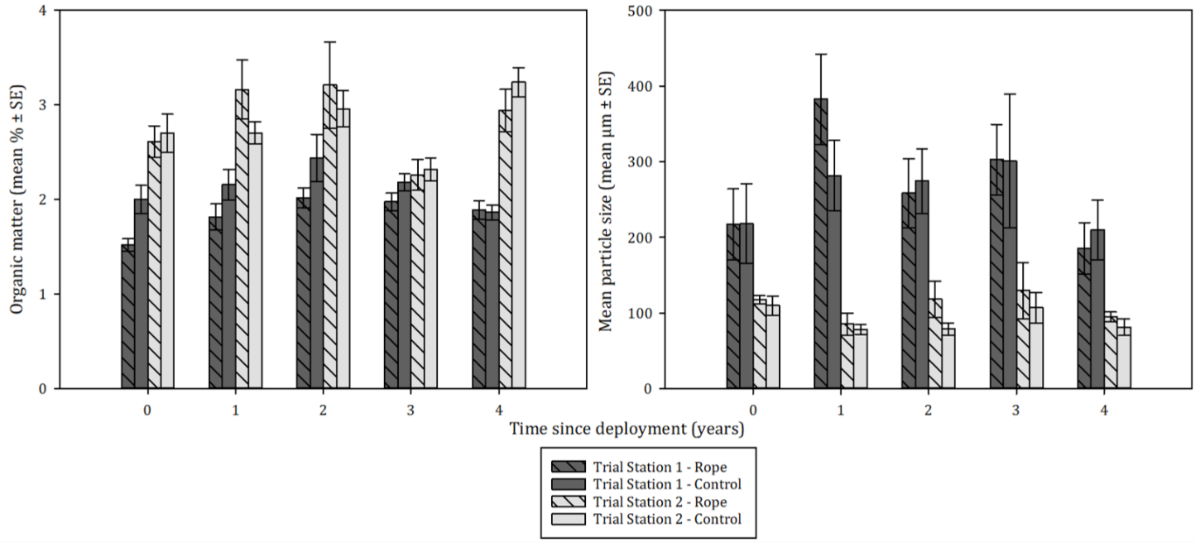

Figure 4.7: Sediment characteristics a) Organic matter (mean % ± SE), and b) Mean particle size (mean µm ± SE) of sediments within Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 0-4).

At Trial Station 1, sediments were classified as either medium sand or fine sand, with 16-29 % gravel, 49-64 % sand and 17-29 % mud. At Trial Station 2, sediments were classified as either very fine sand or fine sand, with 5-10 % gravel, 44-62 % sand and 31-48 % mud (Figure 4.8).

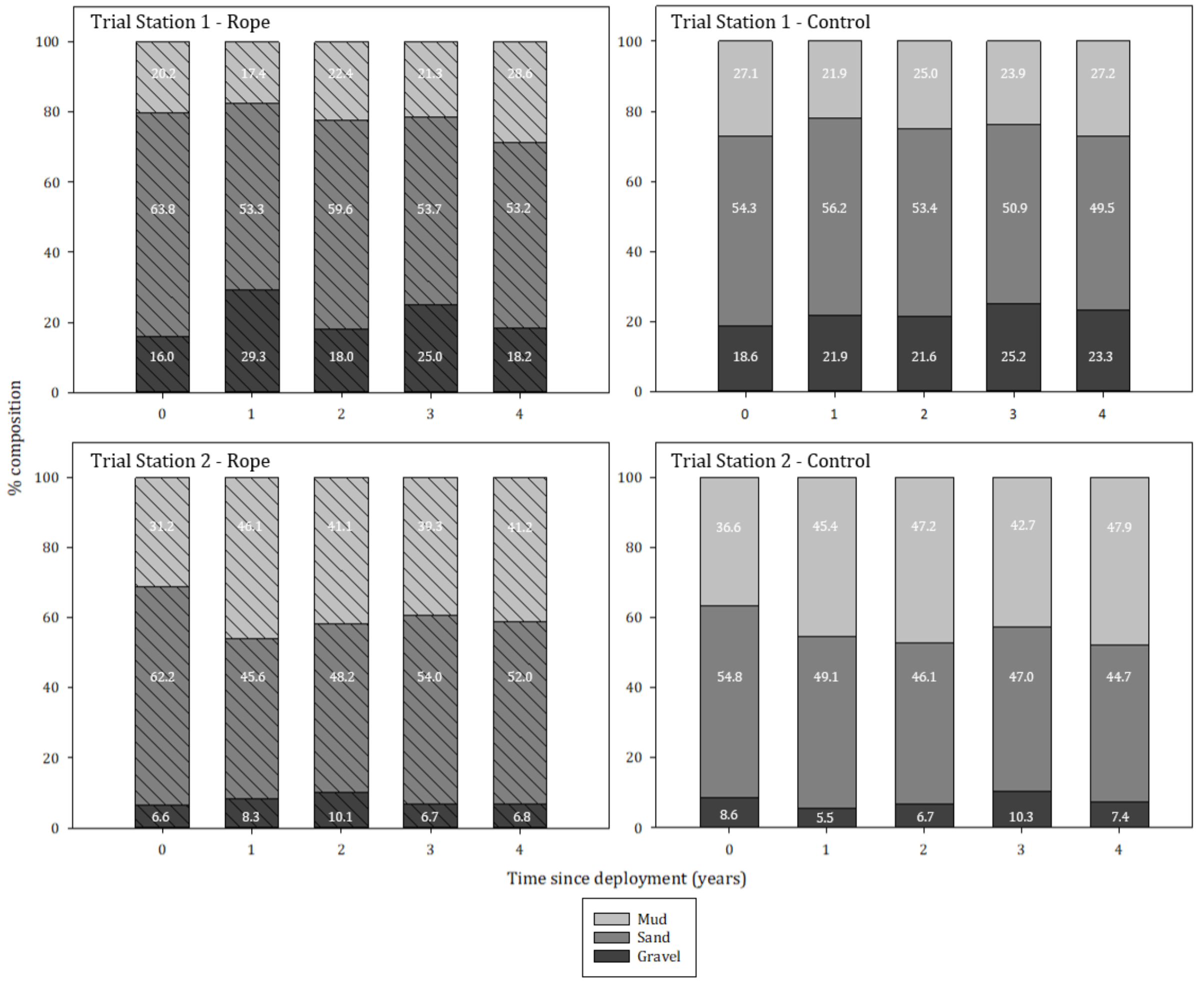

Figure 4.8: Proportion of mud, sand and gravel in sediments within Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 0-4).

There was a significant interaction between Time since deployment and Treatment on redox potential (Ti x Tr(TS): P = 0.0001; Supplementary material, Section B: Table 4a). At Trial Station 1, the Rope and Control treatments were significantly different to each other from Year 0 to Year 2 (all $P < 0.05$; Supplementary material, Section B: Table 4b). Within the Rope treatment, redox potential was significantly greater in Year 0 than all other years, but the same was also true in the Control treatment (all $P < 0.05$; Supplementary material, Section B: Table 4c). However, redox potential was significantly lower than all other years in the Rope treatment but not the Control (Supplementary material, Section B: Table 4c) showing a significant effect of the mussel farm in this year. At Trial Station 2, redox potential was only significantly different between the Rope and Control treatments in Years 2 and 3 (both $P < 0.05$ Supplementary material, Section B: Table 4b). In both Treatments, the only years that redox potential was not significantly different between were Years 2 and 3 (Supplementary material, Section B: Table 4c). Patterns were the same in both Treatments, and Years 2 and 3 recorded the lowest redox potential (Figure 4.9).

There was no statistically significant impact of Depth in sediment ($P > 0.05$; Supplementary material, Section B: Table 4a). Mean redox potential only fell below 0 mV once at Trial Station 1: at 6 cm in the Rope treatment in Year 1 (Figure 4.9). At Trial Station 2, mean redox potential fell below 0 mV more frequently, in both Treatments (Figure 4.9).

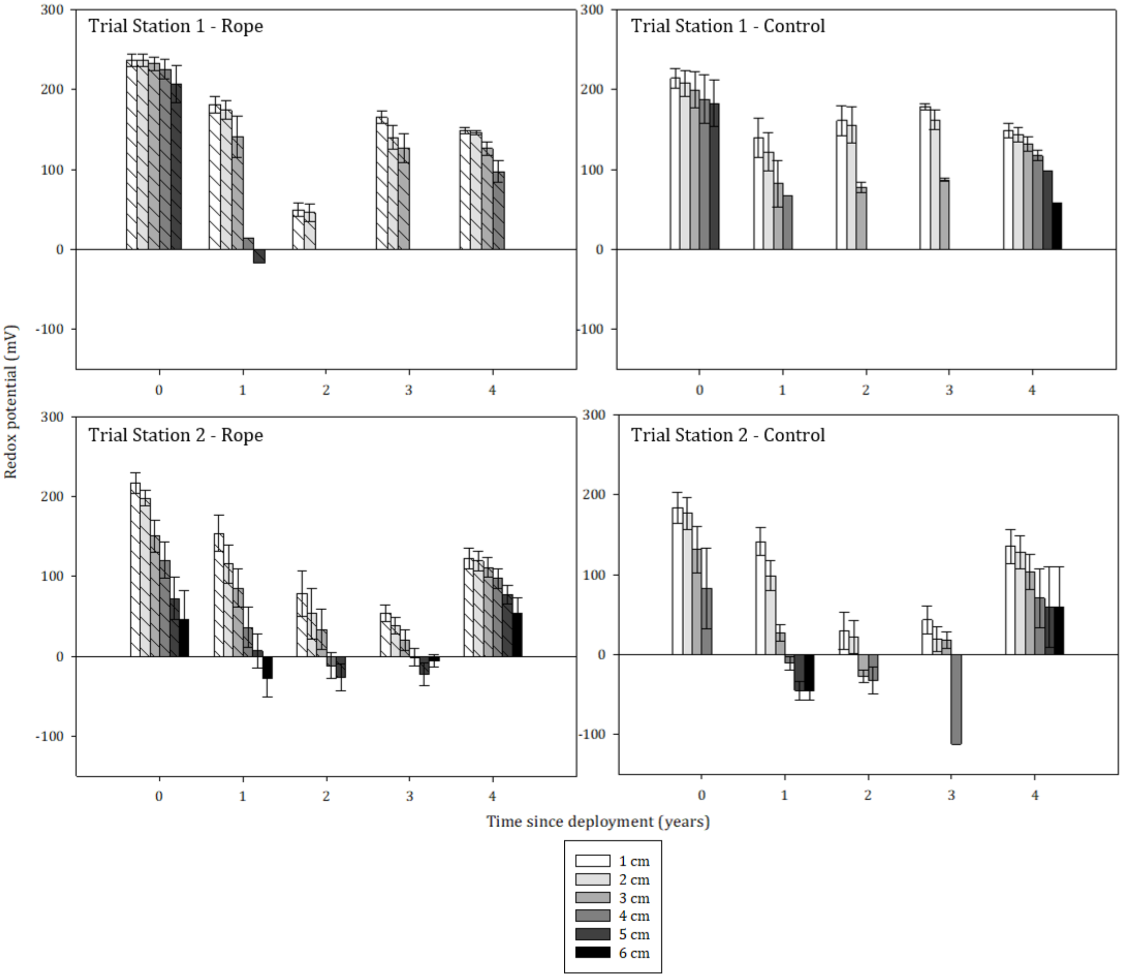

Figure 4.9: Redox potential (mean mV ± SE) with Depth (0-6 cm) within Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 0-4).

4.3.2 Benthic fauna

Sixty-nine taxa were recorded from eight phyla from the three video methods. These were split into two categories: sessile and sedentary (58 taxa) and mobile (12 taxa). A full list of these taxa can be found in Supplementary material, Section B, Table 5. Eighty-five infauna taxa were identified from grab samples. These belonged to the following groups: Annelida (81 %), Crustacea (8 %), Sipuncula (5 %), Mollusca (2 %), and the remaining 4 % of taxa were from Nemertea, Chordata, Echinodermata, Cnidaria, Bryozoa, Entoprocta and Platyhelminthes. A full list of infauna taxa can be found in Supplementary material, Section B: Table 6.

4.3.2.1 Sessile and sedentary epifauna

There was a statistically significant effect of the mussel farm on species richness of sessile and sedentary epifauna (Ti x Tr(TS): $P = 0.0001$; Supplementary material, Section B: Table 7a). At Trial Station 1, species richness was significantly greater in the Rope treatment in Years 1 and 2 after headline deployment (both $P < 0.05$; Supplementary material, Section B: Table 7b). At Trial Station 2, species richness was significantly greater in the Rope treatment in Year 3, but the opposite was true in Year 4 (Supplementary material, Section B: Table 7b). Overall, species richness is variable over time and there is no consistent pattern at either Trial Station (Figure 4.10a).

There was also a statistically significant effect of the mussel farm on total abundance of sessile and sedentary epifauna (Ti x Tr(TS): $P = 0.04$; Supplementary material, Section B: Table 8a). At Trial Station 1, there was a significantly greater abundance in the Rope than the Control treatment in Years 1, 2 and 4 (all $P < 0.01$; Supplementary material, Section B: Table 8b). By Year 4, abundance was marginally greater in Rope than the Control treatment (Rope = 39.34 ± 3.23 m^{-2}, Control = 35.06 ± 2.91 m^{-2}; Figure 4.6b). At Trial Station 2, there was no significant difference between Treatments in any Year (all $P > 0.05$; Supplementary material, Section B: Table 8b). In Years 0, 1 and 4 abundance was greater in the Control treatment than the Rope treatment (Year 4: Rope = 5.49 ± 0.93 m^{-2}, Control = 11.97 ± 1.95 m^{-2}; Figure 4.6b), although not statistically significant.

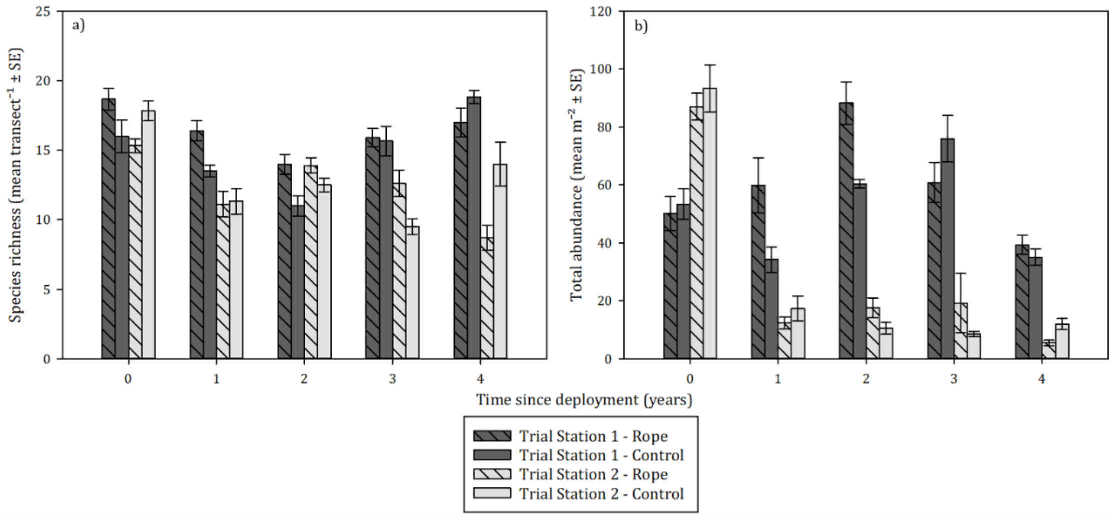

Figure 4.10: Sessile and sedentary epifauna a) Species richness (mean transect^{-1} ± SE), and b) Total abundance (mean m^{-2} ± SE) within Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 0-4).

There was a significant Ti x Tr(TS) interaction term for the assemblage composition of sessile and sedentary epifauna ($P = 0.0001$; Supplementary material, Section B: Table 9a). There is a clear distinction on the nMDS plot between Trial Stations (Figure 4.11). Assemblage composition at Trial Station 1 was consistently significantly different between the two Treatments from Year 0 to Year 4 (all $P < 0.05$; Supplementary material, Section B: Table 9b). SIMPER analysis showed the average dissimilarity between Treatments increased with Time since deployment, with the greatest dissimilarity between Treatments in Year 2 (Table 4.1). This can also be seen in the nMDS plot where the distance between the two Treatments on the plot is greater in Year 2 than any other year (Figure 4.11). SIMPER analysis shows that, of the five main species contributing to this difference between Treatments in Year 2, four were more abundant in the Rope treatment (Table 4.2).

At Trial Station 2, assemblage composition was significantly different between Treatments in Years 1, 3 and 4 after headline deployment (all $P < 0.05$;

Supplementary material, Section B: Table 9b). The average dissimilarity between Treatments increased with Time since deployment, and the greatest dissimilarity between Treatments was in Year 4 (Year 4 = 47.37 %; Table 4.2). The nMDS also shows an increase in distance between Treatments from Year 0 to Year 4 (Figure 4.11). Grouped hydroids substantially contributed to the dissimilarity, with a greater average abundance in the Control treatment in all Years, except Year 2. Hermit crabs *Pagurus* spp. were initially more abundant in the Control treatment before headline deployment, but were more abundant in the Rope treatment in every other year (Table 4.2).

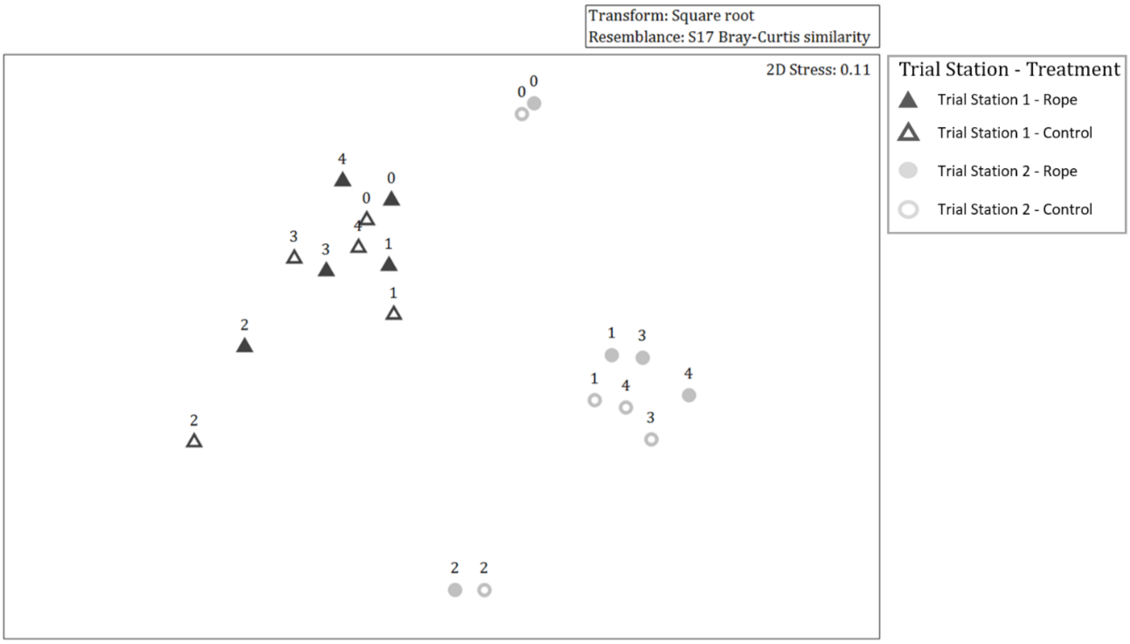

Figure 4.11: nMDS ordination plot illustrating differences in assemblage composition of sessile and sedentary epifauna within Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 0-4).

Table 4.2: SIMPER analysis in groups outlined by PERMANOVA showing the top five organisms which most contributed to the observed differences in sessile and sedentary assemblage composition between Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 0-4).

Taxon	Av. Abun.	Av. Abun.	Av. Diss.	Diss./SD	Contrib. %	Cum. %
Trial Station 1						
Year 0 Av. Diss.: 26.81	**Rope**	**Control**				
Cerianthus spp.	2.92	4.10	3.27	1.51	12.21	12.21
Grouped hydroids	3.22	2.45	3.03	1.58	11.31	23.53
Alcyonidium diaphanum	1.88	0.90	2.88	1.35	10.74	34.27
Turritella communis	3.47	3.97	2.14	1.15	7.98	42.24
Cellepora pumicosa	1.34	0.68	1.92	1.40	7.16	49.41
Year 1 Av. Diss.: 35.30	**Rope**	**Control**				
Cerianthus spp.	3.3	0.92	7.30	1.13	20.68	20.68
Grouped hydroids	3.32	2.81	3.67	1.31	10.41	31.08
Turritella communis	3.75	3.75	3.59	1.32	10.18	41.27
Cellepora pumicosa	0.82	1.04	2.73	1.33	7.73	49.00
Alcyonidium diaphanum	1.05	0.32	2.25	1.64	6.38	55.37
Year 2 Av. Diss.: 37.55	**Rope**	**Control**				
Alcyonidium diaphanum	4.04	1.71	5.53	2.21	14.74	14.74
Macropodia spp.	2.41	4.69	5.23	1.50	13.93	28.67
Pagurus spp.	2.17	0.00	4.52	0.77	12.03	40.70
Cerianthus spp.	1.64	1.24	3.7	1.50	9.86	50.56
Grouped hydroids	3.92	2.44	3.63	1.49	9.67	60.23
Year 3 Av. Diss.: 35.79	**Rope**	**Control**				
Turritella communis	4.04	6.01	4.61	1.69	12.88	12.88
Cerianthus spp.	1.97	1.89	4.44	1.38	12.4	25.28
Cellaria fistulosa	0.22	1.76	3.81	1.56	10.64	35.92
Grouped hydroids	2.86	3.17	3.63	1.70	10.15	46.07
Alcyonidium diaphanum	2.77	2.28	3.29	1.44	9.21	55.28
Year 4 Av. Diss.: 36.71	**Rope**	**Control**				
Turritella communis	2.73	3.77	5.09	1.24	13.87	13.87
Grouped hydroids	2.07	2.07	4.00	1.33	10.89	24.77
Asterias rubens	1.79	0.59	3.83	1.03	10.44	35.21
Cerianthus spp.	1.83	2.46	3.35	1.35	9.12	44.33
Pagurus spp.	3.30	2.25	3.25	1.76	8.86	53.19
Trial Station 2						
Year 0 Av. Diss.: 20.37	**Rope**	**Control**				
Grouped hydroids	7.86	8.02	2.53	1.69	12.43	12.43

Cerianthus spp.	3.64	3.32	2.08	1.35	10.22	22.65
Alcyonidium diaphanum	1.64	2.35	2.01	1.02	9.87	32.52
Lanice conchilega	1.31	0.74	1.71	1.41	8.38	40.90
Pagurus spp.	1.14	1.66	1.22	0.74	6.01	46.91
Year 1 Av. Diss.: 40.51	**Rope**	**Control**				
Grouped hydroids	2.10	3.35	8.52	1.36	21.02	21.02
Ophiura ophiura	1.02	1.33	4.16	1.35	10.26	31.29
Turritella communis	0.66	0.57	3.48	1.22	8.58	39.87
Asterias rubens	0.95	0.40	3.38	1.12	8.33	48.20
Pagurus spp.	1.30	0.84	3.03	0.88	7.47	55.67
Year 2 Av. Diss.: 36.31	**Rope**	**Control**				
Alcyonidium diaphanum	1.26	1.10	4.09	1.29	11.26	11.26
Grouped hydroids	2.24	2.18	3.67	1.42	10.12	21.38
Macropodia spp.	1.62	1.06	3.33	1.48	9.16	30.53
Ophiura ophiura	1.34	1.07	2.89	1.41	7.97	38.50
Turritella communis	0.40	0.75	2.87	1.31	7.90	46.40
Year 3 Av. Diss.: 38.97	**Rope**	**Control**				
Grouped hydroids	1.40	2.20	7.75	1.59	19.90	19.90
Alcyonidium diaphanum	0.99	0.49	4.31	1.18	11.07	30.97
Pagurus spp.	1.10	0.58	3.80	1.71	9.74	40.71
Ophiura ophiura	1.39	1.16	3.77	1.15	9.67	50.38
Turritella communis	0.34	0.21	2.38	1.12	6.10	56.48
Year 4 Av. Diss.: 47.37	**Rope**	**Control**				
Grouped hydroids	1.29	2.89	12.37	2.02	26.12	26.12
Pagurus spp.	0.96	0.72	3.55	1.02	7.50	33.62
Ophiura ophiura	0.78	1.11	3.18	1.48	6.71	40.33
Turritella communis	0.10	0.36	2.54	1.21	5.35	45.68
Cerianthus spp.	0.04	0.30	2.22	1.01	4.69	50.38

4.3.2.2 Mobile epifauna

The introduction of the mussel headlines had no effect on the species richness of mobile epifauna in the Trial Stations (Ti x Tr(TS): $P > 0.05$; Supplementary material, Section B: Table 10); species richness remained similar between Treatments over Years. At Trial Station 1, the greatest difference between Treatments was in Year 2 (Rope = 4.67 ± 0.49 drop^{-1}, Control = 3.50 ± 0.22 drop^{-1}; Figure 4.12a). At Trial Station 2, there was a slighter difference between Treatments (Figure 4.12a).

There was a significant Ti x Tr(TS) interaction term for the total abundance of mobile epifauna (P = 0.02; Supplementary material, Section B: Table 11a). Pairwise tests found that the only difference between treatments was in Year 4 at Trial Station 1 (P = 0.001; Supplementary material, Section B: Table 11b), where there was a significantly greater total abundance of mobile epifauna in the Rope treatment compared to the Control (Rope = 141.94 ± 36.69 maxN min^{-1}, Control = 31.61 ± 6.37 maxN min^{-1}; Figure 4.12b).

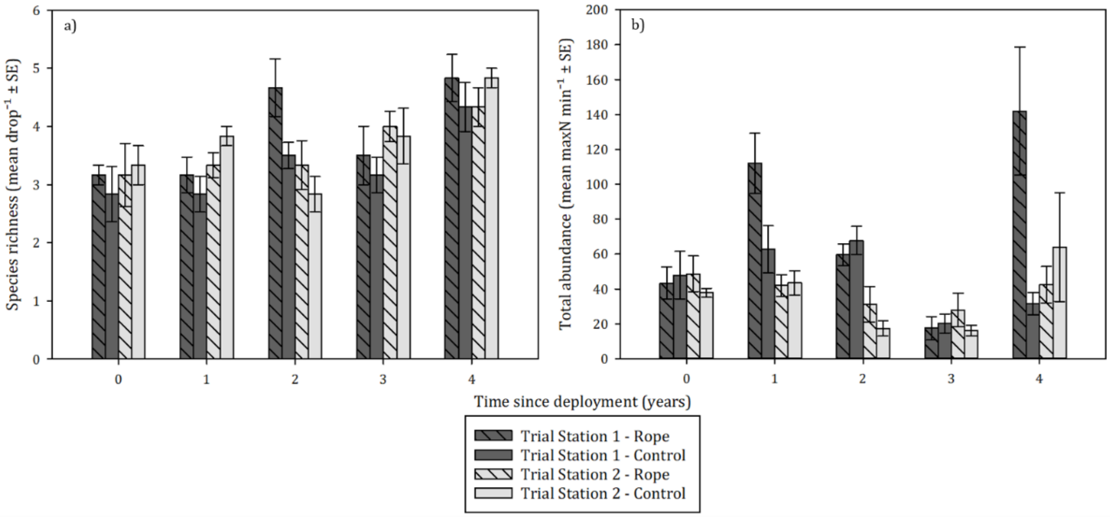

Figure 4.12: Mobile epifauna a) Species richness (mean $drop^{-1}$ ± SE), and b) Total abundance (mean maxN min^{-1} ± SE) within Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 0-4).

There was evidence for a statistically significant effect of the mussel farm on assemblage composition of mobile epifauna (Ti x Tr(TS): P = 0.005; Supplementary material, Section B: Table 12a). At Trial Station 1, assemblage composition was not significantly different between Treatments until Year 4 (P = 0.003; Supplementary material, Section B: Table 12b). This result is visually represented in the nMDS plot, which shows the distance between the two Treatment points in Year 4 is greater than in any other Year (Figure 4.13). The dissimilarity between the Rope and Control treatments at Trial Station 1 was 45.96 % in Year 4, compared to 31.81 % before headline deployment (Year 0) (Table 4.3). Over 50 % of this dissimilarity was due to Atlantic horse mackerel *Trachurus trachurus* being over twice as abundant in the Rope treatment compared to the Control treatment. There was also a greater abundance of poor cod *Trisopterus minutus* and pouting *Trisopterus luscus* in the Rope treatment, and a greater abundance of whiting *Merlangius merlangus* in the Control treatment (Table 4.3).

At Trial Station 2, there were no significant differences in assemblage composition in any Year (all $P > 0.05$; Supplementary material, Section B: Table 12b). The nMDS shows that the Treatment points within each Year since deployment remain relatively similar (Figure 4.13).

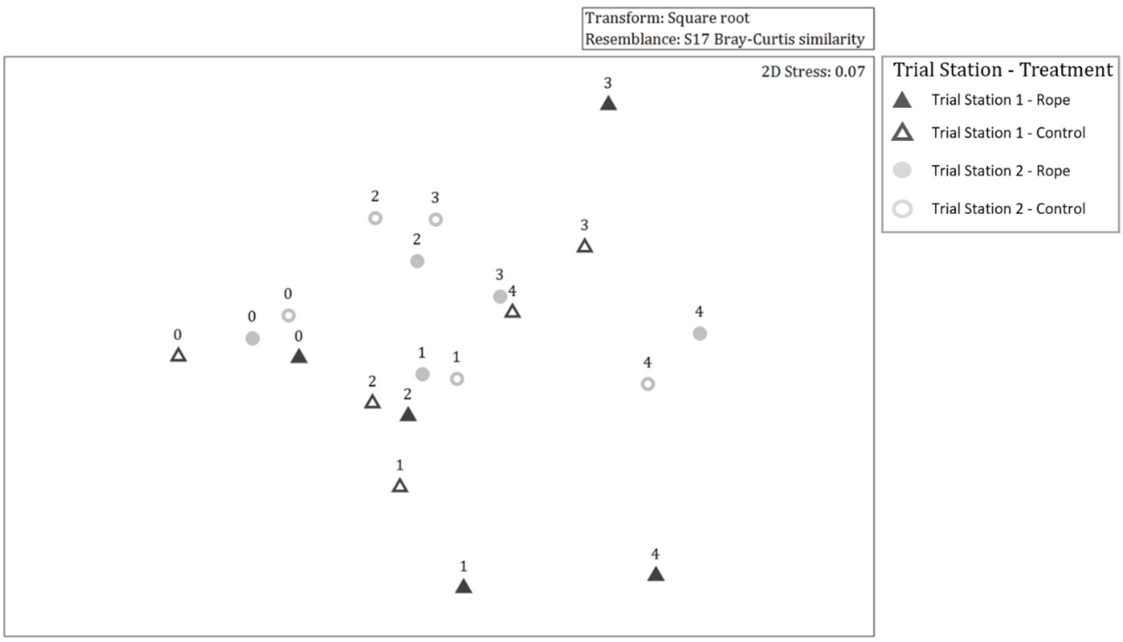

Figure 4.13: nMDS ordination plot illustrating differences in assemblage composition of mobile epifauna within Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 0-4).

Table 4.3: SIMPER analysis in groups outlined by PERMANOVA showing the top five organisms which most contributed to the observed differences in mobile assemblage composition between Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 0-4).

Taxon	Av. Abun.	Av. Abun.	Av. Diss.	Diss./SD	Contrib. %	Cum. %
Trial Station 1						
Year 0 Av. Diss.: 31.81	**Rope**	**Control**				
Trachurus trachurus	2.87	1.84	16.59	1.40	52.15	52.15
Merlangius merlangus	5.03	5.69	8.01	1.25	25.19	77.34
Scyliorhinus canicula	0.92	0.62	4.53	1.43	14.24	91.58
Callionymus lyra	0.57	0.70	2.68	1.16	8.42	100
Year 1 Av. Diss.: 25.49	**Rope**	**Control**				
Trachurus trachurus	9.87	6.35	16.65	1.05	65.32	65.32
Merlangius merlangus	3.06	3.64	4.64	1.54	18.20	83.52
Scyliorhinus canicula	0.31	0.50	2.22	1.09	8.71	92.23
Callionymus lyra	0.42	0.23	1.60	1.21	6.28	98.51
Trisopterus minutus	0.10	0.00	0.38	0.44	1.49	100
Year 2 Av. Diss.: 17.18	**Rope**	**Control**				
Trachurus trachurus	5.62	5.36	5.14	1.18	29.92	29.92
Merlangius merlangus	4.82	5.56	4.43	1.53	25.76	55.68
Scyliorhinus canicula	1.62	1.98	2.11	1.15	12.26	67.94
Callionymus lyra	0.52	0.26	1.80	1.25	10.49	78.43
Trisopterus minutus	0.31	0.00	1.06	0.64	6.16	84.60
Year 3 Av. Diss.: 48.35	**Rope**	**Control**				
Trachurus trachurus	1.41	3.52	25.28	1.63	52.28	52.28
Scyliorhinus canicula	2.35	1.59	6.40	1.47	13.24	65.52
Trisopterus luscus	0.78	0.00	5.18	0.43	10.72	76.24
Merlangius merlangus	0.73	0.82	4.17	1.40	8.63	84.87
Callionymus lyra	0.37	0.33	3.92	1.01	8.11	92.98
Year 4 Av. Diss.: 45.96	**Rope**	**Control**				
Trachurus trachurus	10.50	3.75	24.25	1.88	52.76	52.76
Trisopterus minutus	3.31	0.69	9.73	2.04	21.16	73.92
Merlangius merlangus	1.15	2.56	6.10	1.55	13.28	87.20
Trisopterus luscus	0.73	0.17	2.57	1.21	5.60	92.80
Scyliorhinus canicula	2.04	2.29	1.67	1.05	3.62	96.42
Trial Station 2						
Year 0 Av. Diss.: 27.97	**Rope**	**Control**				
Trachurus trachurus	2.47	1.96	13.54	1.40	48.40	48.40
Merlangius merlangus	5.40	5.35	5.64	1.57	20.16	68.56
Scyliorhinus canicula	1.20	1.47	3.38	1.02	12.08	80.64
Callionymus lyra	0.22	0.48	2.85	0.96	10.19	90.83
Eutrigla gurnardus	0.10	0.14	1.05	0.58	3.75	94.58

Year 1 Av. Diss.: 17.76	Rope	Control				
Trachurus trachurus	4.59	5.19	8.75	1.56	49.31	49.31
Merlangius merlangus	3.85	3.21	4.04	1.14	22.74	72.05
Scyliorhinus canicula	1.60	1.79	2.94	1.57	16.56	88.61
Callionymus lyra	0.21	0.52	2.02	1.36	11.39	100
Year 2 Av. Diss.: 35.61	**Rope**	**Control**				
Trachurus trachurus	2.78	1.76	15.51	1.33	43.55	43.55
Scyliorhinus canicula	2.37	1.15	7.74	2.15	21.75	65.30
Merlangius merlangus	3.27	2.99	7.52	1.06	21.12	86.42
Eutrigla gurnardus	0.30	0.00	2.10	0.68	5.90	92.32
Chelidonichthys lucerna	0.00	0.14	0.81	0.43	2.26	94.58
Year 3 Av. Diss.: 31.17	**Rope**	**Control**				
Trachurus trachurus	3.76	1.84	14.98	1.52	48.08	48.08
Merlangius merlangus	2.15	2.62	7.48	1.20	24.01	72.08
Callionymus lyra	0.40	0.33	2.74	1.12	8.80	80.88
Scyliorhinus canicula	1.84	1.81	2.67	1.34	8.56	89.45
Eutrigla gurnardus	0.19	0.23	1.93	0.90	6.20	95.65
Year 4 Av. Diss.: 45.18	**Rope**	**Control**				
Trachurus trachurus	3.86	5.36	18.39	1.62	40.70	40.70
Trisopterus minutus	1.40	0.68	7.24	0.95	16.02	56.72
Trisopterus luscus	2.36	1.56	6.15	0.99	13.61	70.34
Merlangius merlangus	1.09	1.10	5.56	1.23	12.30	82.63
Scyliorhinus canicula	2.74	1.75	4.61	2.29	10.20	92.83

4.3.2.3 Infauna

There was no statistically significant evidence for an effect of the mussel headlines on infauna species richness, so far (Ti x Tr(TS): $P > 0.05$; Supplementary material, Section B: Table 13). Figure 4.14a illustrates how species richness remains similar between treatments over time.

The introduction of mussel headlines also had no effect so far on the abundance of infauna (Ti x Tr(TS): $P > 0.05$; Supplementary material, Section B: Table 14). However, change may be starting to appear at Trial Station 2, with a greater abundance of infauna in the Rope treatment in Years 2 and 3 (Figure 4.14b).

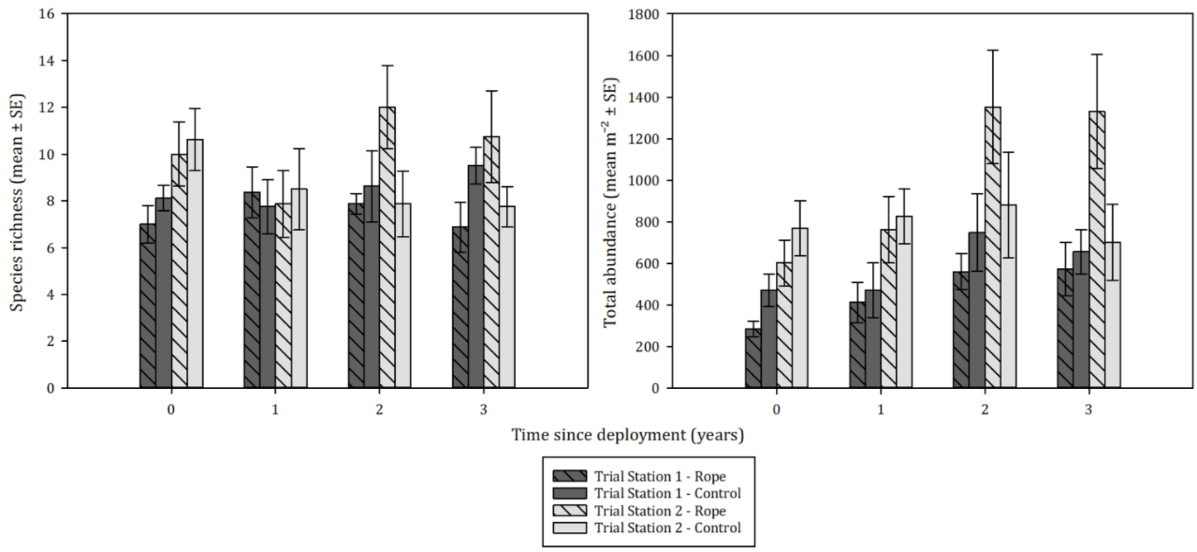

Figure 4.14: Infauna a) Species richness (mean m^{-2} ± SE), and b) Total abundance (mean m^{-2} ± SE) within Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 0-3).

There was no statistically significant evidence for an effect of the mussel headlines on the assemblage composition of the infaunal community (Ti x Tr(TS): $P > 0.05$; Supplementary material, Section B: Table 15). The nMDS (Figure 4.15) shows that at Trial Station 1, Years 1-3 are clustered together, further apart from Year 0. Treatments within Years are similar to each other. Although further apart on the nMDS, the Treatments in Year 3 have the lowest dissimilarity than any other Year (Year 0 = 70.68 %, Year 1 = 61.86 %, Year 2 = 56.15 %, Year 3 = 55.73 %; Table 4.4). At Trial Station 2, there is more of a gradual change in assemblage composition through the Years (Figure 4.15) and the dissimilarity between Treatments remains stable through Time since deployment (Year 0 = 54.92 %, Year 1 = 55.92 %, Year 2 = 55.41 %, Year 3 = 53.31 %; Table 4.4).

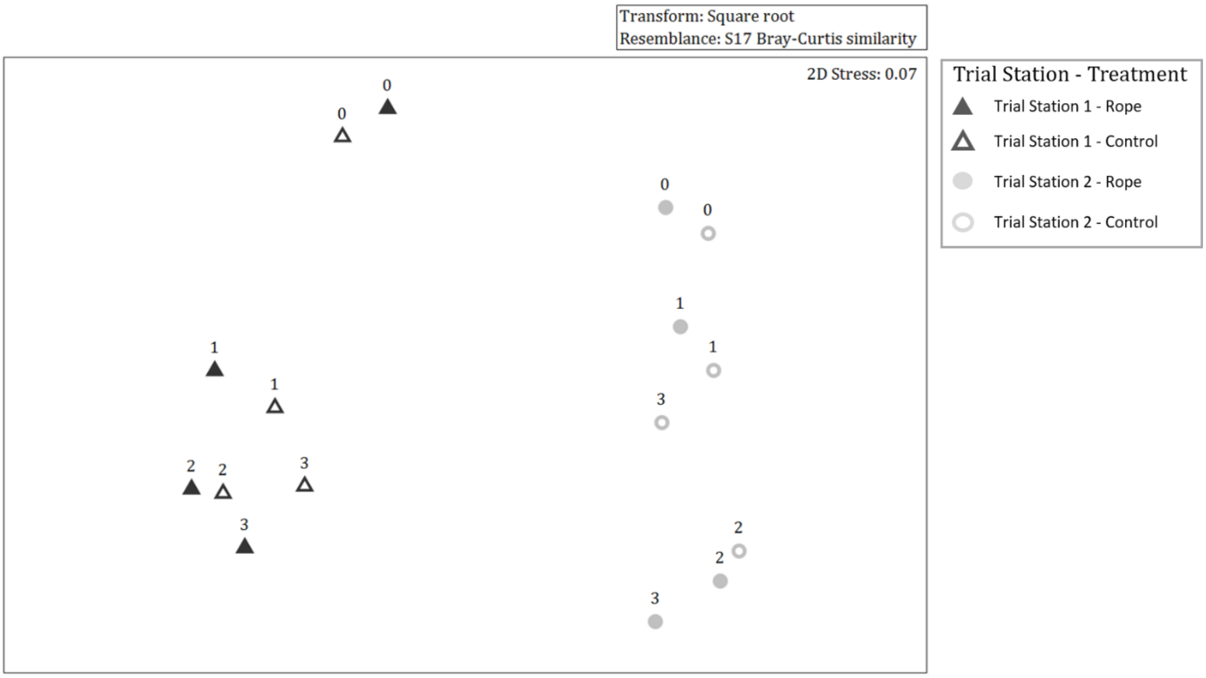

Figure 4.15: nMDS ordination plot illustrating differences in assemblage composition of infauna within Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 0-3).

Table 4.4: SIMPER analysis in groups outlined by PERMANOVA showing the top five organisms which most contributed to the observed differences in infauna assemblage composition between Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 0-3).

Taxon	Av. Abun.	Av. Abun.	Av. Diss.	Diss./SD	Contrib. %	Cum. %
Trial Station 1						
Year 0 Av. Diss.: 70.68	**Rope**	**Control**				
Capitellidae	4.15	6.61	5.03	1.39	7.12	7.12
Phascolion (Phascolion) strombus strombus	4.62	4.73	4.84	1.07	6.85	13.98
Pagurus bernhardus	1.53	4.04	4.46	0.80	6.31	20.28
Scalibregmatidae	3.32	4.3	4.26	1.13	6.03	26.31
Maldanidae	3.16	3.84	3.98	1.20	5.64	31.94
Year 1 Av. Diss.: 61.86	**Rope**	**Control**				
Capitellidae	4.99	6.63	5.43	1.15	8.77	8.77
Maldanidae	6.26	7.41	5.27	1.24	8.52	17.30
Magelonidae	6.06	6.99	4.92	1.16	7.95	25.25
Phascolion (Phascolion) strombus strombus	7.77	5.87	4.38	1.11	7.08	32.33
Ampeliscidae	3.26	4.43	3.79	1.09	6.13	38.46
Year 2 Av. Diss.: 56.15	**Rope**	**Control**				
Magelonidae	11.46	12.71	6.27	1.37	11.16	11.16

Maldanidae	9.24	12.05	4.62	1.17	8.22	19.39
Ampeliscidae	2.31	5.45	3.96	1.16	7.06	26.44
Phascolion (Phascolion) strombus strombus	7.69	6.98	3.61	1.02	6.43	32.87
Phyllodocidae	4.15	2.42	3.23	1.04	5.75	38.62
Year 3 Av. Diss.: 55.73	**Rope**	**Control**				
Maldanidae	12.16	13.16	5.89	0.94	10.57	10.57
Magelonidae	10.59	9.31	5.40	1.13	9.68	20.25
Phascolion (Phascolion) strombus strombus	3.26	4.69	3.97	0.85	7.12	27.37
Ampeliscidae	2.62	4.84	3.70	1.15	6.63	34.00
Capitellidae	1.9	4.58	3.26	1.06	5.85	39.85
Trial Station 2						
Year 0 Av. Diss.: 54.92	**Rope**	**Control**				
Ampharetidae	13.46	17.00	5.15	1.03	9.38	9.38
Capitellidae	9.07	9.42	4.25	1.20	7.74	17.12
Phascolion (Phascolion) strombus strombus	3.06	5.51	3.09	1.04	5.63	22.75
Scalibregmatidae	5.22	2.89	2.98	1.35	5.43	28.17
Nephtyidae	3.89	4.79	2.93	1.13	5.34	33.51
Year 1 Av. Diss.: 55.92	**Rope**	**Control**				
Capitellidae	8.63	8.00	5.57	1.27	9.96	9.96
Ampharetidae	17.55	19.21	5.33	0.92	9.54	19.49
Maldanidae	6.52	5.97	4.93	1.14	8.81	28.3
Magelonidae	6.51	5.10	4.58	0.95	8.19	36.49
Goniadidae	4.85	0.63	3.31	1.28	5.92	42.41
Year 2 Av. Diss.: 55.41	**Rope**	**Control**				
Ampharetidae	20.92	17.57	6.35	1.40	11.45	11.45
Magelonidae	10.49	9.52	5.14	1.36	9.28	20.74
Ampeliscidae	8.83	4.93	3.72	1.38	6.71	27.45
Nephtyidae	11.90	10.92	3.38	1.10	6.09	33.54
Nemertea	4.86	3.80	2.82	1.10	5.09	38.63
Year 3 Av. Diss.: 53.31	**Rope**	**Control**				
Ampharetidae	23.28	17.55	6.79	1.35	12.74	12.74
Magelonidae	13.97	7.17	6.11	1.37	11.46	24.20
Oweniidae	4.49	0.00	3.70	0.90	6.95	31.15
Nephtyidae	8.23	5.94	3.50	1.09	6.56	37.71
Capitellidae	3.78	5.16	3.43	1.76	6.43	44.14

4.3.2.4 Key benthic taxa

European lobster *Homarus gammarus* was exclusively observed in the Rope treatment at both Trial Station 1 and 2 (Figure 4.16a). Brown crab *Cancer pagurus* was exclusively observed in the Rope treatment at Trial Station 1, and only observed in the Control treatment once at Trial Station 2 (Figure 4.16b). However, abundances of these species were too low for statistical analysis.

The abundance of schooling fish (Atlantic horse mackerel *Trachurus trachurus* and whiting *Merlangius merlangus*) was significantly affected by the development of the mussel farm (Ti x Tr(TS): P = 0.03; Supplementary material, Section B: Table 16ai). At Trial Station 1, there was a significantly greater abundance of schooling fish in the Rope treatment compared to the Control treatment by Year 4 (P = 0.01; Supplementary material, Section B: Table 16aii). Schooling fish were over five times more abundant in the Rope treatment compared to the Control treatment in Year 4 (Rope = 124.78 ± 37.75 maxN min^{-1}, Control = 24.11 ± 6.67 maxN min^{-1}; Figure 4.16c). There was no significant difference between Treatments at Trial Station 2 (P > 0.05; Supplementary material, Section B: Table 16aii).

Abundance of common whelk *Buccinum undatum* was not significantly affected by the installation of the mussel headlines (Ti x Tr(TS): P > 0.05; Supplementary material, Section B: Table 16b). However, from Year 2, the abundance of *B. undatum* was consistently greater in the Rope treatment than the Control treatment at both Trial Stations (Figure 4.16d).

There was also no significant effect of the mussel headlines on the abundance of common starfish *Asterias rubens* (Ti x Tr(TS): P > 0.05; Supplementary material, Section B: Table 16c). Although, at Trial Station 1, the abundance of *A. rubens* steadily increased in the Rope treatment, to being over 12 times more abundant in the Rope treatment (4.41 ± 1.65 m^{-2}) than the Control treatment (0.36 ± 0.04 m^{-2}) in Year 4 (Figure 4.16e).

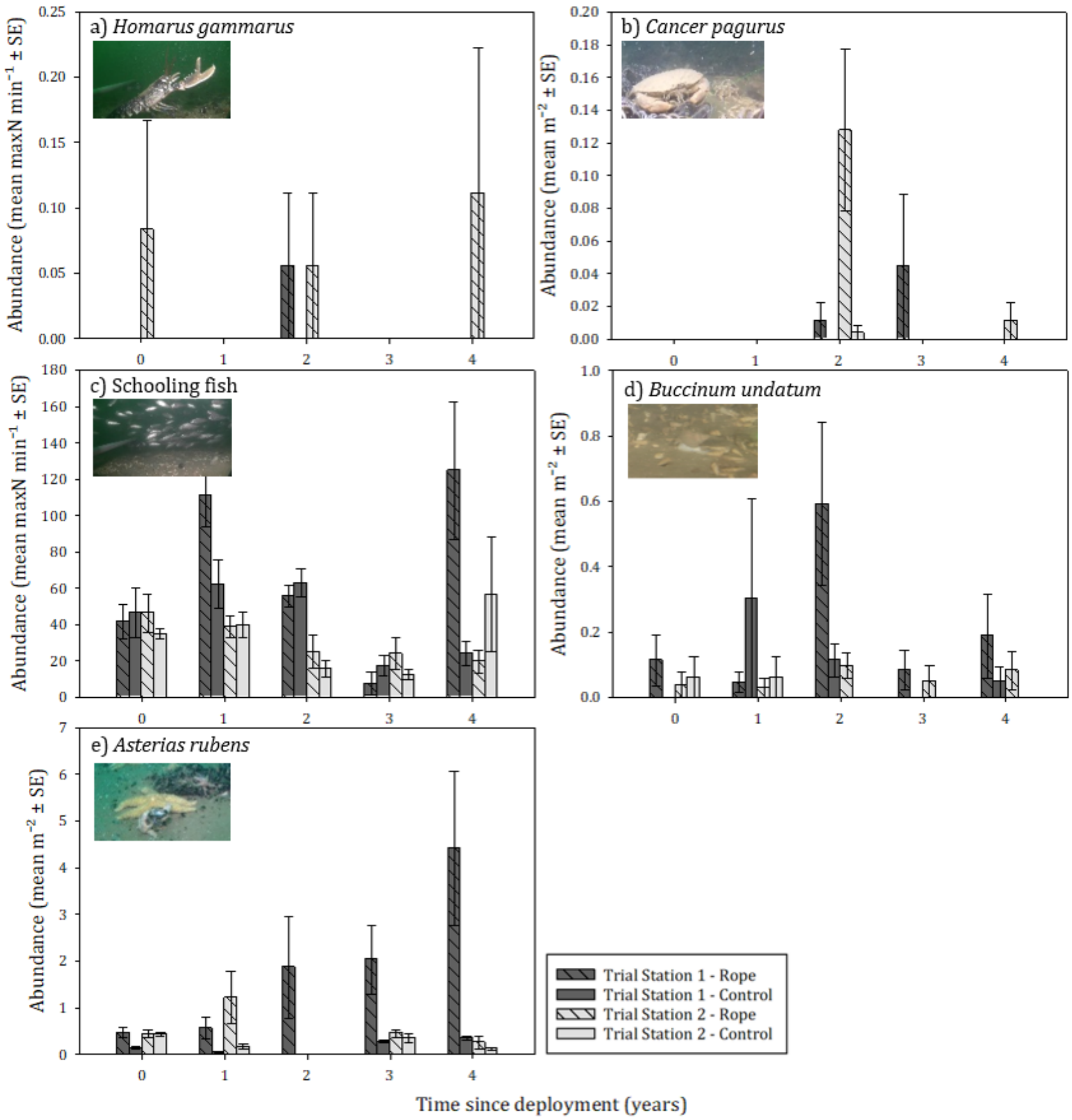

Figure 4.16: Abundance of key benthic taxa a) *Homarus gammarus* (mean maxN min^{-1} ± SE), b) *Cancer pagurus* (mean m^{-2} ± SE), c) Schooling fish (mean maxN min^{-1} ± SE), d) *Buccinum undatum* (mean m^{-2} ± SE), and e) *Asterias rubens* (mean m^{-2} ± SE), within Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 0-4).

Neither polychaete nor amphipod abundance showed a significant interaction between Time since deployment and Treatment (Ti x Tr(TS): both $P > 0.05$; Supplementary material, Section B: Table 17). Despite this, Figure 4.17a shows an increasing abundance of polychaetes in the Rope treatment compared to the Control treatment over time at Trial Station 2, but remained similar between Treatments at Trial Station 1. Amphipod abundance was more variable, with a large peak at Trial Station 2 in Year 2 (Figure 4.17b).

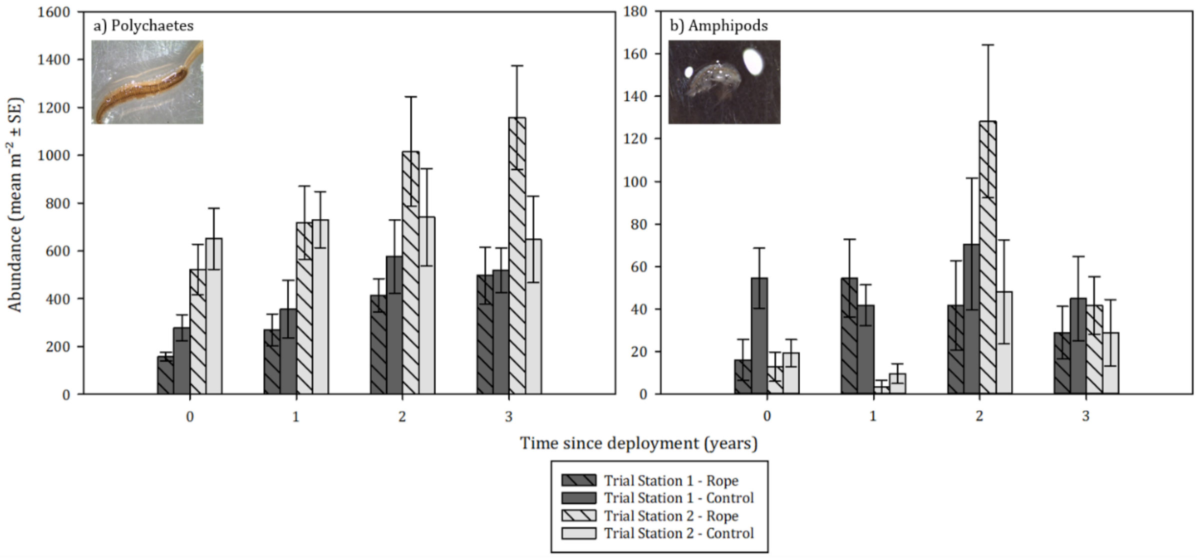

Figure 4.17: Abundance (mean m^{-2} ± SE) of a) Polychaetes, and b) Amphipods within Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 0-3).

4.3.3 Relationship between environmental and biological variables

Neither abundance of schooling fish or *B. undatum* were significantly correlated with % cover of *M. edulis* (both P > 0.05; Supplementary material, Section B: Table 18a+b; Figures 4.18a+b). There was a significant positive correlation between the abundance of *M. edulis* and abundance of *A. rubens* (P = 0.0001; Supplementary material, Section B: Table 18c; Figure 4.18c).

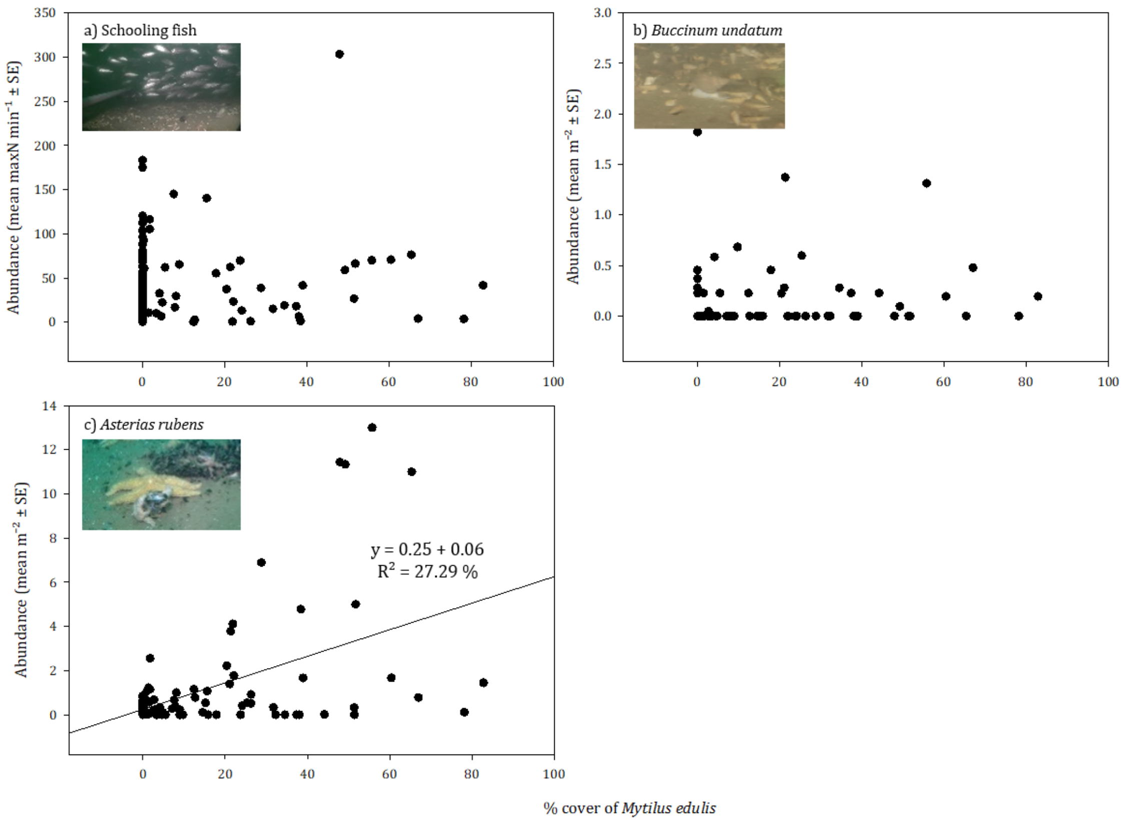

Figure 4.18: Relationship between % cover of *Mytilus edulis* and abundance of a) schooling fish (mean maxN min^{-1} ± SE), b) *Buccinum undatum* (mean m^{-2} ± SE), and c) *Asterias rubens* (mean m^{-2} ± SE).

The BPOFA (Benthic Polychaete Opportunistic Families Amphipods) scores show that the Ecological Quality Status (EcoQs) of the benthos at Trial Station 1 was the same in both treatments: Moderate-Bad in Years 0 and 1, and Poor-Bad in Years 2 and 3. The EcoQs at Trial Station 2 was Poor-Bad in both treatments in all years (Table 4.5).

Table 4.5: Ecological Quality Status of the benthos within Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 0-3).

	Trial Station 1		Trial Station 2	
Time since deployment (year)	Rope	Control	Rope	Control
0	0.19	0.19	0.26	0.26
1	0.19	0.21	0.29	0.28
2	0.23	0.23	0.23	0.26
3	0.26	0.24	0.27	0.26

The BEST (Bio-Env) analysis suggests that a combination of two environmental variables (mean particle size and redox potential) best explains the infauna community assemblage composition. The best single environmental variable to explain infauna composition is redox potential (Table 4.6). However, there were no strong correlations: values between 0 and 0.3 in correlation coefficients generally indicate a weak positive correlation (Ratner, 2009).

Table 4.6: Results from BEST (Bio-Env) analysis to test the relationships between benthic habitat variables and infauna community. OM = organic matter, MPS = mean particle size, RP = redox potential.

No. of variables	Correlation (R)	Selections
2	0.270	MPS, RP
3	0.238	MPS, OM, RP
1	0.203	RP
1	0.195	MPS
2	0.193	MPS, OM
2	0.177	OM, RP
1	0.081	OM

4.4 Discussion

The primary aim of this study was to develop and pilot a time-series monitoring programme that can be used when testing for changes in the benthic ecosystem between areas within an open ocean mussel farm, and control locations. A further aim was to investigate whether the trial headlines at the Lyme Bay mussel farm have had an effect so far on the benthic habitat, as well as the associated epifauna and infauna assemblages.

The three video methods used to sample epifauna and mussel cover were successful in capturing information on the diversity of sessile and sedentary, and mobile epifauna. Using the remotely operated vehicle (ROV) alongside the towed underwater video system (TUVS) was a useful addition to be able to record the seabed directly underneath the mussel ropes. Without the use of the ROV, the extent of the mussel cover beneath the headlines and the epifauna living on or with live mussel clumps may have been lost. Using baited remote underwater video (BRUV) units to record mobile epifauna was very valuable. Seven species were solely recorded during the BRUV survey, including the commercially fished European lobster *Homarus gammarus* and whiting *Merlangius merlangus*. The grab survey was useful in showing patterns in organic matter and mean particle size, although more replication or a different grab may be needed to understand the effects of mussel headlines on the infauna community.

In 2013, when the 'before impact' survey was undertaken, the area in which the mussel farm development was planned was indicative of a disturbed habitat, homogenous with no hard structure: a result from being heavily fished by bottom towed gear. Four years later, after farm structures have been installed and mussels have been grown and harvested, there has been a significant change to the epibenthic habitat. The amount of live and dead mussels covering the seabed has significantly increased within the mussel farm compared to control areas, and over time. Despite the increase in mussel cover within the farm, there have been no mussel shell observations in either of the control areas, showing that mussel drop-off is not spreading to half a kilometre away from the farm. Mussels, when aggregated in beds, are ecosystem engineers, creating habitat, which increases environmental heterogeneity and habitat diversity (sensu Jones et al., 1997). This effect has the potential to increase species richness through the provision of substrata for colonisation (Borthagaray and Carranza, 2007), and provide refuges from predation, nursery areas and food (Díaz et al., 2015). The two Trial Stations were very different to each other in terms of sediment organic matter and mean particle size. Organic matter was higher at Trial Station 2 throughout, and mean particle size was classified as medium or fine sand at Trial Station 1 compared to very fine or fine sand at Trial Station 2. This illustrates the difference between Site 1 and Site 2 of the mussel farm and suggests that sites may show different effects of the addition of mussel headlines. At both Trial Stations, there was a peak in organic matter in two years after mussel headline deployment began. This corresponds with a sharp increase in mussel cover, especially at Trial Station 1. Furthermore, an additional three headlines were installed at Trial Station 2 in Year 2, all being used as spat growing headlines. This could have contributed to the peak in organic matter at Year 2. Mean particle size remained stable at Trial Station 2 throughout the survey. There was a peak at Trial Station 1 in Year 1, although as mean particle size was greater in this year it is unclear what could have cause this. Two headlines had been installed in Trial Station 1 at this point, but were being used as somewhat unsuccessful spat growing headlines. Perhaps, as not many spat were settling, the spat that managed to settle on the ropes were struggling to establish and so fell off the rope droppers, causing mussel shell to break up on the seabed and contribute to a larger mean particle size. Redox potential was generally lower at Trial Station 2, dropping below 0 mV in Years 1, 2 and 3 in both Treatments. Measurements below 0 mV are classified at polluted in relation to organic enrichment (Wildish et al., 2001). At Trial Station 1, redox potential in Year 0 was significantly greater than in any other year. However, the same trend was seen in the Control treatment and so this was most likely caused by something other than the addition of mussel headlines to the system, although it is unclear what this would be. It is possible that the influence of the headlines is extending beyond the farm area and into the control areas, although it is unlikely that the very small number of headlines within the Trial Stations would affect sediment 500 m away.

Sessile and sedentary epifauna abundance was significantly affected by the mussel headlines. There was a sharp decline in 2014 (Year 1) at Trial Station 2 in both treatments; most likely because of the series of extreme storms which hit the southwest coast of England from December 2013 to February 2014 (Masselink et al., 2016), which also significantly affected species abundances in the Lyme Bay MPA (Sheehan et al., 2021). Subsequently, abundance of sessile and sedentary epifauna in the farm remained higher or similar to control areas, and significantly greater in the farm than the control areas at Trial Station 1, four years after headline deployment. However, there was a significantly greater species richness of sessile and sedentary epifauna in the control areas at Trial Station 2 four years after headline deployment. This could be a result of the difference in headline use between treatments. Trial Station 1 was being used for older mussels, which, when they fall to the seabed, could be providing a larger habitat and food source for sessile and sedentary epifauna. The assemblage composition of sessile and sedentary epifauna was significantly different at both sites of the farm compared to in control areas. At Trial Station 1, however, this was apparent from the baseline survey, and so differences in assemblage may be driven by location rather than influence from the mussel headlines. At Trial Station 2, difference is assemblage composition was apparent after the installation of mussel headlines and so is more likely influenced by an increase in *Mytilus edulis* on the seabed and the associated scavenging species attracted by the additional food source, e.g. hermit crab *Pagurus* spp. and common starfish *Asterias rubens*.

Mobile epifauna were not as obviously affected by the installation of the mussel farm. Both abundance and species richness remain similar between treatments throughout the survey. It was only in Year 4 that the abundance of mobile epifauna was significantly greater in the farm compared to control areas, at Trial Station 1 only. Large schools of Atlantic horse mackerel *Trachurus trachurus* and poor cod *Trisopterus minutus* within the mussel farm caused this significant difference in assemblage composition, presumably a result of the increase in food availability or because of the farm structures on the benthos (e.g. anchor blocks) acting as fish aggregation devices (Kingsford, 1993).

All of the key taxa show a positive response to the development of the open ocean mussel farm. Schooling fish (Atlantic horse mackerel *Trachurus trachurus* and *M. merlangus*) were significantly more abundant within the farm than in control areas at Trial Station 1 in Year 4, and abundance of common whelk *Buccinum undatum* was consistently greater in the farm than control areas from Year 2. *A. rubens* abundance steadily increased at Trial Station 1 over time, and by 2017 was over twelve times more abundant in the farm than outside. Two important commercial species to Lyme Bay were also consistently more abundant in the farm compared to control areas: brown crab *Cancer pagurus* and *H. gammarus*. These findings support work by Inglis and Gust (2003) and Drouin et al. (2015).

It is evident that the epibenthic habitat within the open ocean mussel farm has changed as a direct effect of the aquaculture installation. Mussels covering the seafloor have increased and it is apparent that both sessile and sedentary, and mobile epifauna are beginning to respond to the change in epibenthic habitat. If the increasing abundance of commercial species continues, it could increase the catch per unit effort in fishing ground around the mussel farm, known as 'spillover' (Rowley, 1994), enhancing wild fisheries. It is unclear, however, whether the mussel headlines are contributing to the production of epibenthic fauna or whether they are redistributing the species in the area and pulling them away from their natural habitat into, perhaps, a more attractive habitat with a reliable food source. The mussel cover recorded in this study includes both live clumps of mussels and dead shell hash. It should be noted that these are two different habitats and future research would be stronger if it attempted to separate these two habitats into live and dead mussel cover. In a more developed farm, these two habitats may become more apparent and large enough to analyse separately. Whether recruitment of mussels is occurring on the seabed is also worthy of further research, as over time there was observational evidence that the mussel clumps were becoming larger. Despite the opportunity for the mussels to provide habitat and a food source in the epibenthic ecosystem, mussels falling to the seabed is not ideal for the industry itself as it represents a loss of harvest. Even though mussels were not recorded in the control site, 500 m away from the headlines, it would be recommended to sample along a gradient at intervals from the farm, perhaps at 100 m intervals, to record how far mussel drop-off extends from the mussel headlines and whether this increases over time. It may also be possible to link this to epifauna and infauna communities, with percentage mussel cover and distance from the farm included as covariates in statistical analysis to investigate the spread of impact from the farm.

There was also no observed overall effect of the mussel headlines on the infaunal community. The assemblage composition between the two trial stations was very distinct, perhaps due to depth and distance from the shore, or differences in sediment characteristics, namely the obvious difference in organic content and mean particle size between the sites. The four main feeding groups within the infaunal community were deposit feeders (e.g. polychaete families Ampharetidae, Magelonidae and Hesionidae), predators (e.g. polychaete families Nephtyidae and Goniadidae, and anemone family Edwardsiidae), suspension feeders (e.g. amphipod family Ampeliscidae, sea squirt *Ciona intestinalis* and polychaete family Oweniidae) and filter feeders (e.g. polychaete families Sabellidae and Serpulidae). The polychaete family Capitellidae were more abundant in the Control treatment at both Trial Stations 1 and 2 after three years of headline deployment. Capitellidae is considered a strong indicator of organically enriched marine habitat, as it occurs in high densities in heavily polluted areas (Reish, 1971; Wade et al., 1972), and is able to recover quickly after environmental disturbance (Grassle and Grassle, 1974). It has also been used as an indicator of organic enrichment under marine fish farms (Tomassetti and Porrello, 2004). If the mussel headlines were negatively affecting the benthic habitat, we would expect a greater abundance of Capitellidae under the headlines compared to control areas. Stenton-Dozey et al. (1999) reported a shift in community structure from suspension feeders to deposit feeders under an inshore mussel raft. This shift was not apparent so far under the test headlines, where some suspension feeders were more abundant under the headlines than in control areas. This is most likely due to the high hydrodynamic energy at the farm, which was also the conclusion of Fabi et al. (2009) who reported minimal detrimental effects on infaunal communities within an open ocean mussel farm. This illustrates the importance of hydrographical features when planning the location of a mussel farm, as location and hydrological conditions have a fundamental role in potential impact on the benthic conditions (Fabi et al., 2009). This is also confirmed by Hartstein and Rowden (2004), who found minimal impact at sites with the highest hydrodynamic energy.

The two main groups dominating the assemblage were polychaetes and amphipods, and so these groups were picked out as key taxa. Neither group showed a significant response to the installation of the mussel headlines. At Trial Station 2, there was an emerging trend for a greater abundance of amphipods beneath the headlines compared to control areas. Amphipods are known to be sensitive to polluted sediments, disappearing from impacted benthic communities (de-la-Ossa-Carretero et al., 2012), while polychaetes are generally opportunistic and tolerant to polluted sediment (Gomez-Gesteira and Dauvin, 2005). Dauvin et al. (2016) developed the BPOFA (Benthic Polychaete Opportunistic Families Amphipods) index to assess the Ecological Quality Status (EcoQs) of soft-bottom communities. It used a polychaete/amphipod ratio to define the EcoQs, with the idea that if the ratio of polychaetes increases then the sediment became impacted (Dauvin et al., 2016). In this study, the EcoQs was the same in both treatments over time at both Trial Station 1 and 2, from Good-Moderate to Poor-Bad. At Trial Station 2, the EcoQs was highest in the Rope treatment, two years after headline deployment. This corresponds with the high abundance of amphipods recorded. This highlights that the benthic habitat in the area as a whole is impacted. This could be due to the intense fishing pressure that the area has been subject to (Offshore Shellfish Ltd., 2010). Dimitriou et al. (2015) used polychaete/amphipod ratios to assess impact of a small, coastal long-line mussel farm and found that the ecological status of benthic communities did not change because of the farming activities. Although this was an inshore farm, it was located in a gulf with a current from the open ocean leading to constant mixing of the waters. This may have helped flush faeces and psuedofaeces away, as in the Lyme Bay mussel farm.

BEST (Bio-Env) showed that there were no strong relationships between the infaunal community and any of the habitat variables. Overall, abundances of all 85 taxa varied in relation to a combination of mean particle size and redox potential. The highest correlation between infaunal community and a single habitat variable was with redox potential, which suggests that the infaunal community responded negatively when the redox potential was particularly low. However, mean redox potential fell below 0 mV (i.e. classified as polluted) both underneath the farm and in control areas, particularly at Trial Station 2. Either, as identified earlier, this could have been a response of infaunal communities to the area in general, or that the control plots are not beyond the impact of the mussel headlines. Hartstein and Rowden (2004) showed that organic matter was the single parameter best explaining the pattern of infauna assemblage at both inshore and offshore mussel farm sites, although they did not sample redox potential. They also found that organic matter was low both inside and outside the offshore mussel farm, but it was twice as high beneath the inshore mussel farms compared to control areas. Organic matter levels at the offshore site were comparable to those recorded at the Lyme Bay mussel farm. With the increasing need for protein (FAO, 2020) and the increasing acceptance of offshore aquaculture as a mechanism to meet this growing demand, it is likely that aquaculture developments are going to expand further into the open ocean (Froehlich et al., 2017). By moving mussel farms offshore, there is reduced competition with other activities (European Commission, 2012) and the possible mitigation of some of the negative consequences associated with coastal farms. This study has shown that, so far, there have been some interactions with and hints of impact from the mussel headlines on benthic habitat and associated assemblages, although none of these have proved to be detrimental so far, further contributing to evidence that open ocean mussel farms may be preferable from an environmental perspective. However, the evidence provided from this study is from a low number of headlines so it is important that existing monitoring remains in place to determine the impacts of this open ocean mussel farm as more headlines are installed, more mussels are cultivated, and therefore greater potential for adverse benthic conditions to arise.

4.5 Conclusion

The three video methods used to survey epibenthic fauna were useful in their own right for filming the wide variety of taxa and should be included in future monitoring programmes. In particular, the BRUV method recorded species that were not picked up in the other two video methods. However, if researchers were looking to simplify the monitoring, then a combination of BRUV and ROV footage would provide the best means of capturing epifauna patterns, as the TUV system was not able to film directly beneath the mussel headlines, where the majority of the live mussels were recorded. The Shipek grab was not as successful in surveying the infaunal community and may have led to the presentation of inconclusive results. Either using a different sampling method or increasing the replication and frequency of sampling (i.e. summer and winter sampling) would perhaps allow any impacts to be more easily recognised. In the drive to move aquaculture installations into the open ocean, the monitoring of open ocean mussel farms is vital to ensure sustainable aquaculture practices.

Chapter 5: The social perception of open ocean mussel farming.

Target Journal: Ocean & Coastal Management

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DB led the design of the survey, with SR and ES. DB led the data collection with assistance from JR. DB analysed the data and drafted the Chapter. SR, ES and MA reviewed and commented on the Chapter.

The social perception of open ocean mussel farming.

Abstract:

The Blue Growth Strategy has identified aquaculture as a marine sector with the potential to generate economic growth, and moving aquaculture developments further offshore could reduce competition with other activities, including tourism and recreation. However, there is a still a conflict of space with small-scale fisheries. This Chapter investigated whether the Lyme Bay mussel farm had displaced commercial fishers or affected their decision of where to fish. It also looked at the general perceptions the fishers had towards the mussel farm. Overall, mobile gear fishers were more positive about the mussel farm than static gear fishers, despite the farm being designed to allow the deployment of static gear between the headlines. The most common issues that fishers had with the aquaculture installation was the taking up of fishing ground and the lack of information provided prior to development. The fishing activity of both gear type fishers had been affected by the mussel farm. Previous chapters have shown some evidence for an increase in abundance of some commercial species. However, this was not reflected in landings data, and was not in full agreement with fishers comments on their catch inside and around the perimeter of the mussel farm.

Keywords: aquaculture, mussel farming, ocean use, open ocean, social-ecological, wellbeing

5.1 Introduction

The demand for seafood is increasing (FAO, 2020); however, the productivity of our oceans is being challenged by many factors, including overfishing (Pauly et al., 1998; Pauly et al., 2002). One common solution suggested to stop this downward trend is the implementation of marine protected areas (MPAs) (Hilborn, 2011). However, a more direct means of food production is needed to make up the shortfall left by declining capture fisheries. The primary method over the last few decades has been aquaculture expansion (Olin et al., 2012). Aquaculture is now one of the fastest growing food producing sectors in the world (Lem et al., 2014) and has the potential to play a major role in feeding the 9 billion humans predicted for 2050 (Duarte et al., 2009). Further, the 2030 sustainable developments goals (SDGS) Agenda highlights that, in addition to meeting humanity's need for food, fisheries and aquaculture employs one in three of the world's workers, providing livelihood for 2.5 billion people (Committee on Fisheries, 2017). Furthermore, aquaculture is one of the five sectors identified as having the potential to generate economic growth and contribute to Blue Growth (European Commission, 2012). Suitable coastal areas for aquaculture are becoming scarcer (Klinger and Naylor, 2012), and there is increasing knowledge on the possible impacts that inshore aquaculture has on the surrounding environment (Shainee et al., 2013). As a result, coastal countries are starting to expand aquaculture in to the open ocean (e.g. Schatzberg, 2002; Buck et al., 2004; Longdill et al., 2008).

As well as having some environmental benefits over inshore aquaculture, due to the greater depth and distance from shore coupled with faster currents, open ocean aquaculture also has fewer area use conflicts with tourism and recreation (Holmer, 2010; Teitelbaum, 2011). The Blue Growth Strategy recognises that moving aquaculture developments further offshore could reduce competition with other activities (European Commission, 2012). However, there is still an issue over conflicts with commercial small-scale fisheries (Charles, 2011), as leases for open ocean aquaculture developments may be granted in popular fishing areas (Barnaby and Adams, 2002). Small-scale fisheries are important socially and economically as they employ 90 % of fishers and provide over half the world's wild seafood (Shester and Micheli, 2011). Displacement of fishing activity is a concern that has been highlighted within the UK's Marine Policy Statement (MPS) (HM Government, 2011). With the increased demand for marine space, the need to maximise economic opportunities and reduce conflict is recognised within the EU Directive establishing a framework for marine spatial planning (MSP: 2014/89/EU). MSP is a multi-sectoral decision-making approach, which aims to reduce the impacts and conflicts that are commonly encountered when planning the location, type and intensity of ocean stakeholder groups across the seascape (Foley et al., 2010; Lester et al., 2013).

Despite being regarded as an important part of aquaculture development planning and management, stakeholders' perceptions have not been extensively explored (Chu et al., 2010). Effective management needs both environmental monitoring and input from stakeholders to understand how the industry affects local communities. Understanding perceptions also allows managers to respond to stakeholder concerns with scientific evidence (Salgado et al., 2015). Furthermore, studies on stakeholder perceptions can help the government and the aquaculture industry to develop a sustainable sector.

The aquaculture development investigated in this study is a recently installed open ocean mussel farm, situated in Lyme Bay, southwest UK. In 2008, a 206 km^2 MPA was designated in Lyme Bay, excluding bottom towed fishing (e.g. demersal trawlers, scallop dredgers) following concerns about damage to the ecosystem which contains a highly diverse community of highly sensitive gorgonian corals, bryozoans and erect sponges (Mangi et al., 2011). Static gear fishers (e.g. potters) are still allowed within the MPA. A socio-economic impact assessment found that mobile gear fishers were impacted through displacement effects, having to find new fishing ground. Furthermore, there was increased conflict between static and mobile fishers (Mangi et al., 2011). The implementation of the MPA has allowed recovery of the highly sensitive species, and overall species richness and abundance has increased (Sheehan et al., 2013).

In 2013, the area leased to the mussel farm was designated. Prior to this, once the general area had been chosen (between Otterton point and Beer Head, between 3 and 6 miles offshore), discussions took place between Offshore Shellfish Ltd., Devon Sea Fisheries Committee, South Western Fish Producers Organisation and South West Inshore Fishing Association. These discussions resulted in further refining of the location to reduce the effect on the lemon sole industry, and to avoid an important trawling area south of Beer Head. Talks were then held with fishers from Lyme Regis and Exmouth to try to avoid conflict over the proposed farming areas. One third of the total proposed area was then moved so these sites would not interfere with users of mobile fishing gear. Objections from static gear fishers were also taken into account, which reduced the proposed farming area over reefs by half. Attempts to find an area that had no prior usage, whilst also being suitable for development did not succeed. The farm was then designed to allow static fishing methods to carry on within the farm, but remained unsuitable for bottom towed fishing practices. Full information on the underwater layout of the farming equipment is given to static gear fishers to enable their activities within the farm area.

Once completed the farm will cover a total area of 15.4 km^2, adding to the total area of fishing ground that has been closed to mobile bottom towed gear in Lyme Bay. The exclusion of this further area to bottom towed fishing means the mussel farm has the potential to act as a de facto MPA, restoring and/or creating new benthic habitat and ecosystems. Chapter 4, which assessed the effects of the Lyme Bay mussel farm on the epibenthic ecosystem found that there was trend towards greater abundances of common whelk *Buccinum undatum* and schooling fish (Atlantic horse mackerel *Trachurus trachurus* and whiting *Merlangius merlangus*) in the mussel farm compared to still heavily fished control areas away from the farm. There was also observational evidence of greater numbers of the commercial brown crab *Cancer pagurus* and European lobster *Homarus gammarus* within the mussel farm. Furthermore, Chapter 3 showed that *C. pagurus* are living on the mussel rope droppers themselves, which are potentially acting as a nursery and feeding area for the crabs before they are pulled of the rope droppers and returned to the sea during harvesting periods. Field studies of fishing near MPAs have suggested that adults and larvae from reserves can be exported to adjacent fisheries, increasing the catch per unit effort in fishing ground around MPAs (Alcala and Russ, 1990; McClanahan and Kaunda-Arara, 1996). This is known as 'spillover' (Rowley, 1994). It is possible that the mussel farm could contribute towards spillover, and increase the abundance of target species around the mussel farm.

The aim of this study was firstly to investigate whether fisheries landings have changed in Lyme Bay since the development of the mussel farm. Secondly, the study aims to understand the perspectives of local fishers regarding the development of the mussel farm, specifically investigating whether fishers have had to change their fishing activity because of the farm, whether they have noticed any differences in their catch around the farm, and if they support the development of the farm.

5.2 Methods

5.2.1 Study site

The study site is an open ocean long-line mussel farm in Lyme Bay, southwest UK cultivating the native blue mussel *Mytilus edulis*. The farm is located between 4 and 10 km offshore (Figure 5.1) and, on completion, will cover 15.4 km^2. The farm is located close to the Lyme Bay Marine Protected Area (MPA), a 206 km^2 area officially closed to bottom towed fishing gear in 2008 to protect the reef and its associated biodiversity from the impacts of heavy demersal fishing gear (Rees et al., 2010). In 2013, trial headlines were installed to test the ecological impacts of the farm.

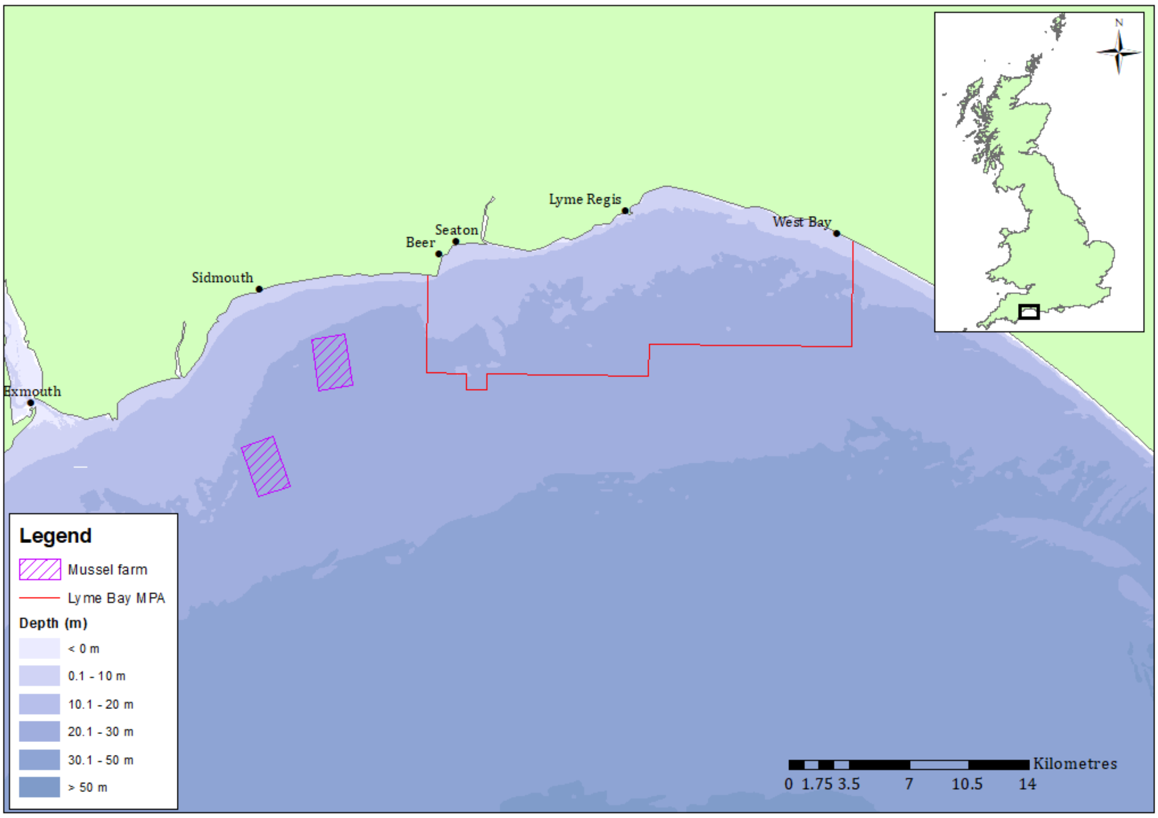

Figure 5.1: The Lyme Bay mussel farm (purple hatched squares) in relation to the Lyme Bay Marine Protected Area (red outline).

5.2.2 Primary data

A questionnaire was developed to collect data on the perceptions of one of the main stakeholder groups in Lyme Bay: commercial fishers. Questionnaires were conducted as face-to-face interviews from 2017-2018 and were designed to separate the opinions of mobile gear fishers (e.g. trawlers and dredgers) and static gear fishers (e.g. potters and netters).

An approximate number of mobile and static gear fishers that were active around the farm area before it was developed were extracted from FisherMap (des Clers et al., 2008). FisherMap was developed by the Finding Sanctuary project to map the nature and extent of fishing activity around the coasts and seas of Devon and Dorset, with the aim of developing a network of MPAs (des Clers et al., 2008). The data describes the activity of 594 commercial fishers who gave their permission for data to be shared (out of 984 interviewed), over the period of 2005-2010. In the 3 km area around the farm (Supplementary material, Section C: Figure 1), a maximum of 22 mobile and 8 static fishers were sighted. However, in the area within and around the close perimeter of the farm area, 17 mobile and 3 static gear fishers were sighted, with the tracks of 2 mobile and 3 static gear fishers actually intersecting the farm area (Figure 5.2). However, the boats may not have been fishing when intersecting the farm area, it is possible that they could have been travelling between fishing efforts. Although many boats use both mobile and static gear methods and switch between the two methods over years and seasons, this is the most accurate data readily available on fishing boat activity by gear type.

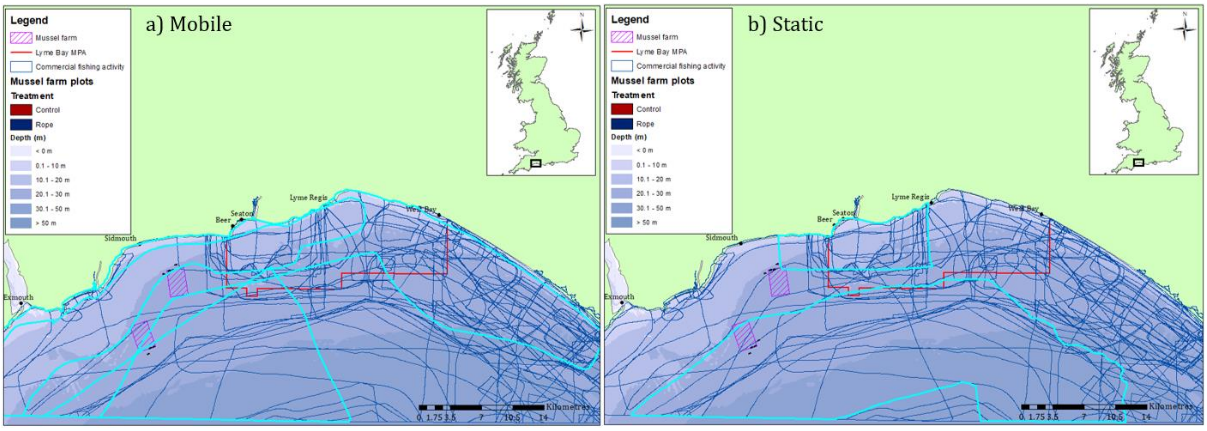

Figure 5.2: Commercial fishing boat tracks crossing the mussel farm area from vessels using a) mobile and b) static gear.

The questionnaire was targeted at adults (over 18) who own or skipper fishing vessels that fish in Lyme Bay. Participants were located through fishing associations, word of mouth and through opportunistic meetings at local ports. The questionnaire (Supplementary material, Section C) was split into two main sections with questions aimed at mobile gear fishers (Section A) and static gear fishers (Section B). All participants were then asked about their personal views on the Lyme Bay mussel farm (Section C) and socio-demographic data was collected.

Sections A and B used dichotomous questions (yes or no), which could then be expanded on with following open-ended questions. These sections gathered information on the fishers' target species, average catch in tonnes and primary fishing ground. They were also designed to identify fishers that fish or have fished in the area around the mussel farm, and whether they had noticed any difference in catch in that area. Fishers were presented with a map of Lyme Bay showing the MPA and the mussel farm with a 3 km buffer and asked to identify any areas where they fish within Lyme Bay, within the buffer, or within the mussel farm itself.

In order to elicit fishers' attitudes towards the mussel farm in Section C, respondents were asked two questions where responses were given on a Likert scale. On the first of these questions, ‘How much has the development of the open ocean mussel farm affected your decision as to where you fish in Lyme Bay?’, respondents ranked their opinion on a scale of 0 – 10 where 0 = no effect and 10 = a large effect. On the second question, ‘To what extent do you support the development of the open ocean mussel farm in Lyme Bay?’, 0 = completely against, and 10 = completely support. Qualitative data were also gathered from open-ended questions relating to the respondents’ views on the mussel farm.

Interviews took between ten minutes and two hours. They were recorded with a Dictaphone and transcribed afterwards to ensure that no answers or comments were missed.

5.2.3 Secondary data

Landings data by ICES rectangle was used to assess how catches have changed from the beginning of the development of the mussel farm (2013) to five years on (2017). Ports within ICES rectangles 30E6 and 30E7 were included, and catch data were split into mobile and static fishing gear types. Specific landings data were extracted for brown crabs *Cancer pagurus*, common whelk *Buccinum undatum* and schooling fish (Atlantic horse mackerel *Trachurus trachurus* and whiting *Merlangius merlangus*).

5.2.4 Data analyses

Data provided by respondents from the Likert scale questions are presented as a histogram showing the number of fishers that scored each number on the Likert scale.

The qualitative responses gathered in the interviews were extracted and analysed using NVivo12 (QSR International). This text analysis software allows open-ended questions to be analysed through coding of themes. Responses were coded into a framework of statements relating to how the fishers feel about the mussel farm, whether it is affecting their fishing activity, whether they think it will have any positive or negative effects and whether they received sufficient information prior to the development of the farm. Statements relating to other issues regarding the mussel farm and other issues not specific to the mussel farm were also coded. These statements were further coded into themes, which were either positive, neutral or negative.

A General Linear Model in Minitab 18 was used to determine whether there was a significant difference in the number of positive, neutral and negative statements between fishers using the two different fishing gear types. One fixed factor was used: Fishing gear (2 levels: Mobile, Static).

Areas where respondents identified that they fish were georeferenced onto a map showing all fishing areas using ArcGIS (version 10.5.1). Total landings data (landed weight and value), split into mobile and static gear, and landings data for *C. pagurus*, *B. undatum* and schooling fish are presented as bar and line charts.

5.3 Results

5.3.1 Fishing activity

Nine fishers were interviewed; all of whom were male within four age groups: 26-35 (1), 36-45 (1), 46-55 (4) and 56-65 (3). Two of the fishers used mobile gear (trawlers), six used static gear (potters and netters), and one used both mobile and static gear (Table 5.1). This fisher (Fisher 1) predominately used mobile gear so was included as a mobile gear fisher in analyses. All three fishers using mobile gear, and three of the six fishers using static gear had fished within the 3 km area around the farm.

Table 5.1: Details of fishers interviewed. Estimated values per fishing trip based on ICES catch statistics (* value only estimated for crabs, average catch for other species is unknown).

Fisher ID	Home port	Boat length (m)	Fishing type M = mobile S = static	Target species	Average catch per fishing trip (tonnes)	Estimated value per fishing trip (£)
1	Axmouth	< 10	M+S	Crab, lobster, plaice, sole, thornback ray	1 – 1.5	3,500
2	Brixham	< 10	S	Crab, lobster, plaice, cod, pollack, cuttlefish, bass	0.1*	300*
3	Brixham	> 10	M	Plaice, cuttlefish, Dover sole, lemon sole, squid	1	800 – 2,000
4	Exmouth	< 10	S	Crab, lobster, cuttlefish, whelk	1	750 – 2,300
5	Exmouth	< 10	S	Whelk	1	1,200
6	Lyme Regis	> 10	M	Plaice, skate, cuttlefish, bass, squid, whiting	1	4,400
7	Lyme Regis	< 10	S	Dover sole	0.2	2,600
8	Lyme Regis	< 10	S	Whelk, sole	0.6	650
9	Lyme Regis	< 10	S	Whelk, crab, lobster, sole	0.6	650 – 1,100

All of the mobile gear fishers interviewed still fished around the outside of the farm (Table 5.2). Two of these fishers noticed changes in their catch around the mussel farm: one commented on larger numbers of skate and suggested it could be a result of mussels on the seabed. The other fisher commented *'I think the fishing did improve slightly to be fair'* and *'it seemed like the closer you go to it* [the mussels farm] *the more cuttle you were seeing'*. When asked why they thought this was, they said they thought it was an effect of the mussel farm e.g. *'they're* [the mussels] *discharging quite a lot of stuff and I think that attracted a bit of fish'* and *' it's a bit of a safe haven for them'*. As a result, both of these fishers had chosen to fish around the mussel farm over other fishing sites (Table 5.2). Fisher 6, who identified whiting *M. merlangus* as a target species did not state that they had seen a difference in their catch of this species around the mussel farm.

Table 5.2: Fishing activity of mobile gear fishers.

Mobile gear fishers (n = 3)	Yes	No
Have you ever fished in the area where the mussel farm is situated? (n = 3)	3	0
Do you still fish around the outside (within 3 km) of the mussel farm? (n = 3)	3	0
Have you noticed any changes in your catch around the mussel farm? (n = 3)	2	1
Have you chosen to fish around the farm over other sites? (n=3)	2	1

Two of the three static gear fishers that had fished in the 3 km area around the mussel farm still fished in or around the outside of the farm but had to change where they put their gear e.g. *'they've put their farm over some of the crabbing ground so we can't get in there'* (Table 5.3). Fisher 5, who solely targeted whelk *B. undatum* had noticed negative changes in their catch around the mussel farm and blamed the *'blankets of starfish feeding on the mussels that have fallen off'*. Despite this, one of the fishers that worked around the mussel farm still chose to fish there over other sites (Table 5.3) as they thought it was still a better fishing ground. When asked how their catch had changed, Fisher 9 commented on the low number of brown crab *C. pagurus* in general, *'it's been dire this year compared to other years'*.

Table 5.3: Fishing activity of static gear fishers.

Static gear fishers (n = 6)	Yes	No
Have you ever fished in the area where the mussel farm is situated? (n = 6)	3	3
Do you still fish in or around the outside (within 3 km) of the mussel farm? (n = 3)	2	1
Have you had to change where you put your gear? (n = 2)	2	0
Have you noticed any changes in your catch around the mussel farm? (n = 1)	1	0
Have you chosen to fish around the farm over other sites? (n = 2)	1	1

The map showing the areas where respondents had identified that they fish in Lyme Bay (Figure 5.3) shows that the mussel farm is located close to crabbing ground (blue squares) and in the middle of whelking ground (green squares). There is also an area of old crabbing ground (orange squares), known as The Exeters, which was destroyed by heavy trawling (Mangi et al., 2011). Black lines show the trawling paths of the three active fishers who all fished around the mussel farm.

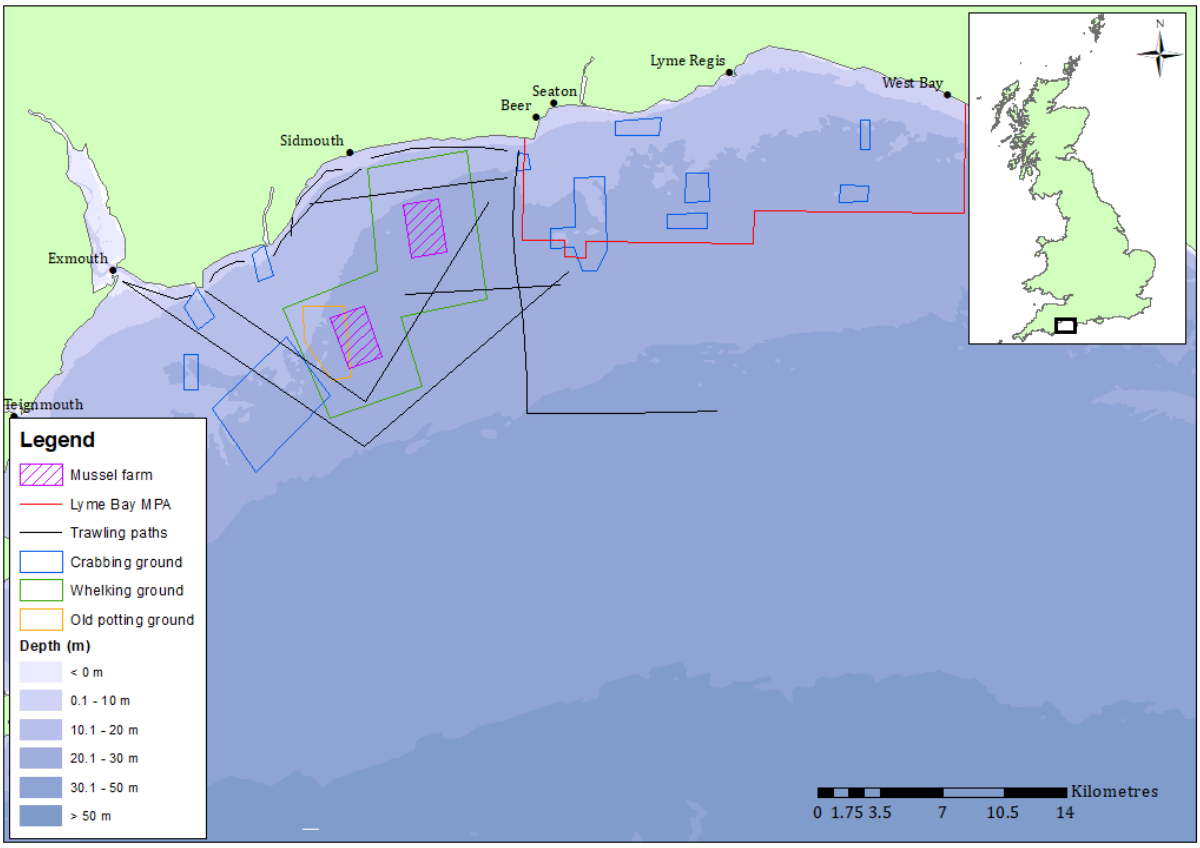

Figure 5.3: Map of Lyme Bay showing trawling paths (black lines), crabbing ground (blue squares) and whelking ground (green squares), and old potting ground (orange squares) around the mussel farm (purple hatched areas) and MPA (red outline).

5.3.2 Perceptions of fishers

The most common response to the question 'How much has the development of the mussel farm affected your decision as to where you fish in Lyme Bay' was 0 – no effect; which was scored by one mobile and three static gear fishers. There were another three responses that were low or towards the middle of the Likert scale (2-4), however two static fishers responded high on the scale with scores of 8 and 10 (Figure 5.4a). When asked 'To what extent do you support the development of the mussel farm in Lyme Bay?' fishers either responded at the two extremes of the scale, or in the middle. Four fishers (one mobile and three static gear) responded that they are completely against the development of the mussel farm (0), one static gear fisher said they are in complete support (10), and the other four fishers gave scores of 4 and 5 (Figure 5.4b).

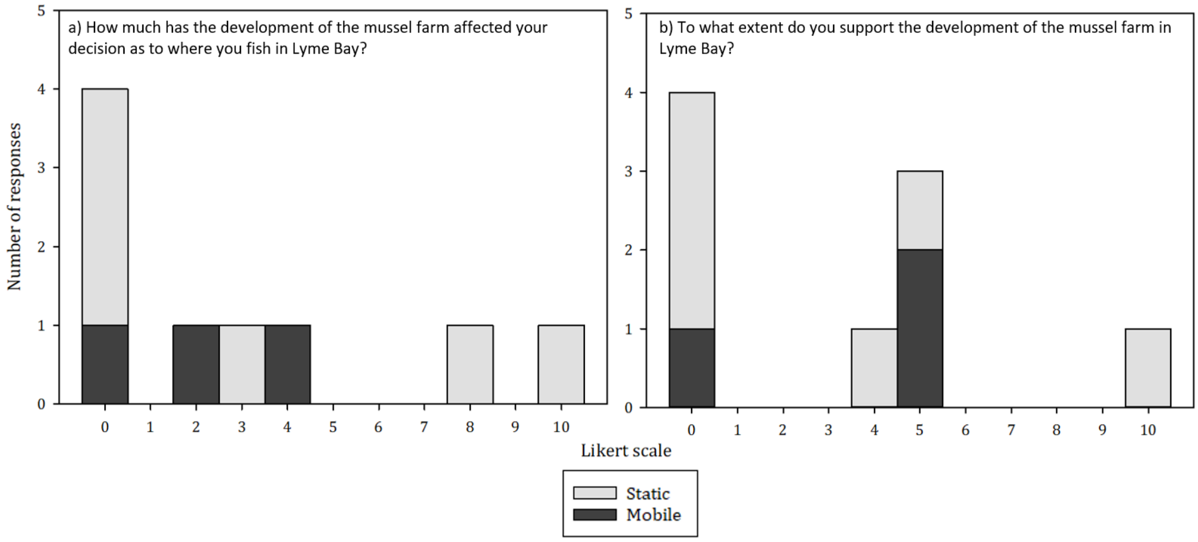

Figure 5.4: Number of responses from mobile and static gear fishers to Likert scale questions a) 'How much has the development of the mussel farm affected your decision as to where you fish in Lyme Bay?', and b) 'To what extent do you support the development of the mussel farm in Lyme Bay?'.

The most common statement under the theme of how fishers feel about the development of the mussel farm was that they were concerned about the size of the farm and it taking up fishing ground (7 sources, 13.67 % of total statements; Table 5.4) e.g. *'They just took too much ground away'* and *'it's colossal'*. However, four of the fishers commented that they have no issues with the mussel farm (4.32 % of total statements; Table 5.4). When talking about whether the mussel farm is affecting fishing activity, the most common statement was that it is (4 sources, 14.39 % of total statements; Table 5.4) e.g. *'It's impounded our netting a lot'* and *'used to fish all along there, now can't whelk any of that'*.

When discussing whether the mussel farm will have any other positive or negative effects, five fishers recognised the potential for farms to increase fish stocks (5 sources, 4.32 % of total statements; Table 5.4), and jobs in the area (2 sources, 2.16

% of total statements; Table 5.4). However, there was a concern raised regarding waste production from mussels (2 sources, 2.88 % of total statements; Table 5.4).

When asked whether they had received enough information prior to the development of the farm, the most common statement was that they had received no information (4 sources, 7.19 % of total statements; Table 5.4) e.g. *'they just plonked it* [the mussel farm] *there, didn't speak to any of us fishermen that are using that area'* and *'it just started appearing*'. A frequent other comment about the mussel farm was that it was too far away to fish there (3 sources, 5.04 % of total statements; Table 5.4). One fisher also commented that they had eaten mussels from the farm and they were *'gorgeous'* and *'some of the best mussels I've had. Massive things!'*.

Other issues brought up that were not specific to the development of the mussel farm were the general overall loss of fishing ground over the years (4 sources, 7.91 % of total statements; Table 5.4) and the unsatisfactory management of fisheries in Lyme Bay (2 sources, 3.60 % of total statements; Table 5.4). For example, one fisher commented that *'they've shut down a lot of trawl ground that we used to fish'* and another referred to the *'bad fishing management by the people who manage the fisheries*'.

Table 5.4 Key themes and statements raised by fishers.

Theme	No. of fishers	No. of comments	% of total
How do you feel about the development of the mussel farm?	**n = 9**	**31**	**22.30**
Concerned about the size of the farm and it taking up fishing ground	7	19	13.67
Have no issues with the mussel farm	4	6	4.32
Commented that the mussel farm should have been placed within the MPA	2	5	3.60
Said the development of the farm is a good thing	1	1	0.72
Is the mussel farm affecting your fishing activity?	**n = 9**	**32**	**23.02**
Yes, it is affecting my fishing activity	4	20	14.39
No, it has had no effect on my fishing activity	2	5	3.60
No effect now, but there may be in the future	1	2	1.44
No effect for me, but there is for other fishers	2	5	3.60
Do you think the mussel farm will have any other positive or negative effects?	**n = 7**	**15**	**10.79**
Recognised potential for farm to increase fish stocks	5	6	4.32
Recognised creation of jobs and income for the area	2	3	2.16
Concerned about waste from mussels	2	4	2.88
Does not think there will be any	2	2	1.44
Did you receive any information prior to the development of the farm?	**n = 8**	**19**	**13.67**
Received information	3	7	5.04
Received some information but not enough	1	2	1.44
Received no information	4	10	7.19
Other comments	**n = 5**	**20**	**14.39**
Mussel farm is too far away for them to fish there	3	7	5.04
Have noticed mussel spat covering pots	1	3	2.16
Commented on the mussels tasting good	1	2	1.44
Have collected and used the mussel farm buoys that break free from anchors	1	2	1.44
Use the farm to catch mackerel for bait	1	2	1.44
Has been involved in sustainable fishing outreach	1	4	2.88
Other issues not specific to the mussel farm	**n = 5**	**22**	**15.83**
Referred to overall loss of fishing ground	4	11	7.91
Think there is a general lack of concern for the needs of fishers in Lyme Bay	2	5	3.60
Referred to unsatisfactory fishing management	2	5	3.60
Stopped trawling because of the MPA	1	1	0.72

In total, active gear fishers made 20 positive and 43 negative comments, with an average of 6.66 ± 3.18 positive comments and 14.33 ± 4.98 negative comments per fisher (Figure 5.5). Static gear fishers made 25 positive, 9 neutral and 42 negative comments, with an average of 4.17 ± 1.66 positive comments, 1.50 ± 0.72 neutral comments and 7.00 ± 2.73 negative comments per fisher (Figure 5.5). There were no statistically significant differences between number of positive, neutral or negative statements and fishing gear type (all $P > 0.05$; Table 5.5).

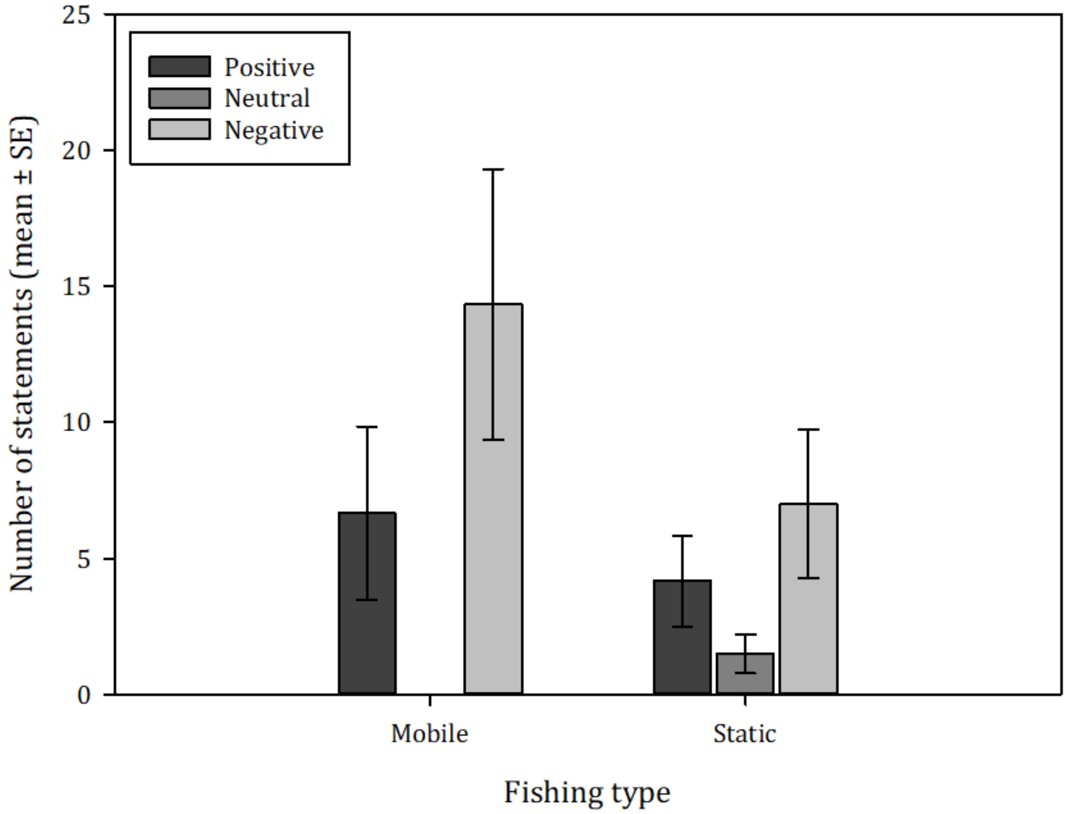

Figure 5.5: Number of positive, neutral and negative comments (mean ± SE) made by mobile and static gear fishers.

Table 5.5: Results from General Linear Model to test the difference in number of positive, neutral and negative comments made by mobile and static gear fishers. Based on untransformed data.

Source	df	Adj SS	Adj MS	F-value	P-value
Positive					
Fishing gear type	1	12.50	12.50	0.61	0.46
Error	7	14.50	20.50		
Total	8	156.00			
Neutral					
Fishing gear type	1	4.50	4.50	2.03	0.20
Error	7	15.50	2.21		
Total	8	20.00			
Negative					
Fishing gear type	1	107.60	107.56	2.02	0.20
Error	7	372.70	53.24		
Total	8	480.20			

5.3.3 Landings data

Total landings from mobile gear increased in Lyme Bay from 2013 to 2017. Landed weight increased from 15,333.70 tonnes in 2013 to 16,388.06 tonnes in 2017, with value increasing from £25.9 million to £43.8 million (Figure 5.6a). Landings of high value cuttlefish mainly contributed to this increase in value. Total landings from static gear increased from 2013 to 2016 and then decreased in 2017. In 2016, there was a peak in the landings of common whelk *Buccinum undatum* and cuttlefish species, which then declined again in 2017. Value of landings increased from 2013 to 2017. Landed weight was 2,266.55 tonnes in 2013 (value of £3.5 million) and 1,867.51 tonnes in 2017 (value of £3.9 million) (Figure 5.6b).

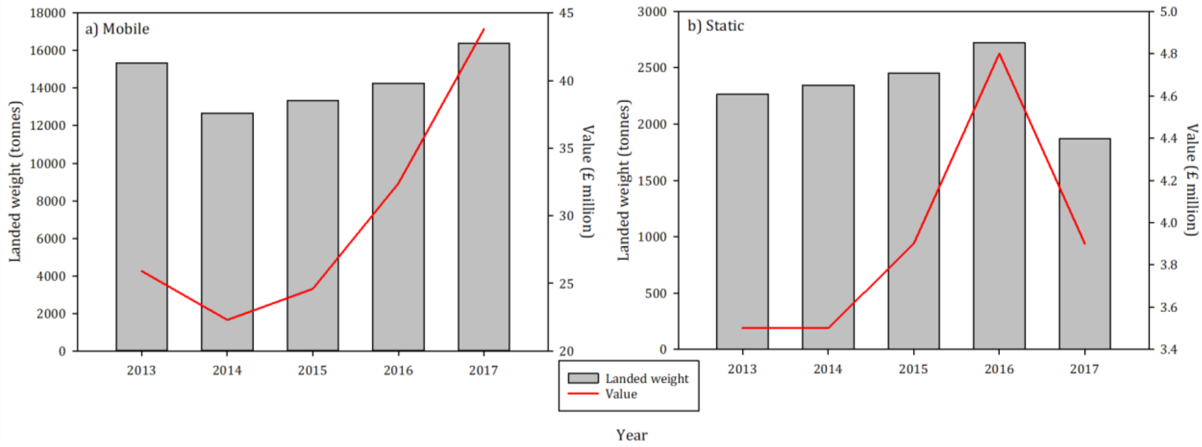

Figure 5.6: Total landed weight (tonnes) and value (£ million) in Lyme Bay from 2013-2017 from a) mobile, and b) static gear.

Landed weight of brown crab *Cancer pagurus* increased from 2013 to 2017 (2013 = 591.24 tonnes, 2017 = 668.58 tonnes; Figure 5.7a), with value reaching £1.4 million in 2017. Landed weight of *B. undatum* increased from 2013 (1,103.52 tonnes) to 2016 (1,607.43 tonnes) but decreased in 2017 (918.53 tonnes) (Figure 5.7b). Despite this, value of landings was greater in 2017 than in 2013 (2013 = £825,422, 2017 = £1 million; Figure 5.7b). Both landed weight and value of schooling fish (Atlantic horse mackerel *Trachurus trachurus* and whiting *Merlangius merlangus*) decreased overall from 2013 to 2017. Landed weight decreased from 266.55 tonnes in 2013 to 153.74 tonnes in 2017, and value decreased from £187,801 in 2013 to £98,716 in 2017 (Figure 5.7c).

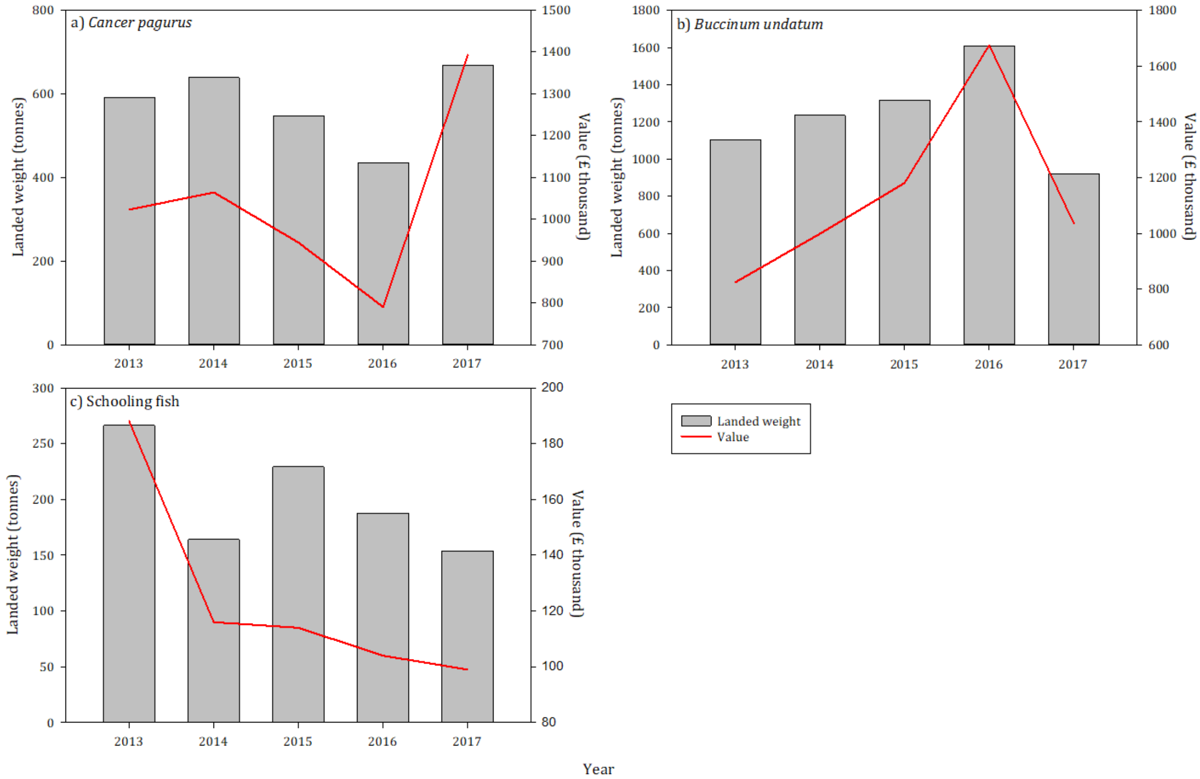

Figure 5.7: Landed weight (tonnes) and value (£ thousand) of a) brown crab *Cancer pagurus*, b) common whelk *Buccinum undatum*, and c) Schooling fish from 2013-2017 in Lyme Bay.

5.4 Discussion

The development of the open ocean mussel farm has affected the fishing activity of commercial fishers in Lyme Bay and elicited both positive and negative perceptions from fishers. In this study, the impacts of the aquaculture installation on commercial fishers were examined in order to evaluate any changes that have occurred after its closure to bottom towed fishing activities.

Three mobile gear fishers, who use otter trawls, were directly displaced from an area of their usual fishing ground because of the installation of the mussel farm. All three of the fishers were concerned about the size of the farm, commenting that they would not want it to get any bigger and take up more fishing ground. However, all three also recognised some potential for the farm to have a positive ecological effect on fish stocks in the area, or have a positive economic effect through the creation of jobs and increase in income for the area. Despite being displaced from some of their fishing ground, one mobile gear fisher said that the farm is not negatively affecting their fishing activity as now they choose to fish around the perimeter of the farm, close to the location of the Special Mark buoys that mark out the farm boundary. This fisher also has a good relationship with the mussel farm workers, often swapping fish for mussels.

The six static gear fishers, using pots and nets, were also concerned about the mussel farm taking up fishing ground, even if they were not directly affected by the farm themselves. Two fishers were concerned on behalf of the mobile gear fishers, and one was concerned that trawlers being displaced from some of their fishing ground could have knock-on effects for static gear fishers, as they might migrate into potting areas leading to concentrated fishing. There had previously been displacement from a large area of their fishing ground as habitats were destroyed by bottom towed fishing (Mangi et al., 2011), which could have exacerbated their concern of the area the mussel farm is taking up. However, a very small area, in comparison to the MPA, has been taken up by the mussel farm. Four fishers commented on the general loss of ground in the area, and so, if Lyme Bay did not already have a large area closed to bottom towed fishing, the fishers may have been less concerned about the loss of area occupied by the mussel farm. There were also comments on the unsatisfactory management measures in Lyme Bay. Somewhat surprisingly, as they are still able to fish there, the static gear fishers were less positive than the mobile gear fishers were, although three recognised the potential for the farm to increase fish stocks, acting as a safe place with a rich food source.

As well as the mussel farm taking over fishing ground, the other main issue that the commercial fishers brought up was the lack of information provided by the mussel farm. Two thirds of the fishers said that they either received no information prior to the development of the farm, or felt that the information provided was insufficient. However, it is unclear as to whether these fishers were not consulted at all, or whether they did not respond during the consultation phase. Prior to development, contact was made with fishers who used within the proposed development area and the final location was refined because of meetings with both mobile and static gear fishers. Engaging fishers in policy and management is not easy, as they spend many hours at sea, and have unpredictable schedules (Nutters and da Silva, 2012). However, increasing communication with fishers can improve their feeling of empowerment and make them feel more part of the decision-making process, which helps alleviate stakeholder dissatisfaction (Pomeroy and Douvere, 2008).

Chapter 4 showed observational evidence of a greater abundance of brown crab *Cancer pagurus* in the mussel farm, seen feeding on clumps of mussels that had fallen to the seabed. Furthermore, Chapter 3 found that *C. pagurus* were also living on the ropes themselves, having settled as larvae and grown within the mussel matrix. National landings data for *C. pagurus* shows a decline in landings from 2016-2017. However, landings data from ICES rectangles 30E6 and 30E7, which includes the Lyme Bay MPA and the mussel farm, show that the landed weight of *C. pagurus* has increased from 2016 to 2017, and landings have significantly increased for static gear fishers operating both inside and outside of the MPA (Rees et al., 2016). This may be a result of MPA management, enabling spatial separation of gear (Rees et al., 2016), recovery of the reef habitat (Sheehan et al., 2013) and wider fisheries management to support the *C. pagurus* fishery (Rees et al., 2021). In terms of the

Lyme Bay MPA, as the reef habitat which *C. pagurus* uses recovers from the effects of bottom towed fishing, abundance of *C. pagurus* increased (Sheehan et al., 2013). Furthermore, *C. pagurus* makes use of space under boulders and within crevices in reefs (Hayward and Ryland, 1995). It is possible that the mussel farm may also support the crab fishery as mussels build up on the seabed (as shown in Chapter 4) forming reefs which may also provide attractive living spaces for brown crabs, and with the mussels themselves also providing a food source (Neal and Wilson, 2008). However, this effect was not experienced by the two fishers who pot for crabs in and around the perimeter of the mussel farm.

Chapter 4 found a trend towards a greater abundance of common whelk *Buccinum undatum* within the mussel farm compared to control areas that were still being heavily fished by demersal trawlers. *B. undatum* occur in a wide variety of habitats, feeding on bivalves, among other food sources (Scolding et al., 2007). Landings from static gear fishers operating outside of the Lyme Bay MPA are dominated by whelk, though catch is declining over time (Rees et al., 2016). There is evidence that the overall decline in landings could be due to unregulated landing sizes, with immature whelks being landed (Lawler, 2013). Landings data from ICES rectangles 30E6 and 30E7 show a decrease in whelk landings from 2016 to 2017. Borsetti et al. (2018) showed that current EU minimum landing size of whelk tends to fall below the estimated size of maturity, which potentially increases the risk of recruitment overfishing (de Vooys and ven der Meer, 2010). Devon and Severn Inshore Fisheries and Conservation Authority (D&S IFCA) reviewed the minimum landings size of *B. undatum* concluding that it was too low (Stephenson, 2015), and have since raised the minimum landing size from 4.5 cm to 5.5 cm (D&S IFCA, 2018).

Abundance of *B undatum* increased in the mussel farm between 2016 and 2017. This could be a result of reduced fishing effort within the mussel farm as fishers found it more difficult to deploy pots around the mussel headlines, despite the farm being designed to allow this. Furthermore, *B. undatum* are scavengers (Nielsen, 1974), so could be benefitting from the increase in mussels as food on the seabed. Therefore, the mussel farm could be allowing the abundance of *B. undatum* to increase within the farm area. However, fishers did not notice an increase in *B. undatum* in their catch in and around the perimeter of the mussel farm, and the fisher who solely targets *B. undatum* noticed a decrease in their catch, blaming an increase in starfish predation. There is ecological evidence for this observation; Chapter 4 showed an increase in the abundance of common starfish *Asterias rubens* in the mussel farm from 2013 to 2017.

There was also evidence for a greater abundance of schooling fish (Atlantic horse mackerel *Trachurus trachurus* and whiting *Merlangius merlangus*) in the mussel farm compared to control areas, both in the pelagic (Chapter 3) and epibenthic (Chapter 4) ecosystems. This could be a result of two factors. Firstly, the exclusion of bottom towed fishing within the mussel farm could be allowing fish stocks to increase in that area. Secondly, the mussel farm structures (e.g. rope droppers) are causing the farm to act as a fish aggregation device (FAD; Kingsford, 1993). Despite landings of schooling fish decreasing from 2016 to 2017, one trawler said that they had noticed a slight increase in overall catch around the edge of the mussel farm, choosing to fish there over other fishing sites.

There is some evidence that the abundances of some commercial species are increasing within the mussel farm. However, there is not sufficient agreement between this evidence and the fishers' landings. It may be that spillover into fishing areas has not yet occurred. Spillover effects may take years to be noticed by fishers, with benefits often not seen for 5-20 years depending on the initial population size and life span of the species, and overall health of the ecosystem (Wu et al., 2009; Aburto-Oropeza et al., 2011; Cuervo-Sánchez et al., 2018).

Despite changes in spatial management measures linked to the Lyme Bay MPA and the mussel farm, total landings and income increased overall from 2013 to 2017 for both mobile and static gear fishers in Lyme Bay. For those species targeted by fishers close to the mussel farm (*C. pagurus*, *B. undatum* and schooling fish), Lyme Bay landings data indicates that there has been variation in landings of *C. pagurus* and *B. undatum*, but with an overall increase over time, and a decline in landings of schooling fish *T. trachurus* and *M. merlangus*. Ecological evidence from the mussel farm indicates an increase in the abundance of *C. pagurus* and *B. undatum*. How this translates to landings data for fishers operating near the farm in tenuous, as it is known that fishers switch their gear type throughout the year in response to available species, to take advantage of market prices, or in response to management events and other factors (Rees et al., 2016). For example, in this survey, one fisher commented that they had changed from mobile to static gear in response to the designation of the MPA, and one no longer uses pots as they get backache.

Effective management of the growing aquaculture sector requires input from stakeholders to understand how the industry affects local communities (Salgado et al., 2015). Greater communication with the fishers could also have reduced the negative perceptions associated with mussel farms as it allows managers to respond to stakeholder concerns with scientific evidence (Salgado et al., 2015). For example, two fishers in the study were concerned about waste production from mussels. If managers frequently engaged with fishers, they could explain the benefit of open ocean mussel farming in regards to reduced benthic effects resulting from greater depth and distance from shore, and faster currents which help flush waste away (Holmer, 2010). As aquaculture is one of the fastest growing food producing sectors (Lem et al., 2014), it is important that installations are properly managed to ensure their sustainability on both the ecology and economy of the local area. As with the implementation of MPAs, it is important to ensure that positive human well-being outcomes are realised to ensure the acceptance of new aquaculture developments (Ban et al., 2011). However, this requires investment in the underpinning social and economic research that can more accurately describe these trends in the long-term.

There is some agreement among the commercial fishers of Lyme Bay that the open ocean mussel farm has the potential to provide a provisioning ecosystem service of enhancing wild fisheries due to its supporting ecosystem service of providing an artificial habitat. This study sets a baseline on effects of the Lyme Bay mussel farm on fishing activity and the perceptions of commercial fishers to the farm. It would be beneficial to repeat the survey when the mussel farm is fully developed to see if the farm is enhancing wild fisheries and whether perceptions have changed as the full effects of the mussel farm on the ecology and economy are more realised.

5.5 Conclusion

Despite being offshore where competition with other activities is reduced, there is still conflict between the Lyme Bay mussel farm and local commercial fishers, mainly due to the farm taking up fishing ground, the perceived lack of information provided prior to the development of the farm and the lack of obvious short-term benefits to landings. The results of this study may help guide policy recommendations for what mussel farm developers should be aware of when considering perceptions of local stakeholders.

Chapter 6: General Discussion

6.1 Introduction

This thesis has taken a holistic approach to the monitoring of mussel aquaculture installations. Previously, studies on the impacts of aquaculture have been focussed on one element of the surrounding environment, typically either effects on the sediment and associated infauna, or the water column and associated plankton. However, with the steady increase in global mussel aquaculture (FAO, 2020), a universal monitoring system is needed to ensure that existing and future mussel farms are managed sustainably. Offshore aquaculture is being increasingly accepted as a mechanism to meet the growing demand for seafood (Froehlich et al., 2017), where there is a higher capacity for nutrient assimilation and less conflict for space (Holmer, 2010; Froehlich et al., 2017). However, research on offshore/open ocean farms remains scarce compared to coastal farms.

This thesis was focused on addressing the following objectives:

1. Develop and pilot a holistic monitoring programme for the assessment of long-line mussel farms
2. Assess the effect of the mussel headlines on the benthic and pelagic ecosystems, and perceptions of local fishers
3. Provide recommendations for future monitoring

The following is an overview of how this thesis addressed each of these objectives:

6.2 Develop and pilot a holistic monitoring for the assessment of long-line mussel farms

The study farm used in this thesis is the UK's first large scale open ocean long-line mussel farm, currently under development in Lyme Bay, south Devon (Chapter 2). Trial headlines at the farm were used to pilot a monitoring programme aimed at assessing the effects of the headlines on the benthic and pelagic ecosystems.

Chapter 3 used methods developed to assess the pelagic ecosystem. Pelagic fishes were monitored using custom-made PelagiCam units. These units were developed as an alternative to methods used in existing literature, which disturbed fish behaviour and led to low counts of pelagic fishes. The methods used in this thesis were successful in the recording and analysis of pelagic fishes around mussel rope droppers. The PelagiCam units are non-destructive, easy to maintain, and the video resolution used on the GoPro cameras gave extremely clear footage. Epibiota on the ropes were also successfully surveyed, with sampling taking place on differently aged mussel ropes showing the succession of epibiota settlement. The methods used to sample plankton, however, may not have given accurate results on the effects of the mussel headlines. The use of the plankton net and vertical haul itself is an effective way of collecting plankton, but a different sampling design may be needed to obtain information on the true effect of mussel farms on the zooplankton community. Furthermore, sampling did not occur before any headlines were installed which made it difficult to conclude whether there was no effect of the headlines, or if the influence of the headlines extended into the control locations.

Chapter 4 used methods developed to assess the benthic ecosystem. All three video methods were useful in their own right for sampling epibenthic fauna under the headlines and in control locations. The towed underwater video system (TUVS) was efficient in sampling next to the mussel headlines and in control areas. However, it is unable to sample beneath the headlines. In this instance, a remotely operated vehicle (ROV) with a GoPro camera was used. This allowed the seabed directly underneath the headlines to be surveyed, and revealed the extent of mussel cover, which was lost in some locations from the TUVS footage that was taken next to the headlines rather than underneath. The baited remote underwater video (BRUV) units were used to record mobile species that would have been missed by the TUVS and ROV. Indeed, the BRUV survey recorded seven species that were not recorded in the TUVS and ROV surveys. The Shipek grab chosen to sample the seabed did not perform as well as the video methods. It was chosen initially as the exact characteristics of the seabed were unknown before the study, and it has been recommended for use in such situations (Kirby et al., 2018). However, throughout the survey there were problems with the grab 'misfiring' and coming up empty. This lengthened the survey day and sometimes caused the survey to have to run over onto a second day, which increased costs and staff time. Furthermore, it has been shown to collect fewer benthic invertebrates per square metres than other grabs (Caires and Chandra, 2012), so using another grab may have given conclusive results not provided by the Shipek grab.

In Chapter 5, a questionnaire was trialled, designed to gain information on the perceptions of local fishers. This questionnaire had three sections; one designed for mobile gear fishers, one designed for static gear fishers, and one aimed at gathering personal views on the Lyme Bay mussel farm. Dichotomous and Likert scale questions alongside open-ended questions allowed the collection of both quantitative and qualitative data. Managing to persuade fishers to talk and take time out their day proved to be difficult, although once they were interviewed, they often gave names of others who may be willing to participate. This method of gathering respondents worked well.

Four video and three physical sampling methods were trialled, along with the questionnaire, in order to assess the effects of the mussel headlines on the surrounding environment and local fishers. It is apparent that some methods were more effective than others, the results of which are summarised in the next section.

6.3 Assess the effect of the mussel headlines on the benthic and pelagic ecosystems and perceptions of local fishers

Results from Chapter 3 highlight that the mussel headlines are acting as fish aggregation devices (FADs), with pelagic fishes filmed around the mussel rope droppers. This was attributed to the addition of hard structure and food source. Furthermore, fishes were more heavily aggregated around headlines growing one-year-old and two-year-old mussels. The species richness of epifauna was also greater on these headlines. There was no apparent effect of the mussel headlines on the species richness and abundance of zooplankton. Results showing the assemblage composition of zooplankton showed that differences over time were similar among treatments. This could mean either that the headlines are having no detectable effect on the zooplankton community, or that the control locations are not beyond the influence of the farm.

Results from Chapter 4 illustrate that there has been a significant change to the epibenthic habitat, with cover of both live and dead mussels on the seabed reaching ~ 25 % after four years of headline deployment. There has been no significant change to the organic content or mean particle size of the sediment, although these results highlighted the difference between the two mussel farm sites. Redox potential has started to show signs of change resulting from the mussel headlines, with values identifying sediment beneath the headlines as polluted towards the end of the survey. Large numbers of schooling fish underneath the headlines led to differences in mobile epifauna abundance and assemblage composition between farm and control locations. Abundance of common starfish *Asterias rubens* was influenced by mussel cover on the seabed and European lobster *Homarus gammarus* was exclusively recorded within the farm.

Chapter 5 identified that the most common issues surrounding the mussel farm development are that the farm area is taking away too much fishing ground and that there was a perceived lack of information provided prior to development. Trends for increases in commercial species from Chapters 3 and 4 were not in full agreement with fishers catch and landings data, suggesting that any potential spillover of these species into fishing grounds is not apparent.

It is possible that if different methods or sampling equipment was used, results that are more conclusive will have been derived on the effects on zooplankton, sediment and infauna. Suggestions of amendments to the piloted monitoring programme are detailed in the next section.

6.4 Provide recommendations for future monitoring

As concluded above, the PelagiCam units were an effective means of monitoring pelagic fishes and so no amendments would be recommended for this survey. Although the rope assemblage survey was successful in monitoring smaller epibiota, it missed the larger organisms such as urchins and starfish, which were more sparsely located throughout the length of the rope, but have been reported by the mussel farmers as very abundant. Future research should aim to capture these organisms as well. One method to be considered would be attaching a GoPro camera to the harvesting equipment that brings the rope droppers in and harvests the mussels off the headlines. Video footage would then be analysed to identify larger epibiota. This would enable the monitoring of epibiota that can cause a potential nuisance to mussel farmers, such as starfish and sea urchins. Monitoring these species would be more important to the mussel aquaculture industry as a whole as it would allow areas where this is more likely to be a problem to be mapped and, potentially, avoided.

In regards to plankton sampling, it would be beneficial to start sampling before any headlines are installed. Missing this sampling in this PhD meant that no solid conclusions could be drawn as it is unclear whether the control locations are beyond the influence of the farm. Furthermore, it may be more effective to sample plankton from multiple areas throughout the farm, based on tidal excursions and flow. This would allow conclusions to be drawn as to how far away from the farm effects are seen, and in which direction. It would also be more thorough to sample phytoplankton as well as zooplankton, as this group has also been reported as depleted within mussel farms (Cranford et al., 2008; Frojan et al., 2018). However, for this PhD it would have required more time, expertise and cost for training and equipment. The few headlines in this survey, however, are not enough to be able to discern differences as in a fully functioning mussel farm.

The video methods used have all been effective in their own right for capturing the diversity of taxa within the epibenthic and pelagic ecosystems at the farm and in control areas. It would be beneficial for future research to employ all four video methods. However, combining the TUVS and ROV into just one method would be just as effective in filming the same species and would streamline the monitoring programme for both collecting and analysing video footage, making it more cost-effective. The TUVS is more time and cost-effective and can sample larger areas of the seabed in a shorter space of time; however, it is unable to fly directly beneath the headlines within the mussel farm. Therefore, if just one of these methods were to be employed, the ROV would be more beneficial for monitoring the seabed within a mussel farm. Making sure that the ROV video quality is clear enough for video analysis is also of note. It would not have been possible to identify as many species if I was to rely on using the footage from the ROV itself, so the addition of the high definition GoPro camera was vital for accurate analysis. It is important to incorporate BRUV into the monitoring programme as the mobile species in the epibenthic ecosystem were very rarely filmed by the TUVS and the ROV, and represent a large proportion of the taxa within the epibenthic ecosystem.

The Shipek grab may not have been as effective as other grabs in sampling the infaunal community. Indeed, it has been shown that it samples fewer organisms per metres squared than three other grabs, including the Ekman grab (Caires and Chandra, 2012). On sampling before any headlines were installed, the seabed was found to be mainly soft homogenous sediments and therefore a day grab would have been the most effective (Rogers et al., 2008). However, these typically sample a 0.1 m^2 area of the seabed, which would have been a lot sediment to process and subsampling techniques would have likely been necessary. Furthermore, throughout the survey there were more mussels being sampled in the grab, which became problematic with the Shipek grab 'misfiring'. The Hamon grab has been identified as the most effective for mixed sediments (Boyd et al., 2006), but again this samples 0.1 m^2 of the seabed leading to longer processing times so would not be suitable if time or budget for staff time is short. A further option would be to use diver-collected cores and increase replication. This would allow separate cores to be taken for infauna and sediment analysis, and redox potential would be able to be more accurately measured at depth intervals throughout the core. This method is widely used in the literature for obtaining environmental data for the effects of mussel farms on the benthic environment (e.g. Chamberlain et al., 2001; Lasiak et al., 2006; Callier et al., 2007), and so would be a suitable method for future surveys.

6.5 Final conclusions

As the productivity of our ocean is being challenged by overfishing (Pauly and Zenner, 2016; Rousseau et al., 2019), aquaculture is now one of the fastest growing food producing sectors (Lem et al., 2014). It has also been recognised as one of the five sectors with the potential to contribute to Blue Growth (European Commission, 2012), and has the potential to play a major role in feeding the 9 billion humans predicted to be on Earth by 2050 (Duarte et al., 2009). Despite aquaculture developments moving further offshore (Clavelle et al., 2019) and mollusc aquaculture identified as one of the lowest impact source foods (Hilborn et al., 2018), research on open ocean mussel farms remains scarce. It is important to understand how open ocean mussel aquaculture will affect ecosystems.

This thesis has developed and piloted a monitoring system for existing and future mussel farms, whilst highlighting the strength of taking an interdisciplinary approach to research the effects of an open ocean mussel farm. It has drawn on ecological and social aspects of aquaculture development and demonstrated the importance of surveying the whole ecosystem as well as local stakeholders. Effective management of marine space cannot rely on ecological evidence alone; it requires input from local stakeholders to ensure that the needs of other marine users are taken into account. The sustainability of the Lyme Bay mussel farm, and overall sustainable growth of the aquaculture sector, will be influenced by both ecological and socio-economic factors, with success also reliant on the acceptance of stakeholders.

This thesis has provided research that has increased the evidence base available to policy makers that could be used to help guide the initiative to move aquaculture installations offshore, supporting the Blue Growth agenda. It can also inform Maritime UK South West (MUK SW) which brings together the ocean economy of South West England to grow the marine sector. As part of MUK SW, The South West Aquaculture network aims to sustainably enhance aquaculture production and feed into the developing Great South West strategy to support initiatives for sustainable development.

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Supplementary material

Section A: Chapter 3

Table 1: a) Results from PERMANOVA analysis to test the difference in abundance of *Trachurus trachurus* between Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 1-4), and b) Results from Pairwise test used to examine the difference between Treatments for the significant interaction term Ti x Tr(TS). Based on the Euclidean distance of square root transformed data. Bold values indicate statistically significant results.

a)

Source	df	SS	MS	Pseudo-F	P(perm)
Ti	3	132.71	44.24	1.37	0.42
TS	1	2.06	2.06	0.37	0.55
Tr(TS)	2	615.25	307.62	55.43	**0.0001**
Ti x TS	3	95.48	31.83	5.73	**0.001**
Ti x Tr(TS)	6	258.20	43.03	7.75	**0.0001**
Res	74	410.69	5.55		
Total	89	1514.40			

b)

	Trial Station 1		Trial Station 2	
Ti	t	P	t	P
1	1.80	0.18	23.45	**0.01**
2	4.35	**0.002**	3.50	**0.002**
3	No test		2.94	0.06
4	16.33	**0.004**	3.03	0.06

Table 2: Results from PERMANOVA analysis to test the difference in species richness of plankton between Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 1-4). Based on the Euclidean distance of square root transformed data. Bold values indicate statistically significant results.

Source	df	SS	MS	Pseudo-F	P(perm)
Ye	3	323.73	107.91	11.88	**0.03**
TS	1	31.31	31.31	8.57	**0.004**
Tr(TS)	2	6.09	3.05	0.83	0.44
Ye x TS	3	27.20	9.07	2.48	0.07
Ye x Tr(TS)	6	24.39	4.06	1.11	0.39
Res	79	288.50	3.65		
Total	94	701.22			

Table 3: Results from PERMANOVA analysis to test the difference in abundance of plankton between Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 1-4). Based on the Euclidean distance of square root transformed data. Bold values indicate statistically significant results.

Source	df	SS	MS	Pseudo-F	P(perm)
Ti	3	118.92	39.64	30.36	**0.02**
TS	1	1.83	1.83	2.15	0.15
Tr(TS)	2	2.62	1.31	1.54	0.23
Ti x TS	3	3.91	1.30	1.53	0.21
Ti x Tr(TS)	6	5.09	0.85	0.99	0.43
Res	79	67.18	0.85		
Total	94	199.54			

Table 4: a) Results from PERMANOVA analysis to test the difference in assemblage composition of plankton between Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 1-4), and b) Results from Pairwise test used to examine the difference between Treatments for the significant interaction term Ti x Tr(TS). Based on the Bray-Curtis similarity of square root transformed data. Bold values indicate statistically significant results.

a)

Source	df	SS	MS	Pseudo-F	P(perm)
Ye	3	42095	14032	5.14	**0.01**
TS	1	5392.30	5392.30	19.66	**0.0001**
Tr(TS)	2	600.87	300.44	1.10	0.34
Ye x TS	3	8176	2725.30	9.94	**0.0001**
Ye x Tr(TS)	6	3472.90	578.81	2.11	**0.0002**
Res	79	21667	274.27		
Total	94	81404			

b)

	Trial Station 1		Trial Station 2	
Ti	t	P	t	P
1	0.88	0.50	0.64	0.71
2	2.12	**0.008**	2.03	**0.009**
3	1.74	**0.003**	1.40	0.07
4	1.50	**0.04**	1.22	0.14

Table 5: Results from PERMANOVA analysis to test the difference in abundance of a) Decapods, b) Bivalves, c) Copepods, and d) Chaetognaths between Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 1-4). Based on the Euclidean distance of square root transformed data. Bold values indicate statistically significant results.

a) Decapods					
Source	df	SS	MS	Pseudo-F	P(perm)
Ti	3	118.92	39.64	30.36	**0.02**
TS	1	1.83	1.83	2.15	0.15
Tr(TS)	2	2.62	1.31	1.54	0.23
Ti x TS	3	3.91	1.30	1.53	0.21
Ti x Tr(TS)	6	5.09	0.85	1.00	0.43
Res	79	67.18	0.85		
Total	94	119.54			
b) Bivalves					
Source	df	SS	MS	Pseudo-F	P(perm)
Ti	3	1.19	0.40	7.02	0.06
TS	1	0.005	0.005	1.20	0.28
Tr(TS)	2	0.02	0.01	2.48	0.09
Ti x TS	3	0.17	0.06	13,34	**0.0001**
Ti x Tr(TS)	6	0.03	0.005	1.15	0.34
Res	79	0.33	0.004		
Total	94	1.74			
c) Copepods					
Source	df	SS	MS	Pseudo-F	P(perm)
Ti	3	43.88	14.63	125.01	**0.02**
TS	1	2.79	2.79	11.12	**0.002**
Tr(TS)	2	0.17	0.08	0.33	0.72
Ti x TS	3	0.35	0.12	0.46	0.71
Ti x Tr(TS)	6	1.34	0.22	0.89	0.50
Res	79	19.82	0.25		
Total	94	68.35			
d) Chaetognaths					
Source	df	SS	MS	Pseudo-F	P(perm)
Ti	3	0.15	0.05	1.45	0.41
TS	1	0.10	0.10	20.24	**0.0001**
Tr(TS)	2	0.005	0.002	0.48	0.62
Ti x TS	3	0.10	0.03	6.83	**0.0004**
Ti x Tr(TS)	6	0.005	0.008	1.61	0.15
Res	79	0.39	0.005		
Total	94	0.79			

Devon & Severn IFCA Inshore Fisheries and Conservation Authority

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10th April 2018

TO WHOM IT MAY CONCERN

University of Plymouth Scientific Research

This is notification that the University of Plymouth survey team has permission to remove a number of *Cancer pagurus* (brown crab) under the minimum conservation reference size (MCRS) of 150mm for hens and 160mm for cocks, for scientific purposes under Devon and Severn Inshore Fisheries and Conservation Authority (D&S IFCA) Byelaw 2. The permission is granted for surveys between **10th April 2018- 1st October 2018.**

Under this dispensation undersized crabs may be retained on-board and measured, then returned to the sea alive where possible. Should larger samples be taken, including the mussel rope, to be analysed ashore, then dispensation will be required from the Marine Management Organisation (MMO) for the retention of brown crab below the national MCRS of 130mm. Care must be taken to return these removed crabs alive where possible once measuring has been carried out.

If other species with a MCRS are to be removed, such as: velvet crabs, spider crabs, lobsters or spiny lobsters, further dispensation will be required.

In all cases where survey work is planned to go ahead under this authorisation please ensure D&S IFCA is notified via email to office@devonandsevernifca.gov.uk or telephone 01803 854648 informing the date, area and number of rope samples, at least one day before commencing the work.

Please inform D&S IFCA of the number of samples collected within two weeks of any survey work being undertaken.

A copy of this permission is to be kept with the survey team throughout the survey period.

Please contact the office if you require any further information.

Yours sincerely,

Sarah Clark
Deputy Chief Officer

Figure 1: Permission granted to remove crabs under D&S IFCA Byelaw 2.

Table 6: a) Results from PERMANOVA analysis to test the difference in abundance of *Trachurus trachurus* between Treatments (M_0, M_1, M_2), and b) Results from Pairwise test for the significant Treatment difference. Based on the Euclidean distance of square root transformed data. Bold values indicate statistically significant results.

a)

Source	df	SS	MS	Pseudo-F	P(perm)
Tr	3	5757.40	1719.10	24.52	**0.0001**
Res	44	3084.70	70.11		
Total	47	8242.10			

b)

Treatment	t	P
M_0, M_1	5.88	**0.0001**
M_0. M_2	4.96	**0.0001**
M_1, M_2	1.18	0.26

Table 7: Results from PERMANOVA analysis to test the difference in abundance of *Chelon labrosus* between Treatments (M_0, M_1, M_2).

Source	df	SS	MS	Pseudo-F	P(perm)
Tr	3	6.52	2.17	1.92	0.12
Res	44	49.89	1.13		
Total	47	56.41			

Table 8: a) Results from PERMANOVA analysis to test the difference in biomass of mussels between Treatments (M_0, M_1, M_2), and b) Results from Pairwise test for the significant Treatment difference. Based on the Euclidean distance of square root transformed data. Bold values indicate statistically significant results.

a)

Source	df	SS	MS	Pseudo-F	P(perm)
Tr	2	1966.50	983.25	38.22	**0.0002**
Res	13	334.48	25.73		
Total	15	2301			

b)

Treatment	t	P
M_0, M_1	7.53	**0.003**
M_0. M_2	8.87	**0.006**
M_1, M_2	1.55	0.15

Table 9: a) Results from PERMANOVA analysis to test the difference in species richness between Treatments (M_0, M_1, M_2), and b) Results from Pairwise test for the significant Treatment difference. Based on the Euclidean distance of square root transformed data. Bold values indicate statistically significant results.

a)

Source	df	SS	MS	Pseudo-F	P(perm)
Tr	2	5.86	2.93	10.95	**0.004**
Res	13	3.48	0.27		
Total	15	9.34			

b)

Treatment	t	P
M_0, M_1	2.71	0.06
M_0. M_2	10.50	**0.004**
M_1, M_2	1.56	0.17

Table 10: a) Results from PERMANOVA analysis to test the difference in crab carapace width between Treatments (M_0, M_1, M_2), and b) Results from Pairwise test used to examine the significant Treatment effect. Based on the Euclidean distance of square root transformed data. Bold values indicate statistically significant results.

a)

Source	df	SS	MS	Pseudo-F	P(perm)
Tr	2	78.84	39.42	51.91	**0.00001**
Res	419	318.20	0.760		
Total	421	397.04			

b)

Treatment	t	P
M_0, M_1	4.01	**0.0004**
M_0. M_2	6.10	**0.0001**
M_1, M_2	9.41	**0.0001**

Section B: Chapter 4

Table 1: a) Results from PERMANOVA analysis to test the difference in % cover of mussels between Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 0-4), b) Results from Pairwise test used to examine the difference between Treatments for the significant interaction term Ti x Tr(TS), and c) Results from Pairwise test used to examine the difference between Time since deployment for the significant interaction term Ti x Tr(TS). Based on the Euclidean distance of square root transformed data. Bold values indicate statistically significant results.

a)

Source	df	SS	MS
Ti	4	162	40.50
TS	1	3.82	3.82
Tr(TS)	2	285.57	142.79
Ti x TS	4	5.62	1.40
Ti x Tr(TS)	8	103.35	12.92
Res	129	403.02	3.12
Total	148	963.36	

b)

	Trial Station 1		Trial Station 2	
Year	t	P	t	P
0	No test		No test	
1	1.40	0.24	1.71	0.21
2	3.45	**0.006**	4.20	**0.002**
3	5.31	**0.0006**	5.34	**0.0002**
4	3.39	**0.005**	3.29	**0.004**

c) Rope

	Trial Station 1		Trial Station 2	
Year	t	P	t	P
0, 1	1.40	0.24	1.71	0.21
0, 2	3.45	**0.007**	4.20	**0.002**
0, 3	5.31	**0.0007**	5.38	**0.0003**
0, 4	3.39	**0.005**	3.29	**0.004**
1, 2	3.64	**0.002**	1.64	0.12
1, 3	5.33	**0.0002**	1.97	0.07
1, 4	3.72	**0.002**	1.36	0.18
2, 3	0.22	0.83	0.31	0.75
2, 4	0.46	0.66	0.15	0.89
3, 4	0.32	0.75	0.42	0.68

Table 2: Results from PERMANOVA analysis to test the difference in organic matter between Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 0-4). Based on the Euclidean distance of square root transformed data. Bold values indicate statistically significant results.

Organic matter Source	df	SS	MS	Pseudo-F	P(perm)
Ti	4	0.47	0.12	1.05	0.48
TS	1	2.77	2.77	112.22	**0.0001**
Tr(TS)	2	0.20	0.10	3.95	**0.02**
Ti x TS	4	0.45	0.11	4.51	**0.002**
Ti x Tr(TS)	8	0.18	0.02	0.93	0.50
Res	140	3.46	0.02		
Total	159	7.52			

Table 3: Results from PERMANOVA analysis to test the difference in mean particle size between Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 0-4). Based on the Euclidean distance of square root transformed data. Bold values indicate statistically significant results.

Mean particle size Source	df	SS	MS	Pseudo-F	P(perm)
Ti	4	90.05	22.51	0.65	0.65
TS	1	1331.30	1331.30	98.87	**0.0001**
Tr(TS)	2	16.19	8.09	0.60	0.55
Ti x TS	4	138.81	34.70	2.58	**0.04**
Ti x Tr(TS)	8	35.89	4.49	0.33	0.95
Res	140	1885.20	13.47		
Total	159	3497.40			

Table 4: a) Results from PERMANOVA analysis to test the difference in oxidative reduction potential between Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 0-4), b) Results from Pairwise test used to examine the difference between Treatments for the significant interaction Ti x Tr(Si), and c) Results from Pairwise test used to examine the difference between Time since deployment for the significant interaction Ti x Tr(Si). Based on the Euclidean distance of square root transformed data. Bold values indicate statistically significant results.

Oxidative reduction potential

a)

Source	df	SS	MS	Pseudo-F	P(perm)
Ti	4	1583.40	395.86	6.85	0.05
TS	1	797.59	797.59	286.38	**0.0001**
De	5	739.84	147.97	26.42	**0.003**
Tr(TS)	2	23.64	11.82	4.24	**0.01**
Ti x TS	4	178.73	44.68	16.04	**0.0001**
Ti x De	19	121.56	6.40	2.17	0.12
TS x De	5	18.77	3.75	1.35	0.24
Ti x Tr(TS)	8	133.48	16.69	5.99	**0.0001**
Tr(TS) x De	9	6.13	0.68	0.24	0.97
Ti x TS x De	12	32.34	2.69	0.97	0.48
Ti x Tr(TS) x De	26	30.79	1.18	0.43	0.99
Res	527	1467.70	2.79		
Total	622	5134.10			

b)	Year 0				Year 1			
	TS 1		TS 2		TS 1		TS 2	
	t	P(perm)	t	P(perm)	t	P(perm)	t	P(perm)
Rope, Control	2.62	**0.009**	0.63	0.54	2.57	**0.01**	0.95	0.34
	Year 2				Year 3			
	TS 1		TS 2		TS 1		TS 2	
	t	P(perm)	t	P(perm)	t	P(perm)	t	P(perm)
Rope, Control	7.20	**0.0001**	2.12	**0.04**	1.07	0.30	2.42	**0.02**
	Year 4							
	TS 1		TS 2					
	t	P(perm)	t	P(perm)				
Rope, Control	0.78	0.44	0.25	0.80				

c) Trial Station 1					Trial Station 2			
	Rope		Control		Rope		Control	
Year	T	P	t	P	t	P	t	P
0, 1	5.66	**0.0001**	4.89	**0.0001**	3.64	**0.0006**	5.39	**0.0001**
0, 2	21.17	**0.0001**	2.95	**0.005**	6.06	**0.0001**	9.84	**0.0001**
0, 3	8.36	**0.0001**	2.27	**0.03**	8.89	**0.0001**	8.40	**0.0001**
0, 4	13.32	**0.0001**	5.60	**0.0001**	2.83	**0.006**	2.24	**0.03**
1, 2	6.04	**0.0001**	1.59	0.12	2.21	**0.03**	3.91	**0.0003**
1, 3	0.007	0.99	2.34	**0.03**	3.65	**0.0006**	2.94	**0.004**
1, 4	1.49	0.15	1.41	0.17	2.00	**0.04**	3.49	**0.0005**

2, 3	10.22	**0.0001**	0.79	0.44	0.86	0.38	0.76	0.45
2, 4	9.76	**0.0001**	1.09	0.28	5.18	**0.0001**	8.03	**0.0001**
3, 4	2.23	**0.03**	2.72	**0.009**	9.24	**0.0001**	6.69	**0.0001**

Table 5: Full epibenthic taxa list with category (S+S = sessile/sedentary, M = mobile). Green ticks indicated that they were enumerated from this video method. Red ticks indicate that they were also recorded from this video method.

Phylum	Taxa	Common name	Category	Frames	Video	Baited
Porifera	Branching sponges	Branching sponges	S+S	✓ (green)	✓ (red)	
	Suberites spp.	A sponge	S+S	✓ (green)	✓ (red)	
	Sycon ciliatum	A sponge	S+S	✓ (green)	✓ (red)	
Cnidaria	*Alcyonium digitatum*	Dead man's fingers	S+S	✓ (red)	✓ (green)	
	Cereus pedunculatus	Daisy anemone	S+S	✓ (green)	✓ (red)	
	Cerianthus spp.	Burrowing anemones	S+S	✓ (green)	✓ (red)	
	Hydroid spp.	Hydroids	S+S	✓ (green)	✓ (red)	
	Metridium dianthus	Plumose anemone	S+S	✓ (green)	✓ (red)	
	Nemertesia antennina	Sea beard	S+S	✓ (green)	✓ (red)	
	Nemertesia ramosa	A hydroid	S+S	✓ (green)	✓ (red)	
	Sagartiidae	A sea anemone	S+S	✓ (green)	✓ (red)	
	Urticina felina	Dahlia anemone	S+S	✓ (green)	✓ (red)	
Mollusca	*Aequipecten opercularis*	Queen scallop	S+S	✓ (red)	✓ (green)	✓ (red)
	Buccinum undatum	Common whelk	S+S	✓ (green)	✓ (red)	✓ (red)
	Calliostoma zizyphinum	Painted topshell	S+S	✓ (green)	✓ (red)	
	Pecten maximus	King scallop	S+S	✓ (red)	✓ (green)	
	Sepia officinalis	Common cuttlefish	S+S	✓ (red)	✓ (green)	✓ (red)
	Tritia reticulata	Netted dog whelk	S+S	✓ (green)	✓ (red)	✓ (red)

	Turritella communis	Common tower shell	S+S	✓	✓	
Annelida	*Acromegalomma vesiculosum*	A fanworm	S+S	✓	✓	
	Aphrodita aculeata	Sea mouse	S+S	✓	✓	
	Chaetopterus variopedatus	Parchment worm	S+S	✓	✓	
	Lanice conchilega	Sand mason	S+S	✓	✓	
	Myxicola infundibulum	A fanworm	S+S	✓	✓	
	Salmacina dysteri	Coral worm	S+S	✓	✓	
	Serpula vermicularis	A tube worm	S+S	✓	✓	
Crustacea	*Atelecyclus rotundatus*	Circular crab	S+S	✓	✓	
	Cancer pagurus	Brown crab	S+S	✓	✓	✓
	Goneplax rhomboides	Angular crab	S+S	✓	✓	✓
	Homarus gammarus	European lobster	M			✓
	Hyas coarctatus	Toad crab	S+S	✓	✓	✓
	Inachus spp.	Scorpion spider crabs	S+S	✓	✓	✓
	Liocarcinus spp.	Harbour crabs	S+S	✓	✓	✓
	Macropodia spp.	Slender spider crabs	S+S	✓	✓	✓
	Maja squinado	Common spider crab	S+S	✓	✓	✓
	Necora puber	Velvet swimming crab	S+S	✓	✓	✓
	Pagurus spp.	Hermit crabs	S+S	✓	✓	✓
Bryozoa	*Alcyonidium diaphanum*	Sea chervil	S+S	✓	✓	
	Bugulidae	Erect bryozoan	S+S	✓	✓	
	Cellaria fistulosa	A bryozoan	S+S	✓	✓	
	Cellepora pumicosa	A bryozoan	S+S	✓	✓	
	Flustridae spp.	Hornwrack	S+S	✓	✓	
Echino-dermata	*Asterias rubens*	Common starfish	S+S	✓	✓	✓

	Astropecten irregularis	Sand sea star	S+S	✓	✓	✓
	Luidia ciliaris	Seven-armed starfish	S+S	✓	✓	
	Ophiura ophiura	Serpent star	S+S	✓	✓	✓
	Psammechinus miliaris	Green sea urchin	S+S	✓	✓	
Chordata	*Ascidia conchilega*	A sea squirt	S+S	✓	✓	
	Ascidiella aspersa	Fluted sea squirt	S+S	✓	✓	
	Callionymus lyra	Common dragonet	M	✓	✓	✓
	Cepola macrophthalma	Red bandfish	S+S		✓	
	Chelidonichthys cuculus	Red gurnard	M	✓	✓	✓
	Chelidonichthys lucerna	Tub gurnard	M			✓
	Eutrigla gurnardus	Grey gurnard	M			✓
	Gobiidae spp.	Gobies	S+S	✓	✓	✓
	Limanda limanda	Dab	S+S		✓	
	Merlangius merlangus	Whiting	M			✓
	Microstomus kitt	Lemon sole	S+S	✓	✓	
	Molgula manhattensis	Sea grapes	S+S	✓	✓	
	Parablennius gattorugine	Tompot blenny	M			✓
	Pleuronectes platessa	European plaice	S+S	✓	✓	
	Phallusia mammillata	White sea squirt	S+S	✓		
	Scyliorhinus canicula	Small-spotted catshark	M	✓	✓	✓
	Solea solea	Sole	S+S	✓	✓	
	Syngnathus acus	Greater pipefish	S+S	✓	✓	
	Trachurus trachurus	Atlantic horse mackerel	M			✓
	Trisopterus luscus	Pouting	M		✓	✓
	Trisopterus minutus	Poor cod	M		✓	✓
	Zeus faber	John dory	M			✓

Table 6: Full infauna taxa list.

Phylum	Class	Order	Taxa
Cnidaria	Anthozoa	Alcyonacea	*Alcyonium digitatum*
	Anthozoa	Ceriantharia	*Cerianthus lloydii*
	Anthozoa	Actinaria	Edwardsiidae
	Anthozoa	Actinaria	Actiniidae
Platyhelminthes	Turbellaria		Turbellaria
Nemertea			Nemertea
Sipuncula	Sipunculiidae		Sipunculiidae
Sipuncula	Sipunculiidae	Golfingiida	*Golfingia (Golfingia) vulgaris vulgaris*
Sipuncula	Sipunculiidae	Golfingiida	*Phascolion (Phascolion) strombus strombus*
Entoprocta			Entoprocta
Annelida	Polychaeta	Terebellida	Ampharetidae
	Polychaeta	Amphinomida	Amphinomidae
	Polychaeta	Phyllodocida	Aphroditidae
	Polychaeta	Capitellida	Capitellidae
	Polychaeta	Terebellida	Cirratulidae
	Polychaeta	Eunicida	Eunicidae
	Polychaeta	Terebellida	Flabelligeridae
	Polychaeta	Phyllodocida	Glyceridae
	Polychaeta	Phyllodocida	Goniadidae
	Polychaeta	Phyllodocida	Hesionidae
	Polychaeta	Spionida	Magelonidae
	Polychaeta	Capitellida	Maldanidae
	Polychaeta	Phyllodocida	Nephtyidae
	Polychaeta	Phyllodocida	Nereididae
	Polychaeta	Terebellida	Pectinariidae
	Polychaeta	Phyllodocida	Phyllodocidae
	Polychaeta	Phyllodocida	Polynoidae
	Polychaeta	Opheliida	Opheliidae
	Polychaeta	Orbiniida	Orbiniidae
	Polychaeta	Sabellida	Oweniidae
	Polychaeta	Sabellida	Sabellidae
	Polychaeta	Opheliida	Scalibregmatidae
	Polychaeta	Sabellida	Serpulidae
	Polychaeta	Spionida	Spionidae
	Polychaeta	Phyllodocida	Syllidae
	Polychaeta	Terebellida	Terebellidae
Crustacea	Malacostraca	Decapoda	*Alpheus glaber*
	Malacostraca	Amphipoda	Ampeliscidae
	Malacostraca	Amphipoda	Aoridae
	Malacostraca	Amphipoda	Atylidae
	Malacostraca	Decapoda	*Philocheras* spp.
	Malacostraca	Amphipoda	Dexaminidae
	Malacostraca	Cumacea	*Diastylis* spp.
	Malacostraca	Decapoda	Galatheidae
	Malacostraca	Isopoda	*Gnathia* spp.
	Malacostraca	Decapoda	*Ebalia granulosa*

	Malacostraca	Amphipoda	Leucothoidae
	Malacostraca	Amphipoda	Maeridae
	Malacostraca	Amphipoda	Melitidae
	Malacostraca	Decapoda	*Pagurus bernhardus*
	Malacostraca	Decapoda	*Palaemon* spp.
	Malacostraca	Amphipoda	Photidae
	Malacostraca	Decapoda	*Pisidia longicornis*
	Malacostraca	Decapoda	Portunidae
	Malacostraca	Decapoda	*Processa* spp.
Mollusca	Gastropoda	Littorinimorpha	*Aporrhais pespelecani*
	Bivalvia		Bivalvia
	Gastropoda	Neogastropoda	*Buccinum undatum*
	Bivalvia	Myida	*Corbula gibba*
	Polyplacophora	Lepidopleurina	*Leptochiton* spp.
	Bivalvia	Mylitida	*Mytilus edulis*
	Gastropoda	Nudibranchia	*Onchidoris* spp.
	Gastropoda	Heterobranchia	Heterobranchia
	Bivalvia	Adapedonta	*Ensis* spp.
	Gastropoda	Cephalaspidea	*Philine* spp.
	Bivalvia	Veneroida	*Abra alba*
	Gastropoda	Caenogastropoda	*Turritella communis*
Bryozoa	Gymnolaemata	Ctenosomatida	*Alcyonidium diaphanum*
	Gymnolaemata	Cheilostomatida	*Bugula* spp.
	Gymnolaemata	Cheilostomatida	*Cellepora pumicosa*
	Gymnolaemata	Cheilostomatida	*Schizomavella* spp.
Echinodermata	Asteroidea		Asteroidea (juv.)
	Holothuroidea		Holothuroidea (juv.)
	Ophiuroidea		Ophiuroidea
	Ophiuroidea		Ophiuroidea (juv.)
	Ophiuroidea	Ophiurida	*Amphipholis squamata*
	Ophiuroidea	Ophiurida	*Amphiura filiformis*
	Echinoidea	Spatangoida	*Echinocardium cordatum*
	Holothuroidea	Apodida	*Leptosynapta* spp.
	Ophiuroidea	Ophiurida	*Ophiura ophiura*
Chordata	Ascidiacea		Ascidiacea
	Ascidiacea		Ascidiacea (juv.)
	Ascidiacea	Phlebobranchia	*Ascidiella scabra*
	Ascidiacea	Phlebobranchia	*Ciona intestinalis*
	Ascidiacea	Phlebobranchia	*Molgula* spp.

Table 7: a) Results from PERMANOVA analysis to test the difference in species richness of sessile and sedentary epifauna between Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 0-4), and b) Results from Pairwise test used to examine the difference between Treatments for the significant interaction term Ti x Tr(TS). Based on the Euclidean distance of square root transformed data. Bold values indicate statistically significant results.

a)

Source	df	SS	MS	Pseudo-F	P(perm)
Ti	4	238.10	59.52	0.81	0.58
TS	1	439.02	439.02	87.19	**0.0001**
Tr(TS)	2	63.44	31.72	6.30	**0.002**
Ti x TS	4	293.27	73.32	14.56	**0.0001**
Ti x Tr(TS)	8	189.91	23.74	4.71	**0.0001**
Res	129	649.56	5.04		
Total	148	1873.30			

b)

	Trial Station 1		Trial Station 2	
Year	t	P	t	P
0	1.90	0.11	2.91	**0.04**
1	2.86	**0.002**	0.16	0.92
2	2.78	**0.02**	2.02	0.07
3	0.54	0.67	3.18	**0.01**
4	0.97	0.37	3.06	**0.01**

Table 8: a) Results from PERMANOVA analysis to test the difference in abundance of sessile and sedentary epifauna between Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 0-4), and b) Results from Pairwise test used to examine the difference between Treatments for the significant interaction term Ti x Tr(TS). Based on the Euclidean distance of square root transformed data. Bold values indicate statistically significant results.

a)

Source	df	SS	MS	Pseudo-F	P(perm)
Ti	4	1089.10	272.28	1.12	0.42
TS	1	3255.10	3255.10	190.85	**0.0001**
Tr(TS)	2	386.00	193.00	11.32	**0.0001**
Ti x TS	4	962.59	240.65	14.11	**0.0001**
Ti x Tr(TS)	8	275.41	34.43	2.02	**0.04**
Res	129	2200.20	17.06		
Total	148	8168.40			

b)

	Trial Station 1		Trial Station 2	
Year	t	P	t	P
0	0.81	0.44	0.94	0.37
1	2.81	**0.009**	0.19	0.85
2	2.96	**0.008**	1.82	0.08
3	0.07	0.94	1.55	0.15
4	3.66	**0.004**	0.02	0.99

Table 9: a) Results from PERMANOVA analysis to test the difference in assemblage composition of sessile and sedentary epifauna between Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 0-4), and b) Results from Pairwise test used to examine the difference between Treatments for the significant interaction term Ti x Tr(TS). Based on the Bray-Curtis similarities of square root transformed data. Bold values indicate statistically significant results.

a)

Source	df	SS	MS	Pseudo-F	P(perm)
Ti	4	63231.00	15808.00	3.77	**0.006**
TS	1	58441.00	58441.00	84.33	**0.0001**
Tr(TS)	2	9.82E+03	4912.40	7.09	**0.0001**
Ti x TS	4	1.67E+04	4171.50	6.02	**0.0001**
Ti x Tr(TS)	8	11658.00	1457.30	2.10	**0.0002**
Res	129	89403.00	693.04		
Total	148	2.49E+05			

b)

	Trial Station 1		Trial Station 2	
Year	t	P	t	P
0	1.86	**0.007**	1.16	0.24
1	1.55	**0.04**	0.41	**0.04**
2	2.33	**0.008**	1.47	0.08
3	1.73	**0.007**	1.74	**0.004**
4	2.21	**0.009**	1.82	**0.01**

Table 10: Results from PERMANOVA analysis to test the difference in species richness of mobile epifauna between Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 0-4). Based on the Euclidean distance of square root transformed data. Bold value indicates a statistically significant result.

Source	df	SS	MS	Pseudo-F	P(perm)
Ti	4	30.72	7.68	2.99	0.17
TS	1	0.21	0.21	0.27	0.61
Tr(TS)	2	4.42	2.21	2.83	0.06
Ti x TS	4	10.25	2.56	3.28	**0.02**
Ti x Tr(TS)	8	3.83	0.48	0.61	0.77
Res	100	78.17	0.78		
Total	119	127.59			

Table 11: a) Results from PERMANOVA analysis to test the difference in abundance of mobile epifauna between Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 0-4), and b) Results from Pairwise test used to examine the difference between Treatments for the significant interaction term Ti x Tr(TS). Based on the Euclidean distance of square root transformed data. Bold values indicate statistically significant results.

a)

Source	df	SS	MS	Pseudo-F	P(perm)
Ti	4	453.19	113.30	2.30	0.21
TS	1	84.15	84.15	10.23	**0.002**
Tr(TS)	2	89.98	44.99	5.47	**0.006**
Ti x TS	4	197.41	49.35	6.00	**0.0002**
Ti x Tr(TS)	8	163.67	20.46	2.49	**0.02**
Res	100	822.37	8.22		
Total	119	1810.80			

b)

	Trial Station 1		Trial Station 2	
Year	t	P	t	P
0	0.29	0.79	0.20	0.83
1	1088	0.08	0.45	0.65
2	0.03	0.98	1.58	0.15
3	0.25	0.80	0.97	0.38
4	4.65	**0.001**	0.27	0.78

Table 12: a) Results from PERMANOVA analysis to test the difference in assemblage composition of mobile epifauna between Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 0-4), and b) Results from Pairwise test used to examine the difference between Treatments for the significant interaction term Ti x Tr(TS). Based on the Bray-Curtis similarities of square root transformed data. Bold values indicate statistically significant results.

a)

Source	df	SS	MS	Pseudo-F	P(perm)
Ti	4	51943.00	12986.00	5.81	**0.003**
TS	1	5093.10	5093.10	9.23	**0.0001**
Tr(TS)	2	3.27E+03	1633.70	2.96	**0.01**
Ti x TS	4	8.94E+03	2233.80	4.05	**0.0001**
Ti x Tr(TS)	8	9428.80	1178.60	2.13	**0.005**
Res	100	55207.00	552.07		
Total	119	1.34E+05			

b)

	Trial Station 1		Trial Station 2	
Year	t	P	t	P
0	1.13	0.29	0.38	0.92
1	1.42	0.10	1.14	0.29
2	0.87	0.63	1.20	0.23
3	1.63	0.06	1.17	0.31
4	3.45	**0.003**	1.18	0.24

Table 13: Results from PERMANOVA analysis to test the difference in species richness of infauna between Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 0-3). Based on the Euclidean distance of square root transformed data. Bold value indicates a statistically significant result.

Species richness

Source	df	SS	MS	Pseudo-F	P(perm)
Ti	3	17.31	5.77	0.59	0.68
TS	1	63.28	63.28	4.85	**0.03**
Tr(TS)	2	49.53	24.77	1.90	0.16
Ti x TS	3	29.16	9.72	0.74	0.54
Ti x Tr(TS)	6	94.09	15.68	1.20	0.30
Res	112	1462.50	13.06		
Total	127	1715.90			

Table 14: Results from PERMANOVA analysis to test the difference in total abundance of infauna between Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 0-3). Based on the Euclidean distance of square root transformed data. Bold values indicate statistically significant results.

Total abundance					
Source	df	SS	MS	Pseudo-F	P(perm)
Ti	3	732.57	244.19	176.12	**0.02**
TS	1	1421.90	1421.90	19.83	**0.0001**
Tr(TS)	2	288.29	144.15	2.01	0.14
Ti x TS	3	4.16	1.39	0.03	0.99
Ti x Tr (TS)	6	586.02	97.67	1.36	0.24
Res	112	8031.10	71.71		
Total	127	11064.00			

Table 15: Results from PERMANOVA analysis to test the difference in assemblage composition of infauna between Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 0-3). Based on the Bray-Curtis similarities of square root transformed data. Bold values indicate statistically significant results.

Assemblage composition					
Source	df	SS	MS	Pseudo-F	P(perm)
Ti	3	36269.00	12090.00	3.41	**0.03**
TS	1	45982.00	45982.00	25.64	**0.0001**
Tr(TS)	2	3655.70	1827.80	1.02	0.44
Ti x TS	3	10622.00	3540.80	1.97	**0.0005**
Ti x Tr(TS)	6	11381.00	1896.80	1.06	0.35
Res	112	2.01E+05	1793.50		
Total	127	3.09E+05			

Table 16: Results from PERMANOVA analysis to test the difference in abundance of ai) Schooling fish, b) *Buccinum undatum*, and c) *Asterias rubens* between Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 0-4). aii) Results from Pairwise test used to examine the difference between Treatments for the significant interaction term Ti x Tr(TS) for schooling fish. Based on the Euclidean distance of square root transformed data. Bold values indicate statistically significant results.

ai) Schooling fish

Source	df	SS	MS	Pseudo-F	P(perm)
Ti	4	410.02	102.51	2.10	0.24
TS	1	114.95	114.95	16.79	**0.0002**
Tr(TS)	2	23.39	11.69	1.71	0.19
Ti x TS	4	195.17	48.79	7.12	**0.0001**
Ti x Tr(TS)	8	123.14	15.39	2.25	**0.03**
Res	100	684.85	6.85		
Total	119	1551.50			

aii)

	Trial Station 1		Trial Station 2	
Year	t	P	t	P
0	0.20	0.86	0.41	0.69
1	1.84	0.09	0.03	0.97
2	0.50	0.63	0.81	0.43
3	1.70	0.10	1.22	0.27
4	3.17	**0.01**	0.70	0.50

b) *Buccinum undatum*

Source	df	SS	MS	Pseudo-F	P(perm)
Ti	4	1.06	0.27	1.80	0.21
TS	1	0.51	0.51	6.83	**0.009**
Tr(TS)	2	0.47	0.24	3.15	**0.04**
Ti x TS	4	0.59	0.15	1.97	0.10
Ti x Tr(TS)	8	0.64	0.08	1.07	0.39
Res	129	9.64	0.07		
Total	148	12.91			

c) *Asterias rubens*

Source	df	SS	MS	Pseudo-F	P(perm)
Ti	4	6.70	1.68	0.97	0.52
TS	1	3.50	3.50	12.87	**0.0001**
Tr(TS)	2	9.94	4.97	18.28	**0.0001**
Ti x TS	4	6.89	1.72	6.33	**0.0001**
Ti x Tr(TS)	8	2.34	0.29	1.07	0.39
Res	129	35.08	0.27		
Total	148	64.45			

Table 17: Results from PERMANOVA analysis to test the difference in abundance of a) polychaetes and b) amphipods between Treatment (Rope, Control) at each Trial Station (1, 2) over Time since deployment (Years 0-3). Based on the Euclidean distance of square root transformed data. Bold values indicate statistically significant results.

a) Polychaetes					
Source	df	SS	MS	Pseudo-F	P(perm)
Ti	3	837.75	279.25	15.98	**0.03**
TS	1	2055.30	2055.30	32.08	**0.0001**
Tr(TS)	2	208.71	104.36	1.63	0.20
Ti x TS	3	52.42	17.47	0.27	0.84
Ti x Tr(TS)	6	381.59	63.60	0.99	0.43
Res	112	7175.10	64.06		
Total	127	10711.00			
b) Amphipods					
Source	df	SS	MS	Pseudo-F	P(perm)
Ti	3	156.77	52.26	0.72	0.64
TS	1	38.53	38.53	2.43	0.13
Tr(TS)	2	102.60	51.30	3.24	**0.04**
Ti x TS	3	217.95	72.65	4.58	**0.004**
Ti x Tr(TS)	6	143.94	23.99	1.51	0.1791
Res	112	1774.70	15.85		
Total	127	2434.50			

Table 18: Results from regression analysis (ANOVA) to test the relationship between % cover of *Mytilus edulis* and a) schooling fish, b) *Buccinum undatum*, and c) *Asterias rubens*. Bold value indicates a statistically significant result

a) Schooling fish					
Source	df	SS	MS	F	P(perm)
Regression	1	860.12	860.12	0.46	0.50
Error	118	220121	1865.43		
Total	119	220981			
b) *Buccinum undatum*					
Source	df	SS	MS	F	P(perm)
Regression	1	0.27	0.27	2.71	0.10
Error	147	14.43	0.10		
Total	148	14.69			
c) *Asterias rubens*					
Source	df	SS	MS	F	P(perm)
Regression	1	169.66	169.66	55.16	**0.0001**
Error	147	452.11	3.08		
Total	148	621.77			

Section C: Chapter 5

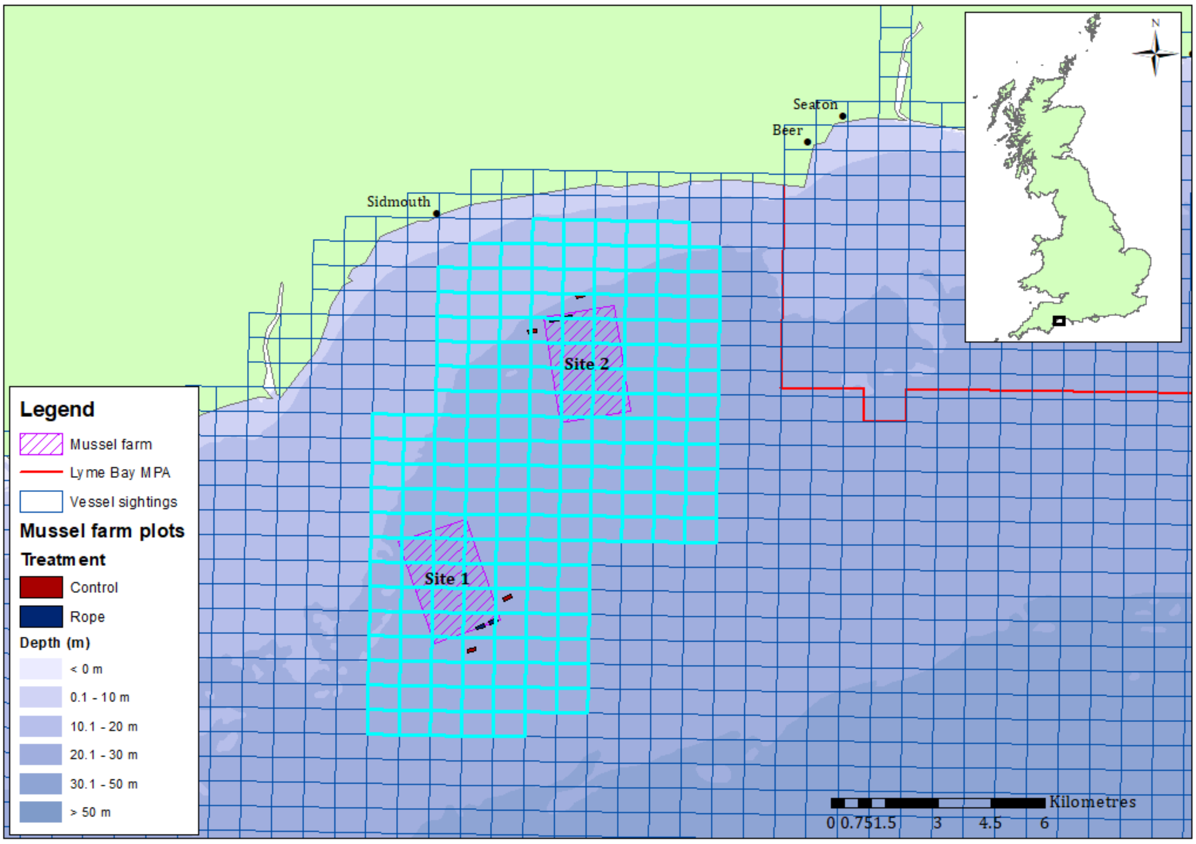


Figure 1: 3 km area around the farm from which vessel sightings were taken.

Fisher's survey

Please make the interviewee aware of the following and provide copies of the information sheet and a reference copy of the consent form:

This interview forms part of a study being carried out by Plymouth University to evaluate the impact of the development of an open-ocean mussel farm on ecosystem services.

The interview should last no longer than 45min -1hr. The interview will be recorded and notes taken. Answers given will **remain confidential** and only anonymised, grouped data will be used in the analysis and reporting. By taking part in this interview, you are consenting to your data being used as part of this study. You have the right to withdraw from this interview or to request your data be removed from the project at any time. You do not have to answer any individual question that you do not wish to answer.

Ticking the following box indicates that you have read and understand the information provided above, that you willingly agree to participate and that you may withdraw your consent at any time and end participation.

☐

Date:

Name ………………………………………………………………

Postcode ………………………….

Home port ………………………………………………………………

Boat name and length ………………………………………………………………

1. What were your main target species in 2017?

   ………

   ………

2. Approximately what was your average catch in tonnes per fishing trip in Lyme Bay in 2017?

   ………

3. Have you ever fished in the area shown on the included map? Yes / No

   If you answered No, please go straight to **Section C: Your views**

If your usual type of fishing gear is '**Mobile**' then please fill out **Sections A and C**. If your usual type of fishing gear is '**Static**', please fill out **Sections B and C**.

Section A: Mobile gear fishers

4. Have you ever fished in the area showed on the map? Yes / No

5. When did you stop fishing in the buoyed sites? Why?

   ……………………………………………………………………………………………………

   ……………………………………………………………………………………………………

6. How often did you fish in the area before it was closed off for the mussel farm?

   ……………………………………………………………………………………………………

7. What were your main target species in this area?

   ……………………………………………………………………………………………………

   ……………………………………………………………………………………………………

8. Do you fish around the outside (within 3 km) of the mussel farm? Yes / No
   If **Yes**, please see included map and mark the areas where you fish. **Go to Q8**

   If **No**, please go to **Section C: Your views**

9. What species have you caught around the mussel farm? Have you noticed any changes in your catch in the last 2 years? Why do you think this might have happened?

   ……………………………………………………………………………………………………

   ……………………………………………………………………………………………………

10. Have you chosen to fish around the mussel farm over other sites? If so, please explain why.

....

....

11. Have you noticed an increase or decrease in any target or non-targets species around the mussel farm? Why do you think this has happened?

....

....

12. How often do you go fishing (average trips per season), what are you target species and what gear type do you use? Approximately what is your average catch by species in tonnes per fishing trip? How has this changed from previous years?

....

....

	Winter Dec-Feb	Spring March-May	Summer June-August	Autumn Sept-Nov
Gear type				
Average number of trips				
Target species				

<u>Section B: Static gear fishers</u>

13. Have you ever fished in the area shown on the map? Yes / No

14. Have you stopped fishing in this area? Yes / No

15. Have you changed where you put your gear in this area? Yes / No

16. How often did you fish in the area before it was developed as a mussel farm?

………

17. What were you main target species in this area?

………

………

18. Do you fish in or around (within 3km) the mussel farm now? Yes / No
If **Yes**, please see included map and mark the areas where you fish. **Go to Q17**

If **No**, go to **<u>Section C: Your views</u>**

19. What species have you caught in or around the mussel farm?

………

………

20. Have you chosen to fish in or around the mussel farm over other sites? If so, please explain why.

………

………

21. Have you noticed an increase or decrease in the abundance of any target or non-target species in or around the mussel farm? Why do you think this has happened?

………

………

22. Approximately what is your average catch by species in tonnes per fishing trip around the mussel farm? ………………………… How has this changed from previous years?

………

………

Section C: Your views

23. How do you feel about the development of the open-ocean mussel farm in Lyme Bay?

……………………………………………………………………………………………………

……………………………………………………………………………………………………

24. Did you receive any information prior to the development of the farm? From who? Did you get the information that you needed?

……………………………………………………………………………………………………

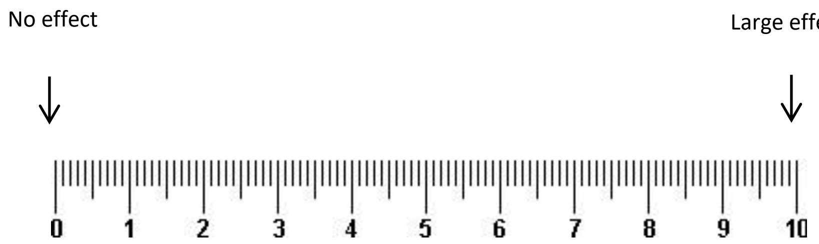
……………………………………………………………………………………………………

25. Do you think the mussel farm will have any positive or negative effects?

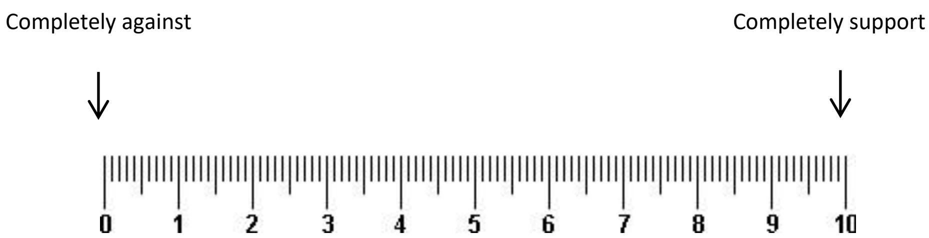
……………………………………………………………………………………………………

……………………………………………………………………………………………………

26. On a scale of 0-10, **where 0 = no effect and 10 = a large effect**, how much has the development of the open-ocean mussel farm affected your decision as to where you fish in Lyme Bay?



27. On a scale of 0-10, **where 0 = completely against and 10 = completely support**, to what extent do you support the development of the open-ocean mussel farm in Lyme Bay?



28. Please feel free to comment on anything that has not been addressed elsewhere on this questionnaire.

………………………………………………………………………………………………………

………………………………………………………………………………………………………

………………………………………………………………………………………………………

Socio-demographic questions

The following questions are required to validate the study; your cooperation in answering them is greatly appreciated. Please remember that the answers are anonymous and confidential, and only aggregated data will be used for the project.

29. Gender a) Male b) Female

30. Age group

a) 18-25 d) 46-55

b) 26-35 e) 56-65

c) 36-45 f) Over 65

31. What is the highest form of education that you have completed?

a) Primary d) Higher education

b) Secondary e) Postgraduate education

c) Further education (e.g. A-levels) f) Other

Thank you for taking part in this survey.

Please could you recommend another fisher to contact?